8-2014

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Citation

MA, Xiaoping; TAN, Hwee Xian; and VALERA, Alvin C.. GTA-m: Greedy Trajectory-Aware (m copies) routing for airborne networks. (2014). *AIRBORNE '14: Proceedings of the third ACM workshop on Airborne networks and communications, Philadelphia, August 11*. 3-8.
Available at: https://ink.library.smu.edu.sg/sis_research/4233

GTA-m: Greedy Trajectory-Aware (m copies) Routing for Airborne Networks

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ABSTRACT

Airborne networks have potential applications in both civilian and military domains – such as passenger in-flight Internet connectivity, air traffic control and in intelligence, surveillance and reconnaissance (ISR) activities. However, airborne networks suffer from frequent disruptions due to high node mobility, ad hoc connectivity and line-of-sight blockages. These challenges can be alleviated through the use of disruption-tolerant networking (DTN) techniques. In this paper, we propose GTA-m, a multi-copy greedy trajectory-aware routing protocol for airborne networks. GTA-m employs DTN capabilities and exploits the use of flight information to forwarded bundles *greedily* to intended destination(s). To alleviate the local minima issues that are inherent in greedy algorithms, GTA-m allows $m \geq 1$ copies of each bundle to be replicated throughout the entire network. We study the performance of GTA-m by simulating flights with varying numbers of aircraft and ground stations. Through simulations in OPNET, we show that GTA-m improves the average bundle delay by 34% and 52% as compared to conventional DTN routing protocols such as Spray-and-Wait and Epidemic respectively.

Categories and Subject Descriptors

C.2.2 [**Network Protocols**]: Routing Protocols

Keywords

Delay/Disruption tolerant networking; Airborne networks; Trajectory awareness

1. INTRODUCTION

An airborne network is an infrastructure that provides communication transport services through at least one node that is on a platform capable of flight [1]. In recent years, airborne networks have found many use case applications in both the military and civilian domains. Military airborne networks comprise assets such as fighter jets, unmanned aerial vehicles (UAVs) and tankers [4], and can be used for airborne intelligence, surveillance and reconnaissance (ISR). Civilian airborne networks are composed of passenger aircraft and ground stations, and have uses in providing Internet connectivity to in-flight passengers as well as complementing the air traffic control system.

Despite the diverse potential applications of airborne networks, several challenges that inhibit the practicality and reliability of these networks need to be addressed. A typical mobile ad-hoc airborne network is susceptible to frequent link disruptions due to: (i) high and uncontrollable aircraft mobility; (ii) large aircraft separation; and/or (iii) flight paths that traverse over regions (*e.g.* water bodies) without ground surface communications infrastructure [9]. Subsequently, many aircraft today rely on expensive, low-bandwidth and high-latency satellite links (SATCOM) for communications.

This paper focuses on the use of ad-hoc, multi-hop air-to-air communications as a complement and/or alternative to SATCOM. Such a decentralized communication model has the advantages of lower per-data-byte-cost, higher data rates and higher scalability over SATCOM; the latter being of particular importance with the expected growth in air traffic and corresponding increase in airborne communications.

We propose GTA-m (Greedy Trajectory-Aware (m copies)) – a multi-copy greedy trajectory-aware routing protocol for airborne networks. GTA-m assumes that all ground stations provide gateways to the Internet, and exploits the *a priori* knowledge of flight trajectories to compute the *estimated time of arrival* (ETA) of an aircraft to the nearest ground station along its flight path. Data bundles are then *greedily* forwarded from an aircraft to another, based on the shortest ETA of the aircraft to *any* ground station. To alleviate the local minima issues that are inherent of greedy algorithms, GTA-m allow multiple ($m \geq 1$) copies of each bundle to be replicated throughout the network. In addition, disruption tolerant networking (DTN) techniques are utilized to store-carry-and-forward bundles in order to mitigate the intermittent link connectivity in airborne networks.

