Reliability, Throughput and Latency Analysis of an Aerial Network

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Abstract. An aerial network is a self-organized network formed by aircraft systems deployed for a mission-specific purpose. Aerial networks are characterized by dynamic topologies and frequent network connections and disconnections primarily due to the fast moving nature of the aircraft systems. This paper considers an abstract paradigm for an aerial network, modeling it as a dynamic graph, and analyzes its reliability, throughput and latency characteristics. It defines metrics to measure the performance of an aerial network in terms of reliability, throughput, and latency. The analysis is intended to provide insights into the performance characteristics of an aerial network as a function of topology and mobility. The insights derived from this analysis are expected to lead to strategies for improving the network performance in real-world applications. This analysis also provides a set of building blocks which would lead to a general framework for identifying reliable and critical paths in a network (Approved for public release: distribution unlimited.).

Keywords: Aerial network · Adhoc network · Reliability · Throughput · Latency

1 Introduction

An aerial network is formed by aircraft systems deployed in the air for a specific mission. The network may include manned and unmanned aircraft systems (UASs), ground vehicles, control stations and services, as illustrated in Fig. 1. In an aerial network, nodes may travel at high speeds, range extends to hundreds of miles, and network topology is constantly changing. The use of airborne networks has typically been restricted to military applications until now. In recent years, with the expanded roles of UASs and the desire to bring dynamic infrastructure to disaster areas, there has been increased interest in airborne network research. Airborne networks are envisioned to play an important role in Next Generation (NextGen) Air Transportation Systems.

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1.1 Aerial versus Terrestrial Networks

Aerial networks can be viewed as a class of Mobile Ad-hoc Networks (or MANETs) consisting of nodes moving in and out of the network as they fly. Typically, MANETs are formed without any supporting infrastructure. Aerial networks differ from traditional MANETs and ground networks due to their extreme high speed, long distances, relative multi-path free operation, and dynamic rate adaptation. These differences solicit different operating characteristics and present challenging problems as well. In addition to operating conditions described above, NextGen air transportation systems envisioned by the U.S.'s Federal Aviation Administration (FAA) require enhanced safety and security. Although significant progress has been made in many dimensions of air transportation systems (e.g. airspace management, data link capability), there is a clear need for continued efforts to enhance the safety and security capabilities (e.g. sense and avoid, safe navigation, and secure communication) of NextGen air transportation systems. Aerial networking is an approach towards achieving these objectives.

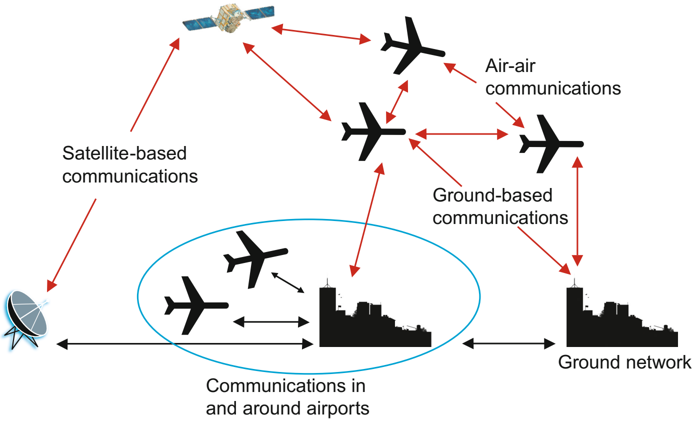

Fig. 1. An illustration of airborne network consisting of terrestrial, satellite, and RF links to connect to control stations on the ground and to other airplanes.

