An Implementation of a Flexible Topology Management System for Aerial High Capacity Directional Networks

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***Abstract*—In recent years, there has been a large push in the U.S. Department of Defense (DoD) to augment ground networks with a high capacity airborne backbone network that uses directional communications technologies. Such a network could supplement the traditional SATCOM infrastructure which can become easily oversubscribed, may be degraded, or may even be unavailable. Although there are several advantages to these high capacity aerial backbone networks, one key challenge is topology formation and maintenance with highly directional links. In this paper, we present an architectural concept and implementation of a flexible topology management (TM) system for topology formation and coordination of aerial high capacity backbone networks. The TM framework is modular and extensible to allow for different algorithms and radio systems to be employed. A simple baseline algorithm is presented that maximizes network connectivity. Performance results from an EMANE/CORE emulation of a simple but representative aerial range extension network show that high link and network availability can potentially be attained by an automated TM architecture in this type of scenario.** [1]

I. Introduction

Current Navy military networks rely heavily on satellite communication (SATCOM) for beyond line-of-sight (BLOS) communications due to lack of wired infrastructure at sea and long communications ranges. This satellite infrastructure is extremely limited in capacity or may be degraded for supporting disaster relief and other missions. As a result, there has been a large push in the U.S. Department of Defense (DoD) to augment ground/surface networks with a high capability airborne backbone network to extend and interconnect ground, surface and other airborne networks [1], [2].

Figure 1 illustrates an example of an air-to-air relay network used to interconnect surface networks at sea. To achieve high capacity at long range, directional communication technologies such as Common Data Link (CDL) [3] and Free-Space Optics (FSO) [4] could be leveraged in the aerial backbone. These directional systems, however, also present many challenges in such as topology formation, maintenance, and network stability. Some of the factors that contribute to these challenges are as follows:

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Fig. 1. High Capability Airborne Backbone Network Example

- **Platform Dynamics** - Because directional systems operate in frequency bands that are highly susceptible to airframe blockage, aircraft movement, antenna placement, and blockage characteristics heavily affect connectivity. Antenna assignment must be dynamic so that the aircraft can maintain line of sight connections to the other nodes as it moves along its flight path.
- **Directional links** - Directional networks provide high capacity links that reduce interference from off-axis sources, but they require each node to be aware of peer positions, frequencies, and transmission modes in order to successfully form links between peers. All of this information needs to be distributed and maintained at each node. Low-rate out of band radio links are typically needed for this distribution, especially at network initialization. Challenges associated with the use of directional links include defining a minimal set of information to be distributed as overhead and determining how frequently and by what channels such information is broadcast.
- **Synchronization** - In order to support the dynamic antenna assignment required to form and maintain the network topology, every node needs to be synchronized to make the same topology decisions and to switch antennas when needed. The topology management architectural design is critical to achieving this synchronization. A centralized system may alleviate this issue, but introduces a single point of failure, while a distributed system will need coordination among all the nodes.

To address the challenges of leveraging directional technologies in an high capacity airborne network, an flexible and extendable Topology Management (TM) solution is needed. This TM solution requires several key features:

- **Waveform extensibility** - Current military tactical radios often provide vendor-unique solutions for both control plane and data plane radios. The TM framework must support interfacing with and controlling several different radios systems with disparate interfaces without the need to significantly change the core TM software.
- **Algorithm extensibility** - Each deployment of an airborne backbone network may seek to optimize different aspects of the network such as maximizing air-to-air link up time versus air-to-ground link up time or maximizing overall connectivity or data rate. The TM framework must enable new algorithm implementation without significant changes to the core TM software.
- **Coordination flexibility** - Distributed topology management requires information exchange between nodes. The TM framework must enable leveraging different available paths to distribute and synchronize state across multiple nodes in the network to enable topology formation.

In short, any TM system must be able to address the primary challenges and be flexible and dynamic to accommodate vendor specific radio solutions, new algorithms, and synchronization techniques. In this paper we present a flexible and extendible topology management system for coordinating aerial high capability directional networks to maximize network connectivity. Primary contributions of the work include:

- An extendable TM system for integration into existing and future airborne directional systems.
- An example implementation of position distribution and TM algorithm.
- A basic performance evaluation of the system.

The remainder of this paper is organized as follows: Section II highlights some previous work on topology management of a directional network. Section III describes the topology management system design and implementation details of each component. Section IV and V describes an evaluation of the management system over a specific scenario. Section VII concludes the document.