We implemented GTA-m in the OPNET simulator, and studied its performance by simulating flights in Continental Europe, with varying number of aircraft and ground stations. Through simulations in OPNET, we show that GTA-m improves the average bundle delay by 34% and 52% as compared to conventional DTN routing protocols such as Spray-and-Wait and Epidemic respectively.

AIRBORNE'14, August 11, 2014, Philadelphia, PA, USA.

http://dx.doi.org/10.1145/2636582.2636828.

2. BACKGROUND AND RELATED WORK

Airborne networks are one of the top ten emerging technologies that will have great impacts on the world [2]. However, airborne network characteristics are radically different from that of the wired Internet [12], whereby end-to-end connections are relatively stable (with rare disruptions or disconnections) and link latencies are significantly smaller. Although modifications to conventional networking techniques such as TCP/IP have been proposed for airborne networks [11][3], these are insufficient to overcome the highly dynamic links of a network composed of mobile airborne nodes.

Mobile ad hoc network (MANET) routing protocols [16] - which are designed for self-configuring and infrastructureless networks of mobile nodes - have been proposed for use in aeronautical networks [7][9][14]. [9] studies the feasibility of an aeronautical MANET over the North Atlantic Corridor and concludes that such an approach delivers almost all packets to the destinations with the respective minimum hop counts. Similarly, [14] suggests the use of MANETs to improve the connectivity of aircraft and ground-based traffic controllers in oceanic regions (such as North Pacific Ocean and North Atlantic Ocean). However, MANET protocols are generally unable to perform well in airborne networks, due to the lack of continuous paths between highly mobile source-destination pairs.

2.1 Disruption Tolerant Networking

Disruption-tolerant networking (DTN) enables communication in extreme environments where there exists a lack of contemporaneous paths between source-destination nodal pairs. Its robustness towards disruptions and long delays makes it an appealing choice for addressing the problems of frequent link failures as well as long and variable latencies in airborne networks [4][5]. In DTN, disruptions and delays in the network are handled through a ‘store-carry-and-forward’ paradigm. Every node can serve as an intermediate forwarder for the intended destination even if it currently does not have a connected path to the destination. Two of the most well-known DTN routing protocols in the literature are Epidemic [15] and Spray-and-Wait [13].

Epidemic routing [15] is a flooding-based protocol whereby messages are continuously replicated and transmitted to all other nodes in the network that do not already have a copy of the message. Although Epidemic routing is simple and robust, it suffers from excessive resource overheads in terms of buffer requirements, energy consumption and bandwidth usage. To reduce resource overheads, Spray-and-Wait routing [13] limits the number of replications that are permissible for each message in the network.

2.2 Geographical Routing

In geographical routing [6], forwarding decisions are made based on the geographic positions of nodes in the wireless network. As there is no need for route discovery and establishment, geographical routing is highly scalable and attractive for dynamic and mobile networks. However, the forwarding decision at each hop along the routing path tends to be locally optimal due to the greedy nature of these protocols. Subsequently, mechanisms for recovery from greedy forwarding failure (*e.g.* face routing and perimeter routing) are often required.

In recent years, many variants of geographic routing have been proposed to optimize its performance based on prevailing network characteristics. For instance, Predictive Graph Relay (PGR) [8] utilizes movement prediction and DTN techniques for routing packets in sparse mobile networks, while ORION [10] makes use of autoregressive moving average stochastic processes for contact prediction.

Our work differs from existing literature in the following aspects: By exploiting the *a priori* knowledge of flight trajectories, we are able to use the estimated time of arrival (ETA) as the routing metric for forwarding decisions. To alleviate the sub-optimality of greedy algorithms, multiple copies of the same message are replicated throughout the network. Finally, our proposed protocol incorporates DTN techniques to ensure message delivery even when there are frequent disruptions in the airborne network topology.

