Topology Management Algorithms for Large-Scale Aerial High Capacity Directional Networks

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Abstract—The U.S. Department of Defense with the Joint Aerial Layer Network (JALN) concept as well as public companies like Google with their Loon project and Facebook with their solar-powered UAV concept have all invested significant funds to develop and deploy airborne high capacity backbone systems. These systems are intended to augment ground networks in support of disaster relief, to extend Internet access to infrastructure-less areas, and to support other similar missions. They can even be used to replace existing satellite backbones which typically offer low capacity and high latency connections. One of the key challenges to building an airborne backbone network is large-scale topology management of directional links in a dynamic environment. In this paper, we present several topology management algorithms for large scale airborne networks and evaluate the performance of these algorithms under various scenarios. In each case, we seek to evaluate link and path availability of each algorithm.

I. INTRODUCTION

In recent years, there’s been a large push in both the U.S. Department of Defense (DoD) as well as industry to supplement satellite communications as well as terrestrial networks with a high capacity aerial backbone network [1], [2]. Projects like Google’s Loon [3], Facebook’s solar-power UAV [4], and the DoD Joint Aerial Layer Network (JALN) [5] concepts all envision providing last-mile reach back for mobile terrestrial or aerial systems. Figure 1 illustrates an example of an air-to-air relay network used to interconnect surface networks at sea. Such an aerial high capacity backbone could be used to replace the current satellite communication (SATCOM) for beyond line-of-sight (BLOS) communications when there is a lack of wired infrastructure such as at sea and long communications ranges. Satellite infrastructure is limited in capacity and during periods of high demand communications may be degraded or even unavailable.

To achieve high capacity at long range, directional communication technologies such as Common Data Link (CDL) [6] and Free-Space Optics (FSO) [7] could be leveraged in the aerial backbone. However, these directional systems present many challenges in such areas as topology formation, maintenance, and network stability. In particular, these issues are exacerbated by the aircraft platform dynamics which lead to periodic outages on certain links. To address the challenges of leveraging directional technologies in a high capacity airborne network, topology management algorithms that minimize downtime due to antenna blockage are needed. Topology control algorithms for directional airborne network have been proposed in previous work [8]. In [8], three topology algorithms that were designed to maximize delivered data or achieve a well connected network were presented. However, this work did not address the issues of airborne blockage and how the topology control algorithm can help maintain the links in the presence of airframe blockage. In our previous paper [9] we presented a flexible and automated topology manager design that dynamically forms, maintains and monitors network topology in the presence of node mobility and intermittent antenna blockages. The architecture abstracts the control plane (back-channel network) radio and its interface to allow integration with various radio solutions. In addition, the topology manager allows various topology algorithms to be inserted and evaluated for performance. In this current paper, we focus on the design of several topology management algorithms to allow dynamic antenna pointing in the presence of blockage and provide an evaluation of the performance of these algorithms under various scenarios. Key contributions include:

- Introduction of classes of topology management algorithms and example implementations of each
- Performance evaluation of the algorithms in 2 example relevant operational scenarios
- Discussion of implications for algorithm design

While there is other work that examines theoretical aspects of topology management in aerial networks with airframe blockage [10], [11], the primary focus of this work is on implementation and evaluation of practical algorithms. The remainder of this paper is organized as follows: Section II provides an overview of the new topology management al-

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algorithms and describes the implementation details of each algorithm. Section III describes an evaluation of the algorithms under various scenarios. Section V concludes the document.

II. TOPOLOGY MANAGEMENT ALGORITHM OVERVIEW

In previous paper [9], we presented a framework that enables implementation and evaluation of several topology management algorithms. The Topology Management System includes a Topology Algorithm Manager which oversees the selection of the topology for the network. This portion of the TM system uses “plugins” for modularity and to allow different algorithms to be used without changes to the other components of the system. In this paper we will focus on the design of these topology algorithms.

The topology algorithms have two major components: topology discovery and antenna selection. Topology discovery is the process of determining which nodes are in the network and which nodes need to be connected. The back-channel network, which relies on omni-directional transmission and reception, is responsible for node discovery, information distribution and collection. Once the topology of the network is determined, the topology algorithm can make decisions about antenna selection for each connection of the topology. Depending on the antenna placement on the aircraft as well as the aircraft movement, an antenna/radio pair needs to be dynamically chosen to make the line of sight connection for each link in the topology. Next we will describe the various approaches on topology discovery and antenna selection of the algorithm.

A. Topology Discovery

The topology algorithm needs to formulate a desired topology before choosing antennas and radios to use to connect nodes. This desired topology can be static, pre-planned, or dynamically discovered by exchanging messages over the back channel network. Three approaches are presented in this paper and each has its benefits and tradeoffs.