II. Related Work

Much previous research has addressed issues relating to topology formation and management in wireless and sensor networks. A survey can be found in [5]. However, most of the work in this area has centered on mathematical optimization challenges for large wireless networks (e.g., sensor networks) rather than on how to solve the practical challenges listed above. Van Hook et. al. [6] [7] specifically addressed automated algorithms for topology formation with directional links, but does not address problems such as platform dynamics and antenna obscuration. Mehta and Ganguly [8] provide an overview of practical issues and potential solution methods for the type of aerial relay network problem of interest in the current paper, but do not investigate algorithms for topology management. In contrast to previous work, we present and implement a framework for developing automated algorithms for topology formation in highly dynamic airborne networks. Our work takes into consideration aircraft dynamics and antenna obscuration and we evaluate the system in a representative airborne backbone network.

III. Topology Manager Framework Overview

The TM runs in a distributed fashion on every node to avoid both a single point of failure and the need for centralized control. This system performs the following functions:

- **Back-channel Network Interface** - Before the topology manager can make any decisions, it needs to discover who is in the network, where they are and how they are connected. This back-channel network will be responsible for node discovery, information distribution and collection. This is essentially a control channel to collect the topology information required by the topology manager to make decisions.
- **Topology Algorithm** - With information collected from the back-channel network, the topology algorithm will make topology decisions includeing how to link the peers by setting antenna pointing, frequency and mode. The specific algorithm described in this paper is designed to maximize the link availability across the network.
- **Directional Radio Network Interface** - With a topology decision, this function will perform the actual radio command and control to point each radio antenna and to set the frequency and mode information as instructed by the topology management system. This function essentially links the data channel for the peer nodes.

Figure 2 shows the overall architecture of the Topology Manager. The system consists of the actual Topology Management along with interfaces to both the data plane (Directional Radio Network) and control plane (Back-channel Network) radios. Both of these interfaces are extensible to enable multiple vendor and multiple API integration via plugins. The Topology Management itself has three main components:

- **Topology Data and Message Managers** - These components provide the back-channel position distribution and synchronization. The Data Manager stores and manages all data needed for topology management including navigation and radio data of the local node and neighbor nodes. The Message Manager provides the messaging interface for the topology management control messages.
- **Topology Radio Manager** - The Radio Manager provides the interface to the command and control the radios. As an example, when the TM formulates a topology, it leverages the Topology Radio Manager to translate pointing commands to the vendor-specific interface of the connected directional radio to point in a specific direction.
- **Topology Algorithm Manager** - The Algorithm Manager runs the topology algorithm and determines topology of the network in terms of peer connections. It also instructs the Radio Manager in how to change the settings (e.g., frequency, position, etc) of the data plane radios.

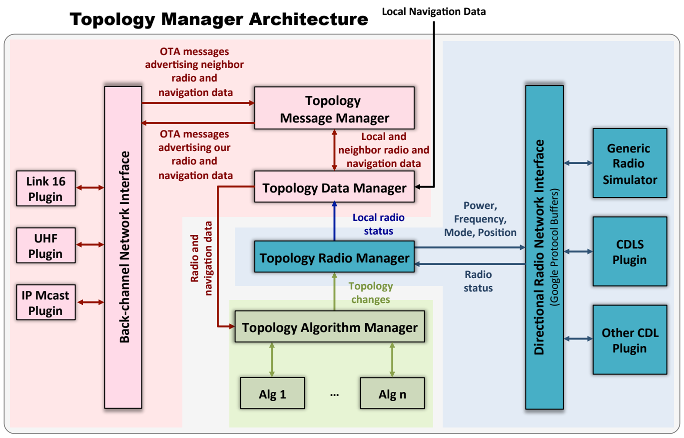

Fig. 2. The Topology Manager Architecture

The TM architecture is designed to provide flexibility in the solutions chosen for the Back-channel network radios, the directional network radios and the actual topology algorithm. The control plane radio interface consists of the Back-channel Network Interface and a set of radio specific "plugins". The Back-channel Network Interface itself is a generic, non-platform specific interface for the Topology Manager while the plugins implement the specifics of the actual control interface. The Back-channel Network Interface is responsible for interacting with the control radios which allows the Topology Manager to be implemented independently from the specific radios. In the same way, the data plane radio interface consists of the Directional Radio Network Interface and a set of radio specific "plugins". The Directional Radio Network Interface, just like the Back-channel Network Interface, is a generic, platform independent interface while the plugins implements the specifics of the actual radio interface.