3. GTA-M

We now describe the details of GTA-m, a multi-copy greedy trajectory-aware routing protocol for airborne networks. In GTA-m, bundles are forwarded *greedily* from one node to another, based on *node trajectories* and *estimated time of arrival* (ETA) to their respective intended destinations.

3.1 Metafile Exchange

When a pair of nodes encounter each other, each transmits a *metafile* containing: (i) trajectory information - such as current location, intended flight destination and average flight speed [1]; (ii) buffer occupancy information that summarizes the message bundles that the node is currently carrying; and (iii) acknowledgement vector of messages (that the node knows of) that have been successfully delivered to the destinations. This exchange of metafiles allows for the computation of the forwarding metric, selection and prioritization of message bundles to transmit and the purging of successfully delivered message bundles.

3.2 ETA Computation

The set of participating ground stations in the network is denoted as G. It is assumed that all the ground stations are inter-connected via reliable, high speed wired links, such that a bundle is considered to be successfully transmitted to its destination as long as the bundle is forwarded to *any* ground station $g \in G$. Thus, the ETA of a bundle to its intended destination is the shortest expected time taken for the bundle to reach *any* any ground station. We estimate the ETA of a node v to an arbitrary ground station g by computing the cross-track distance and along-track distance between v and g (as illustrated in Figure 1).

The cross-track distance $d_{xt}(v, g)$ between v and g is the shortest distance of g from the great-circle flight path of v, and can be computed as follows:

$$d_{xt}(v, g) = |R \cdot \arcsin\{\sin[\frac{d(v, g)}{R}]\} \cdot \sin(\theta_{v,g} - \theta_{v,D})|, \quad (1)$$

where $d(v, g)$ is the great circle distance between v and g; $\theta_{v,g}$ is the (initial) bearing from v to g; and $\theta_{v,D}$ is the (initial) bearing from v to the flight destination D[2].

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[1] The trajectory information is the only data overhead incurred by GTA-m compared to Epidemic and Spray-and-Wait protocols.

[2] The OPNET simulator provides APIs for the computation of the great circle distance and the initial bearing between two points.

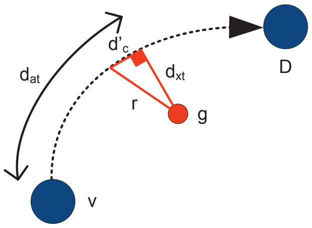

Figure 1: Cross-track distance $d_{xt}(v, g)$ and along-track distance $d_{at}(v, g)$ between node v (with flight destination D) and ground station g. $d'_c(v, g)$ denotes half of the inter-contact distance and r is the communication range of the network elements. $ETA_{v,g} = (d_{at}(v, g) - d'_c(v, g))/speed$.

Algorithm 1 Computation of earliest ETA of v to *any* ground station $g \in G$.

```
Input: Minimum ETA $\Delta_{\min} = \infty$
Output: $\Delta_{\min}$
for all ground stations $g \in G$ do
    Compute cross-track distance $d_{xt}(v, g)$.
    if $d_{xt}(v, g) \leq r$ then
        Compute along-track distance $d_{at}(v, g)$.
        Compute inter-contact distance $2 \cdot d'_c(v, g)$.
        Compute ETA $ETA_{v,g} = \frac{d_{at}(v,g) - d'_c(v,g)}{s}$.
        if $ETA_{v,g} < \Delta_{\min}$ then
            $\Delta_{\min} = ETA_{v,g}$
        end if
    end if
end for
```

If the cross-track distance $d_{xt}(v, g) \leq r$ (where r is the communication range of the network elements), it can be deduced that v and g will be within communication range of each other at some point along the flight path of v. We can then compute the along-track distance $d_{at}(v, g)$ between v and g, which is the distance from v to the closest point along the flight path to g, as follows:

$$d_{at}(v, g) = R \cdot \arccos\{\cos[\frac{d(v, g)}{R}]/\cos[\frac{d_{xt}(v, g)}{R}]\}, \qquad (2)$$

where $R \approx 6371$ km is the radius of the Earth. The approximate inter-contact distance between v and g is given by $2 \cdot d'_c(v, g)$, and can be computed using Pythagoras Theorem, whereby:

$$d'_c(v, g) = \sqrt{r^2 - [d_{xt}(v, g)]^2}. \qquad (3)$$

The ETA of v to g can be computed as:

$$ETA_{v,g} = \frac{d_{at}(v, g) - d'_c(v, g)}{s}, \qquad (4)$$

where s is the average flight speed of v.