- **Fixed/Pre-planned Topology** - With this approach, the topology algorithm does not discover the network, but starts with a pre-planned, fixed topology. Each node will always connect to the same set of nodes. This simplifies frequency management, since radio transmit and receive frequencies may be fixed for each link. Each node needs to distribute only position information to its 1-hop neighbors. This approach is the least flexible topology discovery method because it is not dynamic, but it requires the least overhead.

- **1-hop Discovery** - With this approach, the topology algorithm discovers 1-hop neighbors by sending radio heartbeat messages 1-hop on a periodic basis over the back channel network. Each node discovers its 1-hop neighbors, but its frequency plan is still fixed for each link. With this approach, both position and radio information need to be distributed to its 1-hop neighbors. This approach is more dynamic, but requires more overhead than a fixed topology.

- **2-hop Discovery** - With this approach, the topology algorithm discovers each 2-hop neighbor in its network by sending radio heartbeat messages on a periodic basis over the back channel network. Each node will use a TTL of 2 so that its 1-hop neighbor nodes forward the messages to reach the 2-hop neighbors. Because this information is distributed 2-hop, it allows the frequency plan to be dynamic. This approach is the most flexible and dynamic, but requires the most overhead. Depending on the type of antenna selection, using 2-hop discovery may not be scalable for large networks due to the need to build large numbers of topologies.

B. Antenna Selection

Once the topology discovery is achieved, the topology algorithm needs to decide which antenna should be used to point to each neighbor for the topology. The goal is to maximize the link availability in the presence of blockage. There are two major groups of algorithms: proactive and reactive. A proactive algorithm, as its name implies, will proactively change topology based on what is predicted to happen in the next interval. A reactive algorithm will only change topology after certain events happen such as link outages and is thus reacting to past events. In addition, to minimize the antenna switching time, an antenna pre-slewing mechanism can be applied to both proactive and reactive algorithms to further reduce link down time. In this section, we will describe each type of algorithm.

- **Proactive Algorithm** - This algorithm was described in detail in the previous paper [9] so only a summary is provided here. The proactive algorithm runs periodically and makes a new decision for the topology at every interval. The process that the algorithm follows in shown in Figure 2 and is as follows: build all possible topologies, sort by predicted downtime, and pick the topology with the lowest downtime.

![Fig. 2. Topology Manager Proactive Algorithm Example Steps](image)

- **Reactive Algorithm** - This algorithm is also periodic but only makes a new decision when a persistent outage is detected. An example is shown in Figure 3.

  - **Build Link Map** - Based on the topology discovery mechanism, a 1-hop link map is built with information that defines a link and also assigns each link a priority. This link map differs from the topologies used in the Proactive Algorithm in that a node does
not concern itself with the specific radio that will be used by its neighbors. A node simply selects its own radio to point to a neighbor and assumes that the neighbor is also making a selection.

- **Detect persistent outage** - The algorithm calculates outages for each link based on outage data. If the outage time for a link is greater than a certain threshold, the link is considered in a state of persistent outage and an alternative antenna needs to be chosen.

- **Antenna selection** - The algorithm attempts to find an alternative antenna for the persistent outage link as follows:
  - Free Antenna - If a free antenna has a clear field of view to the remote node, it will be chosen for this persistent outage link. This is the best scenario as no other links will be affected by this selection.
  - Swap antennas - Otherwise, it will check whether there is a link that can swap antennas with the persistent outage link and both antennas have clear field of view to their respective remote nodes. This is the second best scenario because each link will be re-connected when the swap is complete.
  - Break lower priority link - Otherwise, it will need to break a lower priority link. It iterates through all antennas serving lower priority links and checks whether one of these antennas has a clear field of view to the remote node that has the outage. If it does, it will break the lower priority link and use that link to repair the persistent outage. The broken, lower priority link is then declared to have a persistent outage, and the algorithm will attempt to find an alternative.

If all above steps fail to find an alternative antenna/radio that can be used to repair the outage, no new antenna will be chosen for the persistent outage link until the next period.

![Image](https://example.com/image1.png)

**Fig. 3. Topology Manager Reactive Algorithm Example Steps**

- **Pre-Slewing** In both the proactive and the reactive algorithms, an antenna pre-slewing mechanism can be applied. Pre-slewing is a means to reduce antenna switching time by re-pointing a free antenna to its next likely remote node before it is needed to repair an outage. This may involve predicting the beginning of impending link outages, predicting the likely destination to which a free antenna will be pointed, or both. When pre-slewing is used in an algorithm, there are two predefined thresholds to check against as shown in Figure 4.

