Assessing the Capacity of a Federated Ground Station Network

Sara C. Spangelo
Aerospace Engineering
University of Michigan
1320 Beal Ave, Ann Arbor, MI 48109
saracs@umich.edu

Dylan Boone
Aerospace Engineering Sciences
University of Colorado
429 UCB, Boulder, CO 80309-0429
dylan.boone@colorado.edu

James Cutler
Aerospace Engineering
University of Michigan
1320 Beal Ave, Ann Arbor, MI 48109
jwcutler@umich.edu

Abstract—We introduce models and tools to assess the communication capacity of dynamic ground station networks, in particular federated networks that are composed of geographically diverse and independent stations that loosely collaborate to provide increased satellite connectivity. Network capacity is the amount of information exchanged between a network of satellites and ground stations. The constraints on total network capacity which influence transmission capabilities are outlined, such as the satellite, ground station, and overall network parameters. Orbit propagators are combined with engineering analysis software to compare the capacity of existing and future ground station networks. Simulation results from recent clustered satellite launches are presented and discussed. By studying network capacity, we identify the potential for leveraging these federated networks to support multiple missions from multiple institutions. Future work is outlined, including the need to accurately model both satellite communication requirements, develop real time network analysis tools, and work towards developing dynamic optimization techinques for global autonomous networks.

Table of Contents

1. Introduction

This paper assesses the capacity of ground stations, and considers the advantages of combining them in loosely federated ground station networks. We develop standard models and tools to quantify network capacity, which we define as the information exchange between collections of ground stations and satellites over a particular time period.

A goal of a ground station network is to maximize the data transfer capacity, where data is communicated from satellites to ground stations across the entire network. The assessment introduced in this paper aims to identify the maximum capacity of multiple networks, that is the total potential data throughput given a population of satellites and ground stations over a certain time frame, for example over the course of a single day. We then develop the tools to quantify the actual network utilization, and identify the available excess capacity which may be exploited with optimal scheduling. We examine the network capacity properties of ground station communities for various satellite deployments, motivating optimal scheduling algorithms and the development of higher fidelity network models.

Motivation

Current satellite developers face the challenges of complex communication systems and the restrictions of existing ground station infrastructure. The missions and capabilities of these satellites, including the downlink of science and telemetry data, are limited by monolithic designs, narrow interfaces, reliability issues, and high mission costs [1]. In addition, ground stations are often built for a single mission or institution, resulting in an underutilization of ground station capacity. The growing number of satellite users combined with the hundreds of existing ground stations motivate the concept of loosely federated ground stations networks (FGSNs).

This new class of network is a dynamic framework where satellites and ground stations may join and leave the network at will. The FGSN provides downlinking opportunities to satellite users that would not otherwise be available, while allowing flexibility for individual institutions. Our work shows the excess capacity of several potential networks, identifying the resources for overall network capacity improvements. Combined with knowledge of scheduled upcoming satellite launches, we lay the ground work for optimization algorithms which will distribute excess capacity to satellite users through intelligent deployment coordination and flexible scheduling.

In our opinion, many new small satellite developers that may or may not have ground station capabilities will benefit from federated ground station networks. For example, potential beneficiaries are the CubeSat developers, a community of worldwide universities, corporations, and government laboratories who perform space science and exploration using miniaturized satellites. The CubeSat initiative originated at California Polytechnic State University, San Luis Obispo (Cal Poly) and Stanford University, providing a low cost, standardized platform for access to space. The standardized nanosatellites are approximately one liter in volume and one kilogram mass as established by Puig-Suari et al. [2]. They are currently scalable in 10 cm^3 units, termed 1U, 1.5U, 2U, and 3U spacecraft. The most common deployment mechanism for CubeSats is the Poly Pico-Satellite Orbital Deployer (P-POD), which holds any combination summing to three

CubeSat units. Launch opportunities for CubeSats are offered by companies and research institutes such as CalPoly, ISIS, and UTIAS-SFL.

CubeSat developers have launched dozens of small spacecraft in the past decade and have dozens more scheduled for launch in the next year. Since each institution often builds their own ground station, the community has excess ground station capabilities. Harnessing these idle resources will improve global satellite communication capabilities not only for CubeSat developers, but for large scale satellite users as well.

Existing Literature

The introduction and maturation of the Internet led to the concept of commercial, low-cost, autonomous ground station networks in the 1990s. One example is the concept developed for the Extreme Ultraviolet Explorer (EUVE) satellite, operating with the Tracking and Data Relay Satellite System (TDRSS) and Deep Space Network (DSN)[3]. Scheduling and resource allocation, antenna and receiver predictions, service requests, closed loop control, and error recovery for the station subsystems are targeted in the fully automated DSN operations architecture work by Fisher et al. in Ref. [4]-[5], while Ref. [6] developed genetic algorithms for TDRSS satellites.

Ingram et al. [7] consider optimization of steerable phased array technologies in a network of ground stations for a single low earth orbiting (LEO) satellite, and showed significant improvements in netowrk capacity. The potential use of multiple smaller low-cost space fed lens arrays (SFLAs) to replace large, conventional reflectors is studied by Lee in Ref. [8].