This architecture of abstracted interfaces allows the Topology Management system to support multiple control plane and data plane radio solutions. For example, deploying a new radio type on the control plane or the data plane only requires implementation of a plugin for that radio and does not require any changes in the Topology Manager itself. Another important feature of this modular architecture is that the specific algorithm used for the topology management can easily be inserted without changes to the other components of the system. The TM system is designed such that the decisions for radio types and for the algorithm to be used are run-time configurable. This provides a great degree of flexibility in the field when the system is actually deployed.

A. Topology Management Messages

There are four over the air Protocol Data Units (PDUs) that are used by the TM:

- **Navigation PDU** is used to advertise a node's local position, velocity and direction. The Navigation PDU is sent periodically at the *navigation interval*.
- **Radio PDU** is used to advertise a node's radio information including the radio IDs, status, frequency and field of view. This PDU is not sent periodically but only based on specific events. The Radio PDU can advertise all or some of its radios and can be large depending on the number of radios on the platform.
- **Heartbeat PDU** is a keep alive for a node and its radios. Sent periodically, the Heartbeat PDU indicates that the radios are still active (turned on) and that the information previously sent has not changed. It can also be used to advertise radios that have been removed.
- **Request PDU** is used by a node to request another node's radio and/or navigation data.

The Request PDU is sent unicast to the node whose information is being requested. All other PDUs are "flooded" in the network. The term "flooded" is used to indicate that these messages are not unicast but are sent to multiple destinations. This could be just all 1-hop neighbors, it could be 2-hop neighbors or it could be all nodes in the network. The choice of how far from the source node "flooded" messages are sent depends on the needs of the specific topology algorithm in use. One topology algorithm might required just 2-hop information while another might require information about every node in the network. In addition, the specifics of the actual flood mechanism (broadcast, multicast, etc.) is implemented in the back-channel radio plugin. The Topology Manager is NOT responsible for message dissemination and assumes that the radio interfaces will perform this function. If not, then a new plugin is required to implement this capability.

B. Topology Algorithm Manager

The Topology Algorithm Manager has an abstracted interface which allows it to use various topology algorithms. If the user wants to define and implement a new algorithm that can be done without any changes to the Topology Algorithm Manager. Topology Algorithm Manager uses the navigation and radio data for both local and remote nodes from stored by the Topology Data Manager to make topology decisions using the specific algorithm chosen by the user. The information gathered from the other nodes will depend on the specific algorithm and what it requires. One topology algorithm might required just 2-hop information while another might require information about every node in the network. In general, there will be a trade off between the amount of knowledge the algorithm has about the network and the amount of overhead. The more information available then the better the topology decisions can be made but this requires increased network overhead to gather the information.

To demonstrate the functionality of the TM framework, we implement a simple predictive algorithm. The goal of this simple algorithm is to exercise the TM framework. The algorithm was designed to maximum the link availability by minimizing the link outages and requires just 2-hop information.

The algorithm is periodic and has three steps (Figure 3):

1) **Build all possible topologies** - Based on the radio data supplied by the Topology Data Manager, the algorithm makes an extensive search for all possible topologies of the network based on whether nodes are within the range or linkable. These topologies are built using every

possible combination of radio linked pairs. Note that the algorithm only requires 2-hop information to work properly and thus the list of every possible topologies will differ for each node based on the 2-hop information that they have. Figure 3 shows two possible topologies T1 and T2 that differ in how the radios at the air nodes are used to connect to the ground nodes.

2) **Predict Link Outages** - Based on the navigation data supplied by the Topology Data Manager, the algorithm predicts positions for all the nodes in the next X number of seconds, where X is the period of the algorithm. Then for each radio linked pair defined by the topologies built in the first step, the algorithm uses these predicted positions to determine if the radio linked pair will be blocked or not for each second of the interval. Finally, it uses these predicted blockages to determine how much time of the X seconds that the radio linked pair will be down. This step is looking at each possible radio linked pair and not at the topologies as a whole.
3) **Calculate Topology Availability and Select Best Topology** - Based on these link down times, the algorithm calculates the link availabilities for each topology in the upcoming interval. It sums up the link outages from Step 2 to determine a composite availability for the entire topology. Once the algorithm has analyzed all possible topologies, it orders the possible topologies and chooses the best one based on the following criteria:
    a) The lowest total air to air link outages - Used to minimize the air-to-air link down time
    b) The lowest total link outages - Used to minimize overall link down time
    c) The maximum number of original links - Used to minimize total number of antenna switches
    d) Radio ID from low to high - Used as a tie breaker

    Using the example in Figure 3, topology 4 would be selected because it is considered the best topology based on these criteria. As this algorithm requires network wide information for every node, this algorithm suits for a small number of nodes, and that finding scalable algorithms is a future research topic we plan to address.