1.2 Aerial Network Protocols

Until recently, aerial networking is limited to military applications only. Within the civilian domain, aerial networking protocols are still emerging. It is envisioned that aerial networks will use Internet Protocol and require high-data-rate, low-latency, and self-configuration capabilities. The Air Force Research Laboratory (AFRL) has developed a proprietary, IP-based tactical targeting networking technology capable of communicating over 300 nautical miles for defense applications [1]. Aerial networks can also be designed to use a heterogeneous set of physical links (for example, radio-frequency and satellite communications) to interconnect terrestrial, space, and other airborne networks. Link 16, a TDMA-based secure, jam-resistant, high-speed digital data link that operates over-the-air in the L-band portion (969–1206 MHz) of the UHF spectrum, is another example. With Link 16, military aircraft as well as ships and ground control stations can exchange real-time information. Link 16 also supports the exchange of text messages and imagery data and provides two channels of digital voice (2.4 Kbit/s and/or 16 Kbit/s in any combination).

Successful deployment of aerial networks require comprehensive modeling and simulation of airborne networks. Modeling and simulation of airborne networks, in turn, require models of airborne vehicles, antenna propagation patterns, mobility models, terrain models, and weather patterns. Deployment of successful aerial networks also require the implementation of information assurance strategies and their integration with network management and planning tools.

1.3 Contributions

This paper considers an abstract paradigm for an aerial network, modeling it as a dynamic graph, and analyzes its reliability, throughput, and latency characteristics. It defines metrics to measure the performance of an aerial network. The analysis is intended to provide insights into the performance characteristics of an aerial network as a function of topology and mobility. The insights derived are expected to lead to strategies for improving the reliability, throughput and latency in real-world applications.

2 Aerial Network as a Dynamic Graph

This section outlines the mathematical preliminaries of random graphs that are necessary for the analysis presented here. An aerial network with its dynamic topology can best be represented as a random graph. We consider networks with two terminals: a source (s) node and a target (t) node and follow the notation used in [3]. Let $G{=}(V, E, P)$ represent a probabilistic graph with a set of nodes $v_i \in V$, a set of edges $e_{ij} \in E$, and a link failure probability matrix $p_{ij} \in P$. Let G_{st} (V, E_{st}, P_{st}) represent an overlay graph containing a path from s to t with its associated set of edges and probabilities (E_{st}, P_{st}). An overlay graph is created during the route discovery process (RDP); a process followed by a source node to find its target node. Although either nodes or links may fail in a network, the scope of this analysis is limited to networks with link failures only, i.e., nodes are assumed to be failure-free. An edge e_{ij} represents a link connecting two adjacent nodes v_i and v_j. A path between two nodes v_i and v_j that are not adjacent to each other in G is defined as a sequence of distinct links connecting the two nodes. Information flows from one node to another as long as there is a path connecting the two nodes. A ($s - t$) cut divides the set of vertices V in the graph G_{st} (V, E_{st}, P_{st}) into two disjoint subsets S and T such that $s \in S$ and $t \in T$. $C_{st}(i)$ represents a cut-set indexed by i in the overlay graph connecting the two nodes s and t (Fig. 2).

Table 1. Terminology and notation used to represent a graph [3]

G(V,E,P)	A network with the set of nodes V, set of links E and link failure probability matrix P
s	A source node in the network G
t	A target node in the network G
S	The set of all source nodes
T	The set of all target nodes
NS	A set of network states
NS_i	Network state i
G_{st} $(\mathrm{V}, E_{st}, P_{st})$	An overlay network that contains a path from s to t with its associated $(\mathrm{V}, E_{st}, P_{st})$
n	Number of nodes, $\|V\|$
m	Number of edges, $\|E_{st}\|$
nc	Number of cut-sets in a graph
F_p	Probability that a network is disconnected
$s - t$	A cut in G_{st} $(\mathrm{V}, E_{st}, P_{st})$ where $s \in S$ and $t \in T$
$C_{st}(i)$	i^{th} cut-set of G_{st} $(\mathrm{V}, E_{st}, P_{st})$
c_{ij}	Capacity of the link e_{ij}
$c(S, T)$	Capacity of an $s - t$ cut in a static network
$c_p(S, T)$	Capacity of an $s - t$ cut in a probabilistic network
$R_{st}(G_{st})$	Reliability of route between s and t
R	Reliability of an entire network
$\Re_{st}$	Data flow between s and t
z_{st}	Probability that a data flow occurs between s and t
$l(i, j)$	Link latency between two nodes i and j
$L(s, t)$	Path latency between the a source node s and its target node t
F_p	Probability that the network gets disconnected

3 Network Reliability Analysis

This section presents the reliability analysis of an aerial network. It outlines the concept of reliability in the context of an aerial network and provides an approach to estimate the reliability of a path between a source node, s, and a terminal node, t [3].