![Image](https://example.com/image2.png)

**Fig. 4. Pre-Slewing**

The algorithm checks whether the current pointing vector of an antenna supporting a link is nearing the edge of the antenna’s field of view. If the pointing vector is beyond the first threshold, it moves toward the edge of the field of view but not yet to the second threshold, the algorithm will try to find an alternative antenna that is free or swappable with another link so that it can switch to that antenna. If the current pointing vector is beyond the second threshold, the algorithm will try to find a new antenna that is free or swappable as before but in addition it may choose to break a lower priority link to find an alternative antenna. Once the alternative antenna is found, that antenna will be pre-slewed to the new position before an antenna switch is performed. This mechanism can be applied in combination with either of the proactive or the reactive algorithms. In this paper, we present results from using pre-slewing in combination with the reactive algorithm.

**C. Algorithm Design and Implementation**

In this section, we will describe four algorithms that we designed, implemented and tested. Figure 5 shows three types of topology discovery algorithms and two types of antenna selection algorithms.

![Image](https://example.com/image3.png)

**Fig. 5. Topology Manager Algorithm Matrix**

A complete topology management algorithm can be designed by choosing one type of topology discovery and one type of antenna selection. For example: we can follow the dashed blue line to form a Reactive Local Link Maintenance algorithm, which uses a fixed topology and reactive antenna selections. Following the solid red line results in a Proactive Global Path Optimization algorithm, which uses 2-hop topology discovery and proactive antenna selection. This modular design will allow other topology discovery and antenna selection algorithms to be inserted into the framework to form new topology management algorithms.
1) Proactive Global Path Optimization Algorithm: This algorithm uses 2-hop discovery and a proactive antenna selection. Because it builds all possible topologies globally, it has the most accurate information across all nodes and can possibly make better decisions. Unfortunately, due to the 2-hop discovery, it is not scalable to large networks.

2) Proactive Local Path Optimization Algorithm: This algorithm uses a 1-hop discovery and a proactive antenna selection. It has knowledge of its 1-hop neighbors and like the Proactive Global algorithm tries to predict future link outages. Because discovery information is only shared in 1-hop, it is scalable to large networks.

3) Reactive Local Link Maintenance Algorithm: This algorithm uses a fixed topology and a reactive antenna selection. Because it uses a fixed topology and reacts only to changes in a link after an outage has persisted, it is likely to not perform as well as other algorithms in terms of the link availability.

4) Predictive Reactive Local Link Maintenance Algorithm: This algorithm uses a fixed topology and a reactive antenna selection with pre-slewing. It is exactly like the Reactive Local, except that it applies pre-slewing to the highest priority link to attempt to reduce the outages on that link. This is an improvement to the reactive algorithm and should provide better link availability performance.

III. PERFORMANCE EVALUATION

Two scenarios were used to evaluate the topology algorithms described in Section II:

- 5 Node Scenario - This scenario is fairly simple with just 5 nodes including two aircrafts and three stationary ground nodes.
- 10 Node Scenario - This scenario is more complex and includes 10 nodes with 4 aircraft, 4 mobile ground nodes and 2 stationary ground nodes.

Both scenarios are shown in Figure 6. In both scenarios, as the aircraft follow their flight paths, the line-of-sight paths between various antennas at the air and surface nodes may become obstructed due to aircraft wings and airframe. The range of pointing of the aircraft’s antenna gimbals further restricts antenna pointing and hence inter-node connectivity. Based on this it is easy to see that the 10 node scenario is much more complicated from a topology formation point of view because the aircraft will need to form topologies with multiple other aircraft versus each aircraft forming only 1 link to another aircraft. Also, several of the ground nodes are also mobile which further complicates the topology formation.

Total control overhead, link availability, and path availability are the performance metrics used to evaluate the topology algorithms. The results for overhead will depend not only on the the type of discovery, but also on the message frequency. The more often messages are sent, the more accurate the information is for the TM algorithm to make a topology decision. At the same time, the more often messages are sent, the higher the overhead. Thus we need to balance the amount of overhead that will provide the highest link availability. We will first discuss the results for the simpler 5 node scenario then the 10 node scenario.

A. 5 Node Scenario Evaluation

In this particular scenario, there are two aircraft each with four radios and three stationary surface nodes each with one radio. The aircraft fly racetrack orbits with orbital periods of approximately 30 minutes and are separated by an average of approximately 200 nautical miles, with the surface nodes being situated within 100 nautical miles of the aircraft to which they connect. The logical available links are also shown in the figure. The aircraft fly in non-synchronized, straight and level racetrack orbits for a majority of the flight time with 180 degree turns at a constant 7 degree bank angle at each end of the racetrack orbit. Each of the 4 radios on the aircraft exhibit a fair amount of blockage due to airframe and wing obstructions.