Given that we can find the ETA of a node v to an arbitrary ground station g at any point in time, the earliest ETA of v to any ground station $g \in G$ can then be easily computed (as summarized in Algorithm 1).

3.3 Forwarding Decisions

The forwarding decisions in GTA-m are parameterized by the: (i) replication factor m, which is the number of copies that each bundle in GTA-m is generated with; and (ii) forwarding ratio q (where $0 < q < 0.5$), which determines the proportion of copies that are forwarded to an encountered node. Without any loss in generality, we consider a node v that is currently carrying $m' \leq m$ copies of a bundle. Upon meeting another node u at an arbitrary time t, v makes the following forwarding decisions:

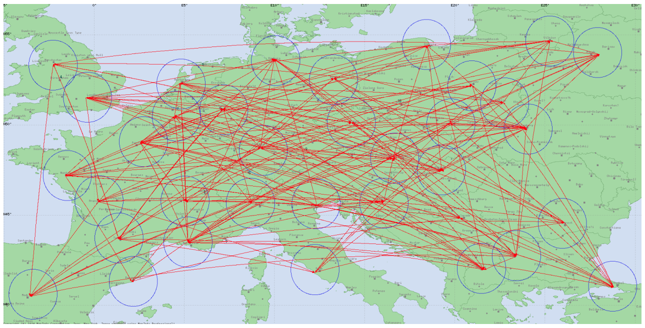

Figure 2: Simulated airborne network shows 35 ground stations (based on actual airport locations) and trajectories of aircraft in Europe. Each circle represents a communication range of approximately 100 km.

1. If u is a ground station (which has $ETA^t_u = 0\ \forall u \in G, \forall t$), forward the bundle to u.
2. Otherwise, if $ETA^t_u \geq ETA^t_v$, forward $\lfloor q \times m' \rfloor$ copies of the bundle to u and keep $m' - \lfloor q \times m' \rfloor$ copies[3].
3. Otherwise, if $ETA^t_u < ETA^t_v$, forward $m' - \lfloor q \times m' \rfloor$ copies of the bundle to u and keep $\lfloor q \times m' \rfloor$ copies.

By forwarding bundle copies to another node u which may have a larger ETA to the destination (i.e. $ETA^t_u \geq ETA^t_v$), GTA-m alleviates the local minima issues in greedy schemes. For example, u may encounter another node that has an earlier ETA to a ground station at time $t' > t$ *after* its encounter with v at time t.

The replication factor $m \geq 1$ in GTA-m determines the maximum number of copies that each bundle can exist in the network at any one time. Generally, the larger the m, the more copies of the bundle that are available for distribution among the nodes in the network but an excessively large value of m will lead to quicker buffer overflows and overflooding of the network.

The forwarding ratio q determines ($0 < q < 0.5$) determines the proportion of copies of a bundle that should be forwarded to an encountered node with a larger ETA value. Generally, a larger q value improves path diversity at the cost of potential increase in incurred delay to the destination, while a smaller q value tends towards the local minima issues. In our simulations, we use a value of $q = 0.25$ as a tradeoff between path diversity and local minima problems.

4. PERFORMANCE EVALUATION

We study the performance of GTA-m as compared to existing DTN routing protocols (viz. Epidemic and Spray-and-Wait) in a civilian airborne network, using OPNET. The

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[3] Note that in this case even when $m = 1$, node v will pass the single copy to node u and remove its own copy.