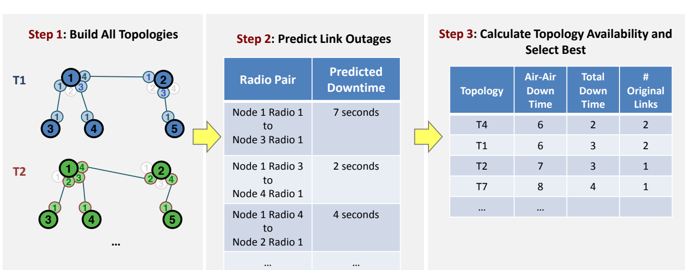

Fig. 3. Topology Manager Algorithm Example Steps

IV. Test and Evaluation Scenario

To evaluate the topology algorithm described in Section III-B, we implement the high capacity airborne backbone network scenario shown in Figure 4. In this particular scenario, there are two aircraft each with 4 radios and three 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 nm, with the surface nodes being situated within 100 nm of the aircraft to which they connect. The logical available links are also shown in the figure.

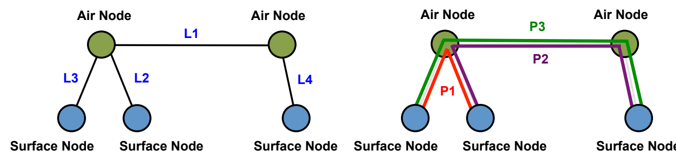

Fig. 4. Evaluation Network Link and Path Definition

The aircraft fly in non-synchronized, straight and level flight racetrack orbits for a majority of the flight time with 180 degree turns at a constant 7 degree bank angle at each end. Each of the 4 radios on the aircraft exhibit a fair amount of blockage due to airframe and wing obstructions. All surface nodes are assumed to have one antenna each. The high-rate relay links are assumed to use different waveforms at different transmit and receive frequency bands from the local wide-area coverage links.

The primary performance metric for candidate topology algorithms and their implementations is the availability of data pathways. Figure 4 shows the four link and three primary data paths of interest in this example scenario. As the aircraft fly around the racetrack flightpaths, the line-of-sight paths between various antennas at the air and surface nodes may become obstructed due to aircraft wings and and airframe. The range of pointing of the aircraft's antenna gimbals for the four relay antennas further restricts antenna pointing and hence inter-node connectivity.

V. Performance Evaluation

The scenario was used to evaluate performance of the TM framework in two ways: 1) evaluation to determine the best case link and data path availability and 2) evaluation of the specific algorithm described in this paper. In order to determine the best case availability, Systems Toolkit (STK) [9] was used to determine the link availability. This analysis assumed that the radios were mounted within a pod underneath the main body of the aircraft and STK was used to simulate three hours worth of flight along racetrack orbits.

In order to determine the performance of the TM algorithm described in this paper, the algorithm was implemented and run in the the Common Open Research Emulator (CORE/EMANE) [10] emulation environment. Each node had an out-of-band channel radio as the back-channel network. An IP Multicast plugin was developed to emulate the radio in Extendable Mobile Ad-hoc Network Emulator (EMANE) [11]. The physical link availability was fed in through a radio simulator based on the analysis shown in Section IV. This radio simulator provides "perfect" prediction of link outages.

The two results used to analyze the performance are link availability and control overhead for the scenario.