An aerial network is characterized by fast moving aircraft systems. Thus, a link failure is primarily attributed to mobility of a node. A link failure may be temporary because an inactive link may become active again when the node comes back within the range of another node that is connected to the network. On the other hand, if a node fails, it will be removed from the aerial network. The topology of the network might change when a node is disconnected from one node and is connected back again possibly to a different node. Hence, it is reasonable to assign a probability of failure to every link in the network. A probabilistic graph is appropriate representation of an aerial network.

An overlay network is created while a node s is discovering a path to its destination t. Although the graphs, in general, may be directed, we consider undirected graphs for simplicity of analysis. The model can easily be extended to directed graphs as well. While the probability of failures may be different from one link to another, for simplification, it is assumed that the failure probabilities are same for all the links, i.e., $p_{ij} = p$ and they are independent of each other.

For illustration purpose, let us consider a benchmark graph from among those given in [2] shown in Fig. 2. It represents a typical overlay network created during a route discovery process.

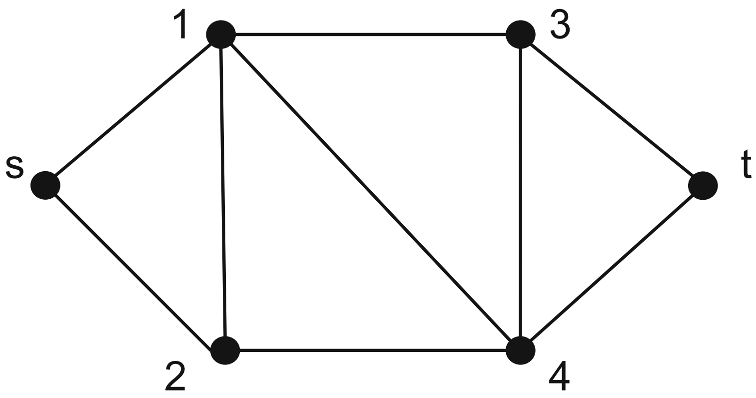

Fig. 2. An illustration of an overlay network [2]

Reliability is a performance measure for the overlay network created during RDP between two nodes. Network reliability can be computed as a function link failure probabilities and cut-sets in the corresponding graph. The problem of enumerating all cut-sets in a graph is an NP-hard problem, for which a solution is proposed in [2]. The graph shown in Fig. 2 has the following cut-sets:

$$\begin{aligned}
C_{st}(1) &= \{e_{s1}, e_{s2}\}\\
C_{st}(2) &= \{e_{3t}, e_{4t}\}\\
C_{st}(3) &= \{e_{s1}, e_{12}, e_{24}\}\\
C_{st}(4) &= \{e_{13}, e_{14}, e_{24}\}\\
C_{st}(5) &= \{e_{13}, e_{34}, e_{4t}\}\\
C_{st}(6) &= \{e_{s2}, e_{12}, e_{13}, e_{14}\}\\
C_{st}(7) &= \{e_{14}, e_{24}, e_{34}, e_{3t}\}
\end{aligned} \tag{1}$$

Assume that there are m physical links in a network between s and t, i.e., $(|E_{st}| = m)$. Let p represent the probability of link failure. The failure probability of a network state NS with exactly i physical link failures, i.e., $(|NS| = i)$ is $p^i(1-p)^{m-i}$. Let N_i be the number of disconnected states NS with $|NS| = i$. Then, the probability that the network gets disconnected (F_p) is the sum of the probabilities over all disconnected states, i.e.,

$$F_p = \sum_{i=0}^{m} N_i p^i (1-p)^{m-i} \tag{2}$$

Reliability of a two-terminal network is defined as the probability of having atleast one path between the two nodes [5]. When viewed as the complement of the network failure probability, it can be expressed as follows:

$$R_{st}(G_{st}) = 1 - \sum_{i=0}^{m} N_i p^i (1-p)^{m-i}. \tag{3}$$

Network failure states (NS) can be completely characterized by cut-sets. With the use of cut-sets, reliability $R_{st}(G_{st})$ of the network $G_{st}(V, E_{st}, P_{st})$ [3] can be expressed in the following closed form:

$$R_{st}(G_{st}) = 1 - \sum_{i=nc}^{m} \mid C_{st}(i) \mid p^i (1-p)^{m-i} \tag{4}$$

where $m = |E_{st}|$ is the cardinality of the edge set E_{st}, nc is the number of cut-sets, and $|C_{st}(i)|$ is the cardinality of cut-set with exactly i edges. The reliability of the entire overlay network can be defined as [3]

$$R = \frac{\sum_{s \in V} \sum_{t \in V, t \neq s} z_{st} R_{st}(G_{st})}{n(n-1)} \tag{5}$$

where $n = |V|$, and z_{st} is the probability that a data flow occurs between the two nodes s and t.

4 Throughput Analysis

Throughput of a network can be estimated using cut-sets of a graph that represents the network. The concept of max-flow min-cut strategy to estimate the throughput of a network was first introduced in [4]. This section extends this concept to probabilistic networks.

Cut-set: An $s-t$ cut is a partition of V such that $s \in S, t \in T$, and S and T are disjoint subsets of V. The capacity of a $s-t$ cut is defined as follows:

$$c(S,T) = \sum_{(u,v) \in (S \times T), (i,j) \in E} c_{ij} d_{ij} \tag{6}$$

where c_{ij} is the capacity of the link e_{ij} and $d_{ij} = 1$ if $i \in S$ and $j \in T, 0$ otherwise. Minimum $s - t$ cut is obtained by minimizing $c(S,T)$.

Max-flow min-cut: The max-flow min-cut theorem suggests that the maximum amount of data passing from the source (s) to the target (t) in a network is equal to the amount of flow corresponding to the minimum $s - t$ cut [4].

Throughput for a probabilistic network needs to take the reliability of the links into account. In its simplistic form, throughput of an unreliable link can be obtained by multiplying the amount of flow on the link with its reliability. Thus, the capacity of an $s-t$ cut in a probabilistic network can be expressed as follows:

$$c_p(S,T) = \sum_{(u,v)\in(S\times T),(i,j)\in E} c_{ij}(1-p_{ij})d_{ij} \tag{7}$$

where p_{ij} represents the failure probability of the link e_{ij}. The minimum $s - t$ cut for a probabilistic network will be different from a static network. Hence, the throughput of a probabilistic network will be different from that of a static network.

5 Latency Analysis

Link latency $(l_{i,j})$ is a parameter that characterizes an aerial communication link (i, j) between two nodes i and j. If a path consisting of n number of nodes exists between a source s node and its target (t) node, then, the path latency, L(s, t), is the sum of the latencies corresponding to the sequence of links {(s, 1), (1, 2), . . ., (i, i + 1), . . ., (n − 1, t)} that constitute the path (s–t).

$$L(s,t) = l_{s,1} + \sum_{i=1}^{n-2} l_{i,i+1} + l_{n-1,t} \tag{8}$$

Path latency can be viewed as the end-to-end delay between the source and target nodes assuming that there is no queuing delay. Latency is a deterministic parameter for a given path unlike throughput which is a function of the reliability of the communication links between the source and target nodes.

6 Discussion and Summary

Modeling an aerial network as a dynamic graph, this paper presents the basic concepts of reliability, throughput and latency as related to an aerial network with intermittent links. The objective of this analysis is to characterize an aerial network and to get insights into the performance of the network in terms of its capabilities and limitations. The analysis presented here is suitable for a scenario in which the topology of the network is known. It will be extended to a more general framework that includes strategies for identifying most reliable and most critical paths in the network and a study of topologies that maximize the network performance.

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