Parameter	Default Value
Aircraft speed	≈ 900 km/h
Aircraft altitude	≈ 10 km
Terrain size	≈ 2300 km × 1500 km
Communication range	100 km
Application message size	50 B to 15 KB
Bundle buffer size	1000 bundles
Data rate	1 Mbps
Simulation duration	2.5 hours
GTA-m forwarding ratio q	0.25

Table 1: Simulation parameters and their default values

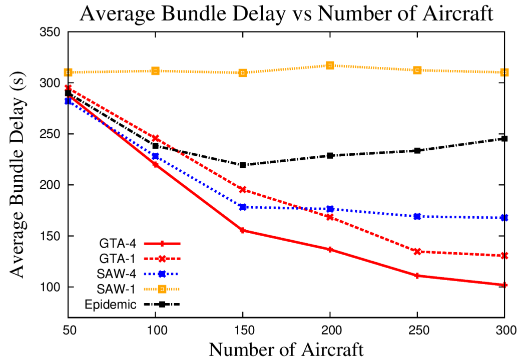

Figure 3: Average bundle delay with varying network density.

simulated network comprises 35 ground stations based on actual airport locations in Europe (see Figure 2). Each flight is generated based on randomly selected source-destination ground stations, and takes off within 60 seconds from the simulation start time. Traffic is generated from each aircraft to an arbitrary ground station after 30 minutes from its takeoff. The study assumes no aircraft body blockage on the radio. The default values for the simulations are summarized in Table 4.

4.1 Varying Network Density

The number of aircraft is increased from 100 to 300, while keeping the total traffic load in the network constant. Figures 3 and 4 illustrate the average bundle delay incurred and bundle delay CDFs by the various schemes with increasing network density. We first note that SAW-1 (Spray-and-Wait with $m = 1$ copy) is equivalent to a **non-forwarding** scheme that carries all message bundles directly to the ground station(s). Hence, it provides the upper bound on the bundle delay that can be incurred by all DTN routing protocols. Generally, **forwarding** schemes such as Epidemic, GTA-m (with $m \geq 1$) and SAW-m (with $m > 1$) tend to perform better with increasing network density, due to increased contact opportunities between aircraft. However, for Epidemic, a high network density (> 150 nodes) leads to buffer overflows and thus performance deterioration of average bundle delay. To alleviate these issues, SAW-4 limits the number of replications of each bundle to $m = 4$, at the cost of being unable to exploit contact opportunities when all copies of the bundle have already been distributed.

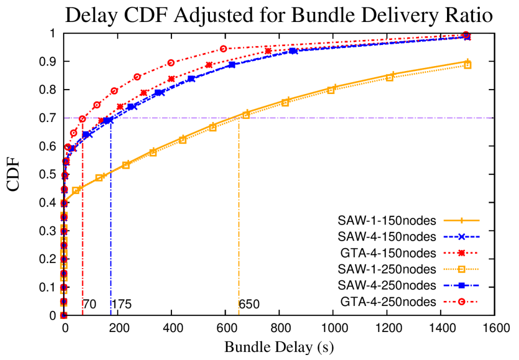

Figure 4: Bundle delay cdfs with varying network density. GTA-4 has the best CDF and improves the most when the number of aircraft increases. In this case the network density has negligible effects on SAW-4 and SAW-1.

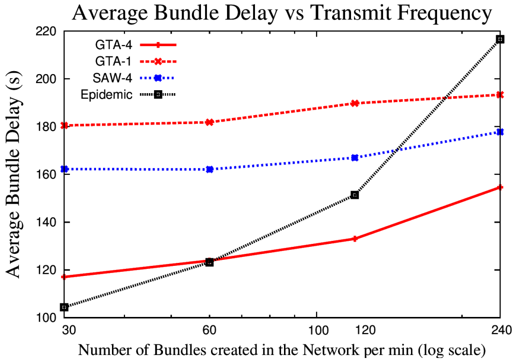

Figure 5: Average bundle delay with varying traffic load.