The challenges of controlling and monitoring ground station networks has been identified in [9], emphasizing the difficulties in scaling up the conventional tools designed for single-satellite or small network operations. This work introduces a 3-D visual monitoring technology which employs alarms to provide operation teams high-level qualitative network operations data. Reference [10] proposes the commercialization of excess network capacity in electro-optical satellites for the benefit of both public and private users. The ground station capacity tools are introduced in work by Boone and Cutler [11], and the downlinking capacity of existing networks are assessed, motivating optimization techniques. These authors studied satellite separation effects on network downlink capacity [12]. The scheduling problem of multiple satellites and widely-distributed ground stations connected through an autonomous, open Ground Station Network (GSN) is traced to a combinatorial optimization problem in Reference [13]. Lee develops an initial prototype algorithm to maximize data transfer for an Internet-enabled ground station with centralized control [14].

Motivated to overcome the financial and engineering barriers and satisfy space operation trends, Reference [15] has contributed to the development of the concept of federated ground station networks. FGSNs are Internet-enabled scheduling systems facilitating communication coverage of satellites over ground station networks. This system acts as a synergy of autonomous, globally distributed ground installations which share functionally diverse resources over an extensive geography. This concept addresses the matching of satellites to ground stations to maximize the network utility while guaranteeing the data transfer requirements of the satellites are met. The FGSNs have centralized or localized control and depend on the ability of the satellites to communicate via any ground station, regardless of geographical position or antenna ownership. FGSNs offer greater access to space science data at a lower cost, and through interoperation of ground stations, improves efficiency and supports ongoing 24/7 satellite coverage [16].

Cutler et al. [17] have developed the Mercury Ground Station Network (MGSN), a prototype ground station control system to support advanced command and telemetry operation with spacecraft. Implemented with Orbiting Satellite Carrying Amateur Radio (OSCAR) class amateur radios [18], this system is comprised of university based ground stations, and satellite research groups including the Opal [19], Sapphire [20], and University Nanosatellite missions [15].

GENSO is a European Space Agency (ESA) project currently working to develop a worldwide network of ground stations and spacecraft which interact through standard software [21]. The goal is to increase the return from educational space missions by allowing for Internet-enabled communication across the network of small spacecraft operators in LEO.

Multi-mission support of the loosely federated MGSN is proposed using virtual machines in Reference [1] and [15]. Software-defined systems capture core ground station operations, enable user customization of ground station capabilities, and reduce station complexity.

Contributions

Prior work has not focused on maximizing the capacity of an entire network in a dynamic ground station environment subject to changing satellite mission objectives. Our larger goal is to develop robust, real-time optimization algorithms for multi-satellite missions and federated ground station networks. Our initial unique contributions to this objective are listed below.

1. Develop standard analytical tools to model network capacity as a function of ground station constraints and satellite requirements and constraints.
2. Assess network capacity of existing ground stations networks and current and future satellite deployments.
3. Formulate an optimization problem to maximize network capacity subject to the identified constraints, study the necessary conditions and identify extremal optimal solutions. Equipped with this understanding, the ultimate objective is to formulate real-time optimal algorithms for FGSN schedul-

ing.

2. Network Capacity Model

The mathematical model developed in this section assesses network capacity, driven by the satellite and ground station needs for data exchange, and when and how communication links are made from satellites to ground stations. In this paper, we are motivated to understand the network utilization of the ground station community, and therefore focus on modeling capacity as a function of ground station constraints. We assume reliable communication, such that the satellite can close the link to a given ground station when in view. This is a simplified representation of the communication operation, and future work will extend this model to include both the spacecraft and link constraints.

Capacity Definition

We define the total capacity C_N of a given network N consisting of m ground stations,

$$C_N = \sum_{j=1}^{j=m} C_j, \tag{1}$$

where C_j is the capacity of ground station j,

$$C_j = \sum_{i=1}^{i=n} \int_{t=0}^{t=T} a_{ij}(t) r_{ij}(t) l_{ij}(t) \eta_j(t) dt. \tag{2}$$

In the single station capacity expression, Equation 2, $a_{ij}(t)$ represents the availability of a link (the existence of a line-of-site) between ground station j and satellite i. The data transfer rate between the ground station j and the satellite i is a function of time t and represented as $r_{ij}(t)$. The establishment of a communication link, driven by the ground station schedule, is represented by $l_{ij}(t)$. The efficiency of the ground station is $\eta_j(t)$. The total capacity of a single ground station in a network comprised of n satellites is computed by summing the integrated data transfer rates to each satellite throughout the full time period of interest, $t = [0, T]$. Note that the total data transfer time between a satellite and ground station is comprised of multiple passes, which may have different data transfer rates and time intervals. The four components of the station capacity model, $a_{ij}(t)$, $r_{ij}(t)$, $l_{ij}(t)$, and $\eta_j(t)$, are now described in more detail.

