Aerospace's Project Description

RIPS 2008

Project Title

Optimizing Network Topologies

The Aerospace Corporation

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Background

In our everyday world people interact with various networks including landline telephones, cellular telephones, cable television, utility distributions, public transportation systems, satellite constellations, and the internet. From an abstract viewpoint, a network is comprised of nodes and the links connecting them. On the other hand, each network is architected with a specific purpose – usually to increase an institution's capabilities or provide some additional services. As such one of the first tasks of the network architect/engineer is to determine the locations of the network nodes. Node placement for a satellite-based network includes determining the physical locations of any terrestrial nodes and satellite ground stations, the area of operation for any mobile terrestrial nodes, and the locations and trajectories of all satellite orbits. Note that for military satellite networks the term "ground terminals" refers to land (fixed and vehicle-mounted), air, and sea "ground terminals." The type of capabilities and services that the network must support will determine the difficulty of optimizing the placement of the network nodes. Another factor that can add to the complexity is the environment; e.g., terrestrial vs. space. Additionally, military satellite networks bring about other unique complexities that include weather, nuclear scintillation, jamming, and terrain considerations. The satellite constellations may also involve satellites that have various types of orbits such as geostationary orbits (GEOs), medium Earth orbits (MEOs), low Earth orbits (LEOs), and possibly, deep space orbits.

Once the node placement has been determined, the network engineer must turn his/her attention to designing the network topology, which is the placement of the links between the various nodes. The engineer must consider various constraints including the number of links that each node can support and the constraints associated with the chosen link-type (cable, fiber, radio transmission, or laser). When one considers a satellite network additional constraints that must be considered include line-of-sight, Earth-blockage, slew rates of the satellite antennas, the satellite orbits, and the position of the Sun. One of the main differences between engineering a terrestrial network vs. a satellite network concerns intermittent connections between the network nodes.

In a wire-line terrestrial system a connection between two nodes is short, highly reliable, and virtually permanent. Additionally, wire and fiber links are immune from weather conditions. In contrast, satellite nodes links, called uplinks, downlinks and crosslinks, are more transitory due to the fact that the nodes are in constant motion with respect to the Earth and each other. This behavior is most pronounced for LEO satellites. On the other hand, satellite orbits are periodic and therefore predictable. Nonetheless, satellite network links can suffer unpredictable outages; e.g., satellite uplinks and downlinks can be severely impacted by inclement weather.

Taking into account the various constraints, the engineer must design a network topology that satisfies a range of objectives. Historically, one of the primary objectives is to have a network topology that is continuously connected in order to guarantee that every node can communicate with any other node via the network at any point in time. Another primary objective is redundancy so that the random loss of a network node or link will not cause the network to lose connectivity with the exception of the lost node. However, there is new research being done on a class of networks called delay tolerant networks (DTNs) that cannot be continuously connected. In this light the network engineer will seek to maximize network connectivity and redundancy given the physical constraints of the system.

In addition to maximizing the network connectivity and redundancy, the network engineer will optimize the network topology in order to satisfy one or more additional objectives. These objectives may include local or global minimization of transmission times between network nodes using the primary routes (and sometimes the secondary routes as well), minimization of the number of link transitions, minimization of the number of satellite crosslinks, maximizing frequency reuse, etc.

Historically, the optimization of network topologies has relied upon three mathematical disciplines: Graph Theory, Combinatorial Optimization, and Mathematical Programming. In fact, many research projects have focused on the optimizing network topologies for static nodes (see [S] and [PM]). However, the research community has only recently focused on extending this work to include non-static networks such as satellite-based constellations and DTNs. In addition, military networks often have their own unique challenges due to their specific usages and threats.

Once the network topology has been optimized, the network engineer can turn his/her attention to other design issues that include wireless channelization, network dimensioning, routing algorithm design, network survivability (fault protection and fault recovery), congestion control, traffic engineering, and network security. In reality these network optimizations involve “trade-offs,” where engineers study the various issues as a whole and look at the outcomes of all of the optimizations in their entirety. This helps the designers understand the costs associated with each portion of the network design, which in turn assists the decision makers as they search for the most cost-effective architecture. Nonetheless, our focus on this project will be limited to optimizing the network topology.

Project Objectives

The objective of this project is to investigate, develop, and validate efficient algorithms that can be used to generate optimal network topologies. The inputs for these algorithms will be time-based information for four distinct satellite networks that each has a ground station in Denver, CO. These sample networks will include a “larger” MEO constellation (relatively simple), a “smaller” MEO constellation, a “larger” LEO constellation, and a “smaller” LEO constellation (relatively complex). For each of these scenarios, the team will be given data that will show, over the course of the scenario, the intervals of times that each pair of network nodes (satellites and/or ground stations) can communicate. In addition, the data will show the time-based distances between each pair of network nodes. By dividing the distance by the speed of light, one can determine the latency, which is the time between when the message is sent from the source and the time when the message arrives at its destination.

The objective will be to design an algorithm that will work on the four constellations, and will optimize each of the network topologies as follows. (Ideally, this project will be accomplished in stages where each subsequent stage builds upon the previous stages.)

Stage I The algorithm will maximize the network connectivity.

Stage II In addition to doing everything from Stage I, the algorithm will maximize the network redundancy.

Stage III In addition to doing everything from Stages I & II, the algorithm will minimize the primary paths between each of the satellites and the ground station in terms of latency.

Stage IV In addition to doing everything from Stages I, II & III, the algorithm will minimize alternate paths between each of the satellites and the ground station in terms of latency. The goal is to minimize the effect on the latency by the loss of a random satellite.

One of the input parameters for the algorithm will be the number of crosslinks per satellite. In addition, it should be assumed that each satellite has one uplink/downlink that work in unison. Finally, it should also be assumed that the ground station has two separate uplink/downlink antennas.

If time permits, it would be interesting to see how the algorithm could be further massaged to determine an optimal network topology for a DTN network with store-and-forward routing capabilities.

Project Deliverables

- Well-documented computer software that implements the team's algorithms (C, C++ or MATLAB)
- Demonstration of the algorithm applied to input data provided by Aerospace
- A final detailed technical report describing the project's accomplishments including algorithm description and documentation
- A final briefing to be given at the RIPS Project Day and at Aerospace

References

[C] Chartrand, G., *Introductory Graph Theory*, Dover Publications, 1985

[PS] Papadimitriou, C. and Steiglitz, K., *Combinatorial Optimization: Algorithms and Complexity*, Dover Publications, 1998

[PM] Pioro, M. and Medhi, D., *Routing, Flow, and Capacity Design in Communication and Computer Networks*, Morgan Kaufmann Publishers, 2004

[S] Sharma, R. L., *Network Topology Optimization: the Art and Science of Network Design*, Van Nostrand Reinhold, 1990