By greedily forwarding replicated bundles to aircraft that have smaller ETA to the destination(s), GTA-m reduces the expected bundle delay. GTA-4 improves the average bundle delay by 34% and 52% as compared to SAW-4 and Epidemic respectively, in a network with 250 aircraft (see Figure 3). In addition, Figure 4 shows that GTA-4 is able to reduce the delay of the 70^{th} percentile of bundles by 60% and 90% as compared to SAW-4 and SAW-1 respectively. Figure 4 also shows that the Bundle Delivery Ratios (BDR) of Epidemic, SAW-4 and GTA-4 are comparable - all about 99% within the simulation time. In fact, in all the simulations conducted all three protocols achieve high and comparable BDR (≈99%) due to their DTN capabilities.

4.2 Varying Traffic Load

The traffic load in the network is varied by increasing the transmit frequency of bundles, while keeping the network density and contact opportunities constant with 150 aircraft. As the transmit frequency increases, the performances of all the schemes decreases correspondingly due to increased traffic load and network congestion.

Figure 5 shows the resulant average bundle delay as the network traffic load increases. At high traffic loads, Epidemic performs significantly worse than both SAW-m and GTA-m, due to network congestion and buffer overflows. SAW-4 and GTA-4 are able to incur lower bundle delays

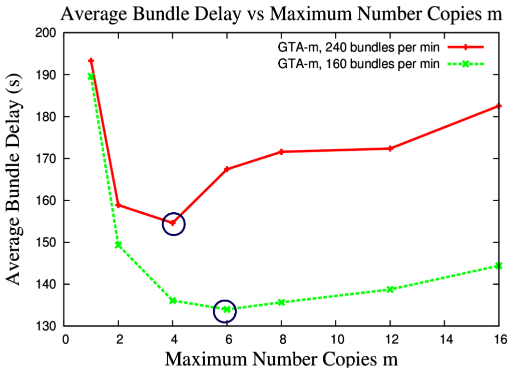

Figure 6: Average bundle delay with varying replication factor m. For different settings, the optimal m to achieve the smallest average delay can be different.

under high traffic loads by limiting the number of replications for each bundle. We observe that GTA-4 generally outperforms SAW-4 across all traffic loads, due to the forwarding of bundles to aircraft with earlier ETA to ground stations. However, the single-copy GTA-1 performs worse for most of the traffic loads as it is highly susceptible to the sub-optimality of greedy forwarding.

4.3 Varying Replication Factor m

We study the effect of varying the replication factor m (between 1 to 16) in GTA-m with 2 different traffic loads, in an airborne network with 150 aircraft and 35 ground stations. The effect of varying replication factor m can be observed more significantly in the bundle delay, as shown in Figure 6. As m increases from 1 to the optimal point, more copies of the bundle are generated, resulting in more opportunities to discover routing paths that provide shorter delays to the destination(s). However, as m increases beyond the optimal point, the effects of over-replication and network congestion become more pronounced, leading to increased average bundle delays. As such, there is an optimal value of the replication factor m that should be used for each airborne network, depending on its characteristics - such as traffic load and network density.

5. CONCLUSION AND FUTURE WORK

In this paper, we propose GTA-m - a greedy forwarding scheme that relies on DTN techniques to mitigate the frequent disruptions in airborne networks comprising highly mobile aircraft nodes. GTA-m utilizes *a priori* flight information to make forwarding decisions that can enhance network performance. We observe through simulations that there is an optimal value of the replication factor m in GTA-m, for a particular network scenario. As part of future work, the value of m in GTA-m will be adaptively adjusted based on prevailing network conditions.

Acknowledgments

The authors would like to thank Mr Nga Chee Wei and Mr Alan Tan Jee Lin from the Defence Science & Technology Agency in supporting this work.

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