Availability— The first component of the network capacity model is based exclusively on the availability of a communication link between a unique ground station and satellite. This is dependent on the existence of a line-of-sight between the satellite and the ground station as a function of time, the minimum elevation visibility constraints of the ground station, and the orbital dynamic properties of the satellites. The availability matrix is $A(t)^{n\times m}$, consisting of elements $a_{ij}(t) \in \{0,1\}$, $1 \le i \le n, 1 \le j \le m$, where an available link between a satellite and ground station at time t is expressed $a_{ij}(t) = 1$, and when there is no visibility, $a_{ij}(t) = 0$. Given our ground station centric capacity model, the satellites are modeled as point masses with perfect communication systems which can always close the link to a ground station in view. Future system-wide capacity models will contain realistic satellite constraints and properties.

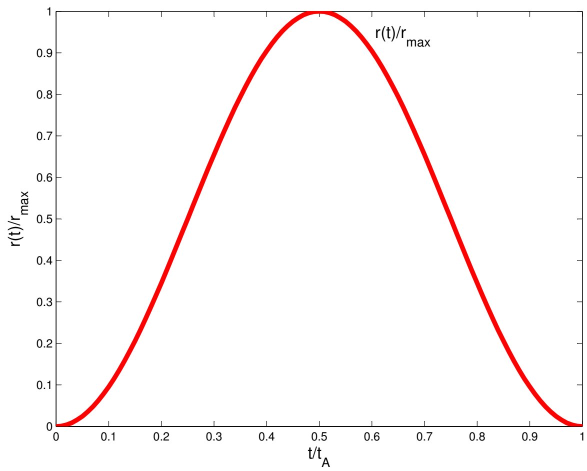


Figure 1. This is a representative data rate distribution for a satellite pass over a ground station where the rate is optimized to accommodate signal to noise ratio changes as a function of range distance.

Data Transfer Rate—The data transfer rate between satellite i and ground station j at time t is $r_{ij}(t)$. Typically, rates are selected at design time and updated during operation of ground stations and satellites. They are constrained by the minimum signal to noise ratio (SNR) requirements for varying communication links, see [22]. For example, Figure 1 shows an optimal communication rate distribution that maximizes throughput, exploiting the increased SNR from decreased range distance as the elevation angle increases.

The data transfer rate matrix is defined as $R_{ij}(t)^{n\times m}$, where the transfer rate between satellite i and ground station j at time t is $r_{ij}(t)$. Population of R_{ij} could be ground station centric and represent the maximum communication of the station for some standard communication scenario. It could also be populated with matched satellite and ground station rates that reflect operational constraints of missions.

Data Transfer Link—Governed by the scheduling constraints of the ground station, a link to a given satellite may or may not be desired even if one is available, $a_{ij}(t) = 1$. $L_{ij}(t)^{n\times m} \in \{0,1\}$ is the link matrix, for which $l_{ij}(t) = 1$ for a desired link between satellite i and ground station j at time t and $l_{ij}(t) = 0$ if the schedule will not allow for communication. For example, consider a ground station j, which can only communicate with one satellite i at a given time t. If $l_{ij}(t) = 1$, when $i = p$, it follows that $l_{ij}(t) = 0, \forall\, i \neq p$.

Ground Station Efficiency— Successful data transfer from satellite to ground station is influenced by the ground station efficiency. We refer to this efficiency as $\eta_j(t)$ for ground station j and it is used to characterize trends in station performance. The efficiency reflects the estimated percentage of contact time when the communication link is not maintained due to antenna slewing and acquisition maneuvers, keyholing, ground station failures, and local noise emissions that degrade SNR. A ground station which always operates perfectly has an efficiency factor $\eta_j(t) = 1 \ \forall\ t \in [0, T]$, while for example, for a ground station which establishes a successful link on average for 90% of the available satellite time, $\eta_j(t) = 0.9\ \forall\, t \in [0, T]$.

Model Representations

We now introduce four example network capacity models where classes of constraintsare progressively considered. The models with successively increasing fidelity are shown in Figure 2, enclosed within smaller ellipses. The area within each ellipse represents the network capacity, which generally decreases with the addition of constraints. Table 1 describes the models and summarizes each component of the ground station capacity from Equation 2.

We first assess the maximum capability of a ground station network. This *maximum capacity model* assumes constant availability, such that $a_{ij}(t) = 1\ \forall\ t \in [0, T]$ and constant data transmission occurs for all time. The maximum level characterizes the ground station system and network at the overall maximum throughput rate, r_{max}, of the given ground station.

Next, we assess the communication link availability between satellites and ground stations as a function of geographical constraints, specifically ground station locations and satellite orbits. This *topological model* considers the line-of-sight availability as a function of time, specifically the matrix $A(t)$.

Station scheduling constraints are introduced in the *scheduled model*, further increasing model fidelity. Ground station operational constraints are key to the scheduled level, particularly in establishing the link matrix $L(t)$. In our example below, we assume that each ground station can have only a unique link to a satellite within the network at any given instance in time, and for the purpose of our analysis we consider only downlinking data transfers.