- **Total Back-channel Control Overhead** - The total control overhead is measured over all the packets that are sent over the control channel links. This includes PDUs sourced at a node and forwarded by a node. The forwarding mechanism used for this implementation was classic flood over a 2-hop distance. The control overhead will vary with the messaging timers, specifically the Heartbeat PDU timer and the Navigation PDU timer. The more often the data is sent, the more accurate the information is for the TM algorithm to make a topology decision. At the same time, the more often the data is sent, the higher the overhead on the links which can be a capacity constrained link. Thus we need to balance the minimum amount of overhead that will provide the highest link availability.
- **Link and Path availability** - The goal of the topology manager is to maximum the link availability of the network in the presence of blockages. This depends not only on the specific algorithm that is used, but also on how frequently that algorithm is run. For our analysis, we varied the algorithm timer. In addition, we compared the algorithm results when preferring air-to-air link down time as the first ranking criteria and also when preferring total link outage as the first ranking criteria. This will help us understand how the topology algorithm performs under the conditions provided in the scenario.

A. Total Control Overhead

Figure 5 shows the average control overhead per node versus the message interval times, specifically the Heartbeat interval and the Navigation interval (both set the same for these tests). The figure shows that the measured total back-channel overhead decreased as the heartbeat timer increased. This is as expected because the less frequently the packets are sent then the less data goes over the link. This total control overhead includes both the payload of the TM PDUs as well as the UDP/IP and Ethernet headers for each PDU sent (42 bytes per PDU). Because not all radios will be IP based, we calculate the amount of overhead for the TM PDU payload only without the UDP/IP/Ethernet header. This is also shown in the figure as “Calculated Payload Only”. In addition, we got a calculated value for the average control overhead. As can be seen in the graph, this calculated value matches the measured value from EMANE.

B. Link and Path Availability

Figure 4 defines the four links that needed to be maximized. The simple algorithm we implemented was a periodic algorithm. The more often the algorithm runs, the more updated topology will be, and thus the link availability might increase with decreased algorithm timer values. Figure 6 shows how the link availability performed as the algorithm timer increased. As seen in the figure, link availability did not vary much with decreased algorithm timers. The reason for this is that

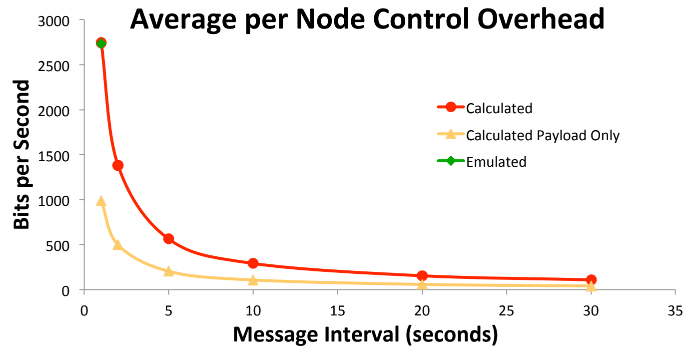

Fig. 5. Total Back-channel Control overhead over Heartbeat Timer

the link outages were fairly long, in the order of 30 seconds, and thus running the algorithm every 5 or 10 seconds did not improve link availability. However, when the algorithm timer was increased to 60 seconds, the link availability dropped because the topology algorithm was not run frequently enough to switch linked radios when the link outages occurred in the existing links.

Link availability could also be affected by the order of the criteria used to select the best topology. We compared two different approaches choosing the ”best” links. One was preferring the air-to-air link first, that is, minimizing the air-to-air link outage, while the other algorithm was preferring the total link outage first, that is, minimize the total link outages. Figure 7 shows that the top criteria change did not affect the link availability much. This is because the air-to-air link dominated the link outages so that ordering the criteria by total link outage generally resulted in the same order as ordering them by air-air outage.

The final item to analyze is the path availability. The paths (shown in Figure 4) consist of multiple links and the path availability merges the availability of the links that comprise each path. Figure 8 shows the path availability with an algorithm timer of 10s and preferring air-to-air link outage as the top sorting criteria. Compared with maximum physical path availability, the algorithm tested achieved a fairly good path availability. The reason for this is that the second step of the algorithm (Predict Link Outages) used a perfect prediction.

VI. Lessons Learned

The design and implementation of the TM system along with the initial topology algorithm provided some valuable insight in topology management. Several important lessons were learned including:

- TM architecture design must be modular and flexible to support multiple back-channel radio systems as well as various directional radio systems. With unique vendor interfaces, it is crucial for the TM not to be tied into particular underlying radio systems.
- The back-channel networks are needed for network discovery and information distribution for TM to make topology decisions. The back-channel network available