The results for this scenario are as follows:

- Total Control Overhead: The total control overhead is measured over all the packets that are sent over the back channel network wide. This includes both sourced and forwarded traffic at a node. The control overhead will vary depending on which type of topology discovery is used. Figure 7 shows the total control overhead for the three types of topology discovery. For all three discovery methods, the navigation data is sent once per second. For fixed topology, which has the lowest overhead (around 1.8kbps), navigation data is distributed over 1-hop of the network and no other messages are sent. For the 2-hop discovery, which has the highest overhead (around 7.2kbps), navigation, heartbeats and radio messages are distributed over 2-hops. Heartbeats are sent every 10 seconds and radio messages are sent only when required by changes in the network state. For 1-hop discovery, which has overhead between the other two methods, navigation, heartbeats and radio information (which is around 2.1kbps) is distributed 1-hop. The overhead for 1-hop discovery is not significantly higher than fixed despite that fact that there are additional messages sent. This is because the navigation data is the overwhelming contributor to the overhead. This also implies that the
difference between 1-hop discovery and 2-hop discovery is due to the additional forwarding of the packets to 2-hop neighbors.

**Link and Path Availability:** Link availability is shown in Figure 8 and path availability is shown Figure 9. Proactive Global and Proactive Local algorithms have the highest link and path availability because they predict future link blockages instead of reacting to an existing blockage. For both of these algorithms, link availability is 97% or higher and path availability is above 95%. The Reactive algorithm has the poorest performance because it simply tries to maintain the link after an outage has occurred. Adding the pre-slewing to the reactive algorithm with the Predictive Reactive improves link and path availability especially on the air to air link because it tries to pre-slew the antenna before the link is broken. Overall, the air to air link is the hardest link to maintain because both aircraft are flying in their orbits and antenna blockage becomes a factor. There is little antenna blockage when the aircraft antenna point to ground nodes so those links have consistently higher availability.

The design and implementation of the topology algorithm provides valuable insights into the concept of topology management. Several important lessons were learned including:

- Topology algorithms include topology discovery and antenna selection as described in the paper. But this paper
Proactive algorithm performance depends on the pre-algorithms to run. This is another trade-off in terms of determining which scalable, but the frequencies need to be fixed per link. Connected topologies. Therefore 1-hop discovery will be scalable for larger or more scenarios, node 2 will need to build more than 55,000 performance issues with larger scenarios. With 10 nodes plan instead of fixed frequencies per link for 1-hop discovery allows us to have a dynamic frequency more general discovery algorithm needs to be developed.

Antennas to be used to maximize connections. Therefore a robust airborne backbone, but it will reduce the connectivity, a barely connected backbone enables performance issues. There is a trade off between building the most robust airborne backbone and building the backbone to maximize the connectivity of surface/ground nodes. If the goal is to build the most robust airborne backbone, we would like to have a mesh backbone, but it will reduce the link availability because of limited number of antennas per air node. On the other hand if the goal is maximum the connectivity, a barely connected backbone enables antennas to be used to maximize connections. Therefore a more general discovery algorithm needs to be developed.

- 2 hop discovery allows us to have a dynamic frequency plan instead of fixed frequencies per link for 1-hop discovery. But 2-hops discovery can cause computation performance issues with larger scenarios. With 10 nodes scenarios, node 2 will need to build more than 55,000 topologies which is not scalable for larger or more connected topologies. Therefore 1-hop discovery will be scalable, but the frequencies need to be fixed per link. This is another trade-off in terms of determining which algorithms to run.

- Proactive algorithm performance depends on the prediction accuracy. The proactive algorithm performs well partly due to accurate blockage prediction because a constant banking angle was applied. In a real flight, this may not be the case. Having accurate blockage prediction will be crucial for algorithm performance.

- The link availability depends heavily on the antenna placement and number of antennas of the air node. Increasing the number of antennas per air node will increase the link availability, but may not be practical because weight and geometry limitations as well as cost may limit the number of antennas that can be mounted to the aircraft. The advances in technology of phase array antenna may help address this issue.

V. CONCLUSION AND FUTURE WORK

In this paper we have presented a framework for building topology algorithms in a directional network that dynamically discovers the network topology and performs antenna re-pointing in the presence of intermittent antenna blockages. We have assumed a network with high-rate directional links carrying data traffic that are supplemented by a low-rate, omni-directional control channel capability.

The topology algorithms have two major components: topology discovery and antenna selection. A complete topology management algorithm can be formed by choosing one type of topology discovery and one type of antenna selection. Four topology algorithms have been implemented and evaluated against specific five node and ten node scenarios. As expected, control overhead depends on how many hops the control messages are sent. Proactive algorithms in general perform better than the reactive algorithms as they try to predict outages in advance of them occurring while reactive algorithms fix an outage after it has occurred, though the Proactive Global algorithm did have issues with computational load. Future work includes developing a more generalized topology algorithm specifically a general discovery algorithm, scalability testing in terms of computational cost of the algorithms, and analysis of the benefits of additional antennas on the aircraft.

REFERENCES