Ground station efficiency is considered in the final layer, the *actualized model*, to include parameters such as antenna pointing accuracy, hardware reliability, the mean time to failure and recovery, and repair downtime. Real-time changes to the availability, data transfer rate, links, and efficiency matrices may also be considered, driven by variable data transfer rates and demands from the ground station and satellite users.

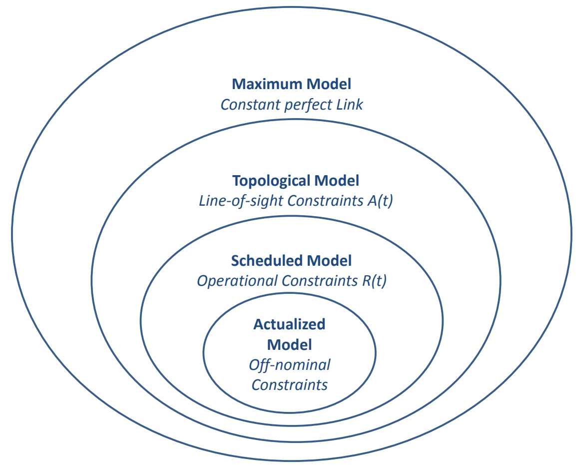


Figure 2. A Schematic of the Ground Station Models: Increasingly higher fidelity models lay within smaller ellipses representing network capacity.

The capacity of each model is captured schematically in Table 1, integrated as a function of the data rate over the time interval. In this example, we consider a single pass with total access time t_A. In the *maximum model*, the capacity is assumed to be a function of the maximum data rate for the complete access time. The optimal elevation to close the communication link controls the capacity in the *topological model* by governing both the optimal data transmission rate, r_{opt}, and the length of time communication is maintained, t. The *scheduled model* considers that multiple satellites may be overhead, and we introduce the average link l_{avg} to represent the relative amount of total access time dedicated to a single ground station and satellite link. Finally, the ground station efficiency further shortens the total data transmission time in the *actualized model*, reducing network capacity.

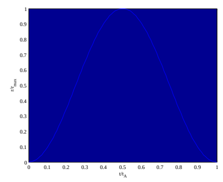
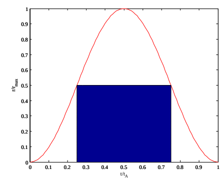
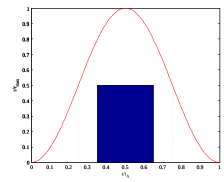
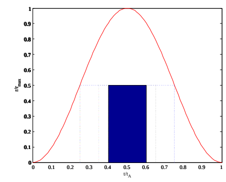
3. Examples of Capacity Assessment

This section provides several example capacity models and discusses their potential for assessing ground station network capacity. First, we describe the simulation environment and tool suite we have developed. We then assess network capacity through simulation using these tools, identifying the factors which have the greatest affect on total network capacity at each level of model fidelity. We conclude by studying the capacity of a few sample existing and potential future networks.

Tool Description

We developed a suite of tools to calculate the capacity modelled in Section 2 for varying sets of ground station networks and satellite populations. Our simulation tools extract data sets from a variety of sources. Information on ground station networks is drawn from default data sets in STK, for exam-

Table 1. Ground Station Models for a Communication Link to a Satellite

Model	Maximum	Topological	Scheduled	Actualized
Schematic				
Additive Constraints	GS Link Budget	Satellite Orbit, GS Locations	GS Operations	GS Downtime, Failures, Switching, Pointing, Keyholing
Parameters	$a = 1$ $r = r_{max}$ $l = 1$ $\eta = 1$	$a(t)$ $r(t) = r_c = \frac{1}{2} r_{max}$ $l(t) = 1$ $\eta(t) = 1$	$a(t)$ $r(t) = r_c = \frac{1}{2} r_{max}$ $l(t) = l_{avg} = \frac{3}{5}$ $\eta(t) = 1$	$a(t)$ $r(t) = r_c = \frac{1}{2} r_{max}$ $l(t) = l_{avg} = \frac{3}{5}$ $\eta(t) = \eta_{avg} = \frac{2}{3}$
Capacity	$C = r_{max} t_A$	$C = r_{max} t$	$C = r_{max} l_{avg} t$	$C = r_{max} l_{avg} \eta_{avg} t$

ple the Air Force Satellite Control Network (AFSCN), and from our custom online databases. We have an ongoing survey of global ground stations that contain necessary information [23].

Satellite data sets are also drawn from a custom database. Current and historical two line element (TLE) sets for these satellites are obtained from *http://www.spacetrack.org/*. TLEs are used for propagating orbits and determining satellite positions over time. Note our custom databases are accessible online and can be easily populated with diverse satellite and ground station networks.

Two orbit propagators are used in our simulation tools. First, a Matlab script extracts historical TLEs from the Space-Track website [24] and loads them into STK along with ground station locations from our database. STK is then used to propogate the orbit and compute all possible contact times between ground stations and satellites. This information is exported to Matlab for further processing. Our second orbit propagator is SatTrack, Version 3 [25]. Like STK, it uses the Simplified General Perturbations Satellite Orbit Model 4 (SGP4) to determine ground station and satellite contact times.