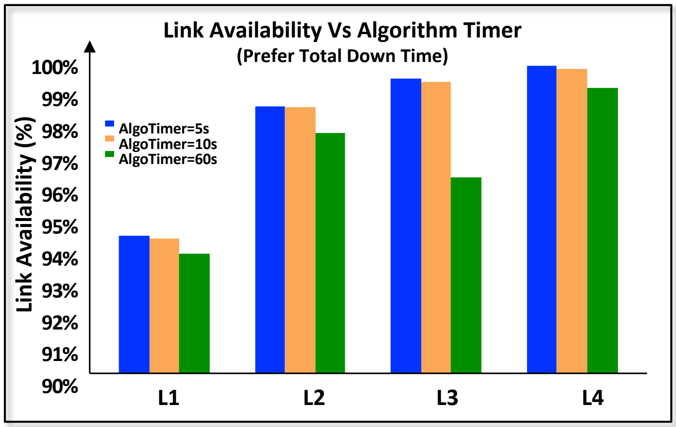

Fig. 6. Link Availability over Algorithm Timer

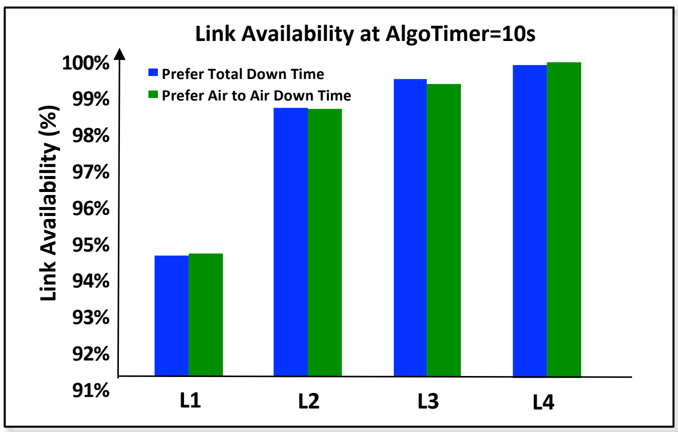

Fig. 7. Link Availability over Algorithm Type

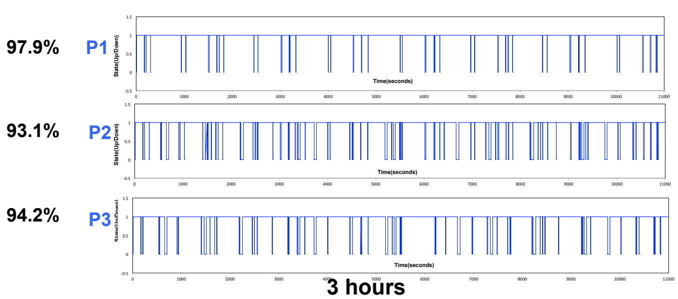

Fig. 8. Path Availability over a 3 hour run

data rate will determine how far and how much information can be distributed across the network. This will impact the topology decision that TM can make, which in turn will impact the network performance. Based on the scenario and algorithm described in this paper, 2-hop information is needed for topology-wide scope of network knowledge. Therefore, how far and how much information can be distributed across the network will be crucial for TM performance.

- In airborne high capacity backbone networks, blockage due to body, wing and pod design poses major challenges for the TM system. An accurate blockage model for the air-to-air link is crucial to characterize the links and provide information needed for TM to make intelligent decisions. Future algorithms should enable loading of antenna blockage profiles to aid in topology management.
- Because many directional systems utilize open-loop pointing (i.e. they require direct commands to point in a certain direction, often at sub-second intervals), TM techniques may be required to predict remote neighbor positions to the fidelity required for open loop pointing.
- Additional studies of predictive TM algorithms and reactive TM algorithms are needed to understand the tradeoffs of errors in prediction vs. missed opportunities.

VII. Conclusion and Future Work

In this paper, we present a flexible and automated topology manager design that dynamically forms, maintains and monitors network topology in the presence node mobility and intermittent antenna blockages. This 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. With a simple periodic algorithm implemented in the topology manager, we demonstrated the topology manager was able to maintain high link availability while the control overhead is limited to less than 3 kbps. Our current implementation requires 2-hop radio information for the algorithm to make decisions. Link overhead may be further reduced by development of a new algorithm using only 1-hop information. A more realistic radio plugin for both data plane radios and control plane radios would enable higher fidelity performance evaluations of the topology management system. Future work includes more advanced TM algorithm and evaluation in larger scenarios. This future work will provide more insight on what is achievable in terms of link and path availability in an actual network and will provide support for field implementation and testing.

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