Algorithms written in Matlab collect contact times and calculate capacity values based on model parameters. These algorithms use output from either of the propagators mentionned above. Analysis output is generated locally on the analyst's computer, or the system can be periodically executed automatically with results published online.

Network Models Simulations

With our simulation tools and example ground station networks and satellite populations, we calculate network capacity with increasing levels of model fidelity. The maximum capacity model can be used to characterize our ground communication system, where we assume an ideal link to a satellite permanently overhead. Figure 3 is a plot of surveyed global amateur radio ground stations. These stations are generally capable of 9600 bps, thus the network of 98 satellites has the potential to move over 80 gigabits of data on a daily basis.

Figure 3. CubeSat Survey of existing ground stations *(http://gs.engin.umich.edu/gs survey/)*.

To assess the capacity of a particular satellite pass with the general model, we integrate the product of the time-dependent data rate, link, and efficiency factors between a specific satellite and ground station throughout the access time, $C_{ij} = \int_0^{t_A} r_{ij}(t)\eta_{ij}(t)dt$. In order to simplify our examples, we assume the data rate and link efficiency are constant throughout the access time. Thus, we simplify the capacity expression to $C_{ij} = r_{ij}\eta_{ij}t_A$, and since r_{ij} and η_{ij} are constant,we discuss network capacity as a function of access time.

In our representative analysis, we focus on the topological and scheduled models. We set $\eta(t) = 1 \ \forall \ t \in T$, due to our lack of expected η values in real world ground station networks. We are deploying monitoring systems in a growing number of ground stations to collect this data in real time.

Equipped with the tools to analyze ground station capacity, we now assess both existing ground station and satellite communities and potential future networks. We introduce additional ground station locations and satellites, and analyze the network capacity properties. The benefits of combined networks are emphasized, motivating optimal scheduling algorithms to maximize network capacity with respect to the network objectives. In the final discussion section, we outline the major trends observed in the following representative examples.

Multiple Ground Stations, Single Satellite—We first consider a simple network with three ground stations and a single satellite. We utilize the topological model to show the obvious effect of ground station location (latitude and longitude) on capacity for a given satellite orbit. Three ground stations in the Air Force Satellite Control Network at different geographical locations illustrate the effect of ground station latitude on capacity. Station locations are found in Table 3 and represent high, mid, and low latitude stations. With a representative orbit of many missions, we selected a single Cubesat from the April 2007 Dnepr launch vehicle, Aerocube-2, as the orbiting satellite. This Cubesat is deployed into an orbit with a high inclination of (99^o) and an altitude of approximately 715 km.

Figure 4 compares the daily access time for the Dnepr-launched Cubesat and the three AFSCN stations. Daily ground station access time for a polar orbiting CubeSat is only 3000 sec/day at a low latitude of 13.6^o, and 11000 sec/day on average at a latitude of 76.5^o.

Single Ground Station, Multiple Satellites—Now we employ the scheduled capacity model to consider multiple satellites communicating to a single ground station. We impose the link constraint in this model, where we assume that the ground station can communicate only with a single satellite at a given time instant. The single ground station in this example is located in Ann Arbor, MI and is considered mid latitude (42.28N, -83.74W). The satellites used are a collection of three Cubesats deployed from the TacSat launch vehicle from the Minotaur I carrier rocket by AFRL on May 19 at an altitude of approximately 460 km and inclination of 40.5^o.

A particularly interesting feature of these satellites is their clustered launch vehicle deployment. They were launched simultaneously with a single launch vehicle interface [26] and separated over time. Figure 5 was generated with our tool suite to show intersatellite separation distances. Position information was obtained from online Keplerian element sets [24]. Note the varying distances that are a function of orbital perturbations, initial separation velocity, and differing drag coefficients. Within a month, the distance between the satellites has grown to up to 1000 km.

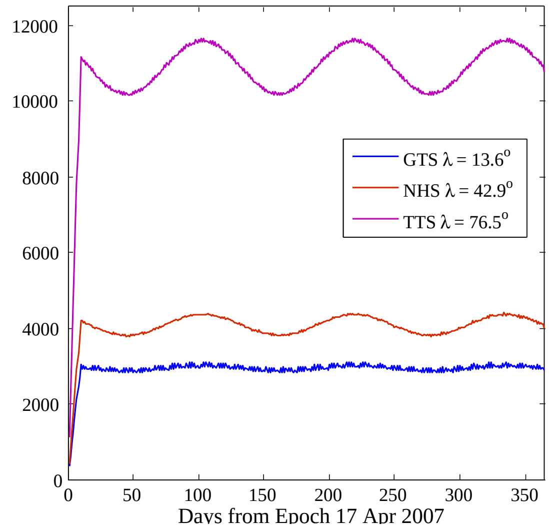


Figure 4. Effects of AFSCN Ground Station Latitude variation on Network Capacity for AeroCube-2 satellite.

The intersatellite separation affects ground station capacity as shown in Figure 6. The dotted lines are the contact periods for an individual satellite to the ground station. The solid line represents the total daily capacity from a single P-POD of satellites. The total capacity is initially equivalent to the capacity of a single satellite (3500 sec/day), a function of the satellite's orbit and Ann Arbor's geographic location. The network capacity grows to an average of 7000 sec/day after two months of separation, doubling the initial capacity for the clustered launch.

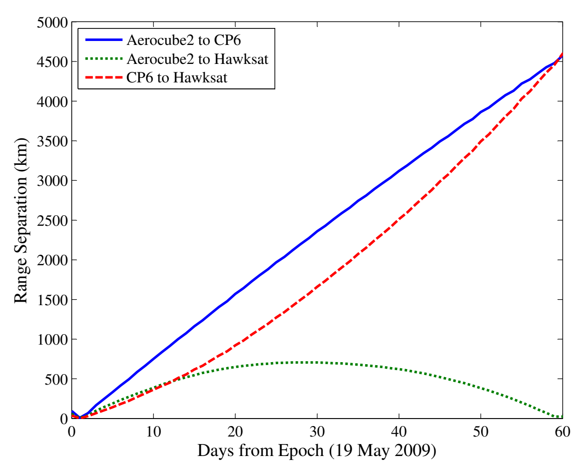


Figure 5. 2009 Minotaur-1 launched CubeSat group separation distance grows following epoch, resulting in increased access time, see Figure 6.

Table 2. Geographical Locations of Sample AFSCN Ground Stations

Ground Station	Location	Latitude	Longitude	Latitude Category
Guam Tracking Station (GTS)	Anderson AFB, Guam	13.6^o	144.8^o	Low
New Hampshire Station (NHS)	New Boston AFS, NH	42.9^o	-71.6^o	Mid
Thule Tracking Station (TTS)	Thule AB, Greenland	76.5^o	-68.6^o	High

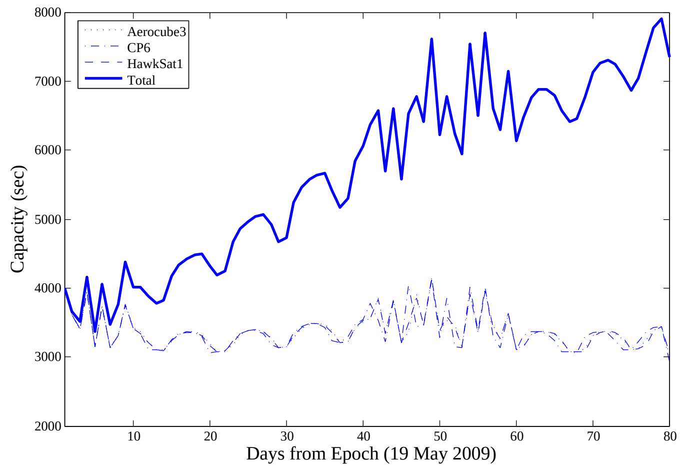


Figure 6. Access Time of 2009 Minotaur-1 launched CubeSat group to Ann Arbor Ground station ($\lambda = 42.27^o, \phi = 83.76^o$).

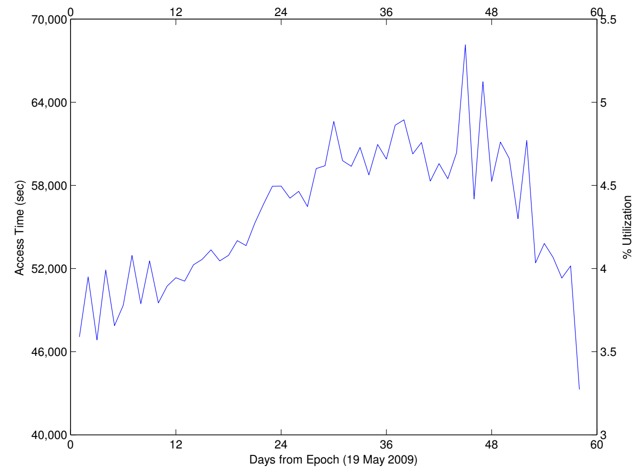


Figure 7. Total Network Capacity for 2009 Minotaur-1 launched CubeSat group.

Multiple Ground Stations, Multiple Satellites—The full AFSCN, consisting of 15 remote tracking stations (antennas) with global locations, is an example of an existing distributed ground station network [27]. Considering the three cubesats launched with TacSat-3 on May 19, 2009 date on a Minoatur-1, we calculate the total access to the full AFSCN network of these satellites. The plot in Figure 7 shows the increase in capacity for the TacSat-3 satellites by using the distributed network. After two months, the average daily capacity jumps from 50,000 sec/day to a peak of 68,000 sec/day.

Discussion—In assessing the capacity of different scalings of problems, we've identified at least three interesting trends contributing to the capacity of a ground station network. This list is by no means exhaustive, but outlines several of the observable trends from the previous section.

- Ground station location and satellite inclination largely influences the orbital parameters governing availability. We noted in Figure 4 the significant influence of ground station latitude relative to the high inclination Dnepr-launched Cubesat orbits.
- Seasonal satellite orbit perturbations affect the availability of communication. The capacity distribution in Figure 4 shows oscillations with access time variations of approximately 15%, a significant trend for satellite communication applications. The period of these curves is dependent on the satellite and ground station parameters. Distinct periods are noted, which are most likely explained by the interaction of the Earth's nominal rotation and perturbations due to Earth's oblateness, characterized by the J_2 gravity coefficient [28].
- Network capacity is also governed by the separation of satellites launched from same P-Pod, influenced by their deployment mechanism and the relative time since they were launched. The effects of seperation distance noted in Figure 5 largely influence the capacity shown in Figure 6 for the satellites deployed from the DNEPR launch vehicle.

Our ongoing work investigates the analytic reasoning behind these trends. We will apply this understanding and assessment tools to the development of our optimization techniques.

4. Conclusions

The models, tools, and assessment introduced in this paper study the capacity problem of a ground station network. We developed an analytic model to describe the communication between ground stations and orbiting satellites, which has enabled us to investigate the effects of successively higher fidelity constraints on network capacity. Integrated tools are used to assess the capacity of existing and future networks, motivating future work on scheduling algorithms to optimize network capacity.

We now introduce two upcoming examples where network capacity may be assessed and the implementation of optimization techniques would be beneficial. The first is the proposed clustered launch of fifty nanosatellites [29] by the Naval Postgraduate School (NPS). They are developing a new CubeSat development system, NPSCuL, designed to work with evolved expendable launch vehicles (EELV). The NPSCuL will have slots for up to 50 1U CubeSats on a single launch.

The second examples is the QB50 Project, whose goal is to set up and coordinate a CubeSat science network on orbit. The network will consist of 50 international CubeSats with the objective of multi-point, in-situ measurements in the lower thermosphere and to perform re-entry research [30]. The 50 CubeSats are anticipated to be launched in mid 2012 from the Russian Shtil-2.1 or Shtil-2R launch vehicle into a circular orbit at an altitude of about 300 km. Atmospheric drag will cause the satellite orbits to progressively lower into layers of the thermosphere, where the objective is to collect scientific data down to altitudes of 90 km.

Future Work

Satellites from these examples are launched with an initial separation velocity (ΔV) that produces an on-orbit separation rate. With our tools, we can assess capacity for three types of deployment spacing: instantaneous deployment, intermediate, and variable injection time delay deployments, where the launch vehicle injects satellites at different initial locations along the orbit. We can then employ optimization techniques to maximize network capacity for a given ground station community.

We have identified several future directions in order to develop scheduling of optimal satellite communication links. Our next effort will identify satellite capacity needs, such that we may develop more complete scheduling and actualized models. We will develop a language and model for satellite operators to express their communication needs over varying time periods, from long term mission averages to short term daily needs. This will enable us to assess communication needs which can that be compared to communication capacity.

Combining satellite communication information requirements with ground station capacity using the tools developed in this work will lay the foundation for real time scheduling tools. The simulations in this paper currently use past satellite tracking data. Using high fidelity orbit propagators, we can build real time tools for determining capacity and eventually scheduling contact between satellites and ground stations. The goal of future work is to optimize scheduling in a dynamic environment, where both the satellite population and the ground station network are evolving and subject to variable conditions (satellite/ ground station failures, change of mission objectives, etc.). In particular, satellites may originate from differing institutions, and ground stations may not be directly under the control of the team who owns the antenna, forming federations of stations. This problem aims at optimizing the schedule for the dual goals of balancing station utilization and satisfying satellite communication needs, evaluated through a cost function. These real time tools will facilitate the creation of optimization algorithms for ground station scheduling which can be used for both mission design and tactical network scheduling.

ACKNOWLEDGMENTS

We would like to thank Andy Klesh, Matt Bennett, Eric Gustafson, and the University of Michigan RAX Team for their valuable input. We would also like to acknowledge Prof. McKague and the CubeSat community for their support in completing the ground station survey.

REFERENCES

[1] J. Cutler and A. Fox, "A framework for robust and flexible ground station networks," in *Journal of Aerospace Computing, Information, and Communication*, March 2006.

[2] J. Puig-Suari, C. Turner, and W. Ahlgren, "Ground station network to improve operation efficiency of small satellites and its operation scheduling method," in *IEEE Aerospace Conference Proceedings*, March 2001.

[3] A. Abedini, J. Moriarta, D. Biroscak, L. Losik, and R. Malina, "A low-cost, autonomous, ground station operations concept and network design for EUVE and other earth-orbiting satellites," in *International Telemetering Conference Proceedings, Theme: 'Re-Engineering Telemetry'*, October 1995.

[4] F. Fisher, D. Mutz, T. Estlin, L. Paal, E. Law, N. Golshan, and S. Chien, "The past, present, and future of ground station automation within the DSN," in *IEEE Aerospace Conference Proceedings*, March 1999.

[5] F. Fisher, M. L. James, L. Paal, and B. Engelhardt, "An architecture for an autonomous ground station controller," in *Proceedings of the 2001 IEEE Aerospace Conference*, March 2001.

[6] W. Zheng, X. Meng, and H. Huan, "Genetic algorithm for TDRS communication scheduling with resource constraints," in *International Conference on Computer Science and Software Engineering Proceedings*, December 2008.

[7] M. Ingram, W. Barott, Z. Popovic, S. Rondineau, J. Langley, R. Romanofsky, R. Lee, F. Miranda, P. Steffes, and D. Mandl, "LEO download capacity analysis for a network of adaptive array ground stations," in *Earth-Sun System Technology Office (ESTO), under Grant Number NAG5-13362*.

[8] R. Lee, Z. Popovic, S. Rondineau, and F. Miranda, "Steerable space fed lens array for low-cost adaptive ground station applications," in *IEEE Antennas and Propagation Society International Symposium*, June 2008.

[9] I. Harrison and U. Schwuttke, "Optimizing satellite,

network, and ground station operations with next generation data visualization," in *IEEE Aerospace Conference Proceedings*, March 2000.

[10] C. Demir, "Commercialization of excess capacity in electro-optical satellites," in *3rd International Conference Proceedings on Recent Advances in Space Technologies*, June 2008.

[11] J. Cutler and D. Boone, "Assessing global ground station capacity." Cubesat Developers' Workshop, April 2009.

[12] D. Boone, "A study of cubesat orbital separation and ground station capacity using satellite tool kit." AERO/AOSS 590 Final Report, Space Systems Project, University of Michigan, Ann Arbor, April 2009.

[13] Y. Nakamura and S. Nakasuka, "Ground station networks to improve operation efficiency of small satellites and its operation scheduling method," in *AIAA Aerospace Conference Proceedings*, January 2006.

[14] N. Lee, "Satellite matching for a federated ground station network." EE364b Final Report, Space and Systems Development Laboratory (SSDL), Department of Aeronautics and Astronautics, Stanford University, May 2008.

[15] J. Cutler, P. Linder, and A. Fox, "A federated ground station network," in *SpaceOps Conference Proceedings*, October 2002.

[16] J. Cutler, A. Fox, and K. Bhasin, "Applying the lessons of internet services to space systems," in *IEEE Aerospace Conference Proceedings*, March 2009.

[17] J. Cutler and C. Kitts, "Mercury: a satellite ground station control system," in *IEEE Aerospace Conference Proceedings*, March 1999.

[18] C. Towns, "History of project OSCAR," in *73 Amateur Radio*, vol. 332, pp. 27–9, 1998.

[19] M. Baker-Harvey, J. Chase, H. Levy, and E. Lazowska, "Opal: A single address space system for 64-bit architecture," in *IEEE Workshop on Workstation Operating Systems*, April 1992.

[20] C. Anderson and C. Kitts, "A MATLAB expert system for ground-based satellite operations," in *IEEE Aerospace Conference Proceedings*, March 2005.

[21] "Genso." `http://www.genso.org`.

[22] J. Wertz and W. Larson, *Space Mission Analysis and Design*. Microcosm Press, 3rd ed., 1999.

[23] J. Mann and J. Cutler, "Global ground station survey." Summer Cubesat Workshop, August 2008.

[24] "Space surveillance data." `www.space-track.org`, 2009.

[25] "Satellite tracking systems." `http://www.sattrackinc.com/services.html`, 2009.

[26] A. Chin, R. Coelho, R. Nugent, R. Munakata, and J. Puig-Suari, "Cubesat: The picosatellite standard for research and education," in *AIAA SPACE Conference and Exposition Proceedings*, September 2008.

[27] L. Hodges and R. Woll, "Air force satellite control network (AFSCN) support for operational responsive space (ORS)," in *6th Responsive Space Conference Proceedings*, April 2008.

[28] D. Scheeres, *AOSS 605: Astrodynamics Notes*. 2001.

[29] P. Bournes and D. Williamson, "Cubesat experiments (Qb X)." CubeSat Workshop, April 2009.

[30] "QB50 2009 von karman institute for fluid dynamics." `http://www.vki.ac.be/QB50/project2.php`.

Sara Spangelo is a graduate student in the Aerospace Engineering Department at the University of Michigan. Her research interests are focused on space communication systems and mission design. She is currently working on a multidisciplinary approach to optimizing the capacity of communication networks.

Dylan Boone is a graduate student in the Aerospace Engineering Sciences Department at the University of Colorado at Boulder. His research interests are focused in astrodynamics, specifically trajectory design. He is currently working on the restricted three body problem for a Europa Orbiter Mission.

James Cutler is an assistant professor in the Aerospace Engineering Department at the University of Michigan. His research interests center on space systems–a multidisciplinary approach to enabling future space capability with particular emphasis on novel, nanosatellite missions. He is developing next generation communication capability, design optimization techniques, and space weather measurement missions. He is Co-PI on the NSF space weather mission, the Radio Aurora Explorer (RAX).