ITACA: Modeling and optimization of space network architectures

Marc Sanchez Net[a], Iñigo del Portillo[b], Bruce Cameron[c] and Edward F. Crawley[d]
Massachusetts Institute of Technology, Cambridge, MA, 02139

Daniel Selva[e]
Cornell University, Ithaca, NY, 14853, USA

Methods to design space communication networks at the link level are well understood and abound in the literature. Nevertheless, models that analyze the performance and cost of the entire network are scarce, and typically rely on computationally-expensive simulations that can only be applied to specific network designs. This paper presents an architectural model to quantitatively optimize space communication networks given future customer demands, communication technology and contract modalities to deploy the network. The model is implemented and validated against NASA's Tracking and Data Relay Satellite System (TDRSS). It is then used to evaluate new architectures for the 4^{th} generation TDRSS given the capabilities of new optical and Ka-band technology, as well as the possibility to deploy network assets as hosted payloads. Results indicate that optical technology can provide a significant improvement in the network capabilities and life cycle cost, especially when placing these terminals on-board commercial satellites as hosted payloads. The cost savings and benefit improvements of such an architectures are discussed and quantified.

[a] PhD Candidate, Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, Room 33-409.
[b] Graduate Student, Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, Room 33-409.
[c] Director, System Architecture Lab, Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, Room 31-161b.
[d] Professor, Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, Room 33-413.
[e] Assistant Professor, Sibley School of Mechanical and Aerospace Engineering, 212 Upson Hall.

Nomenclature

a_i = Available antenna

α = Roll-off factor

BW = Link bandwidth

c = Scheduled contact

ΔT_c = Contact gap

$\boldsymbol{d}$ = Decision vector

D = Decision options matrix

dv = Data volume

η = Coding efficiency

E_{ph} = Photon energy

$\frac{E_b}{N_0}$ = Energy bit to noise spectral density ratio

Γ = Modulation spectral efficiency

f = Link frequency

g = Inequality constraints

$\frac{G_r}{T_s}$ = Receiver gain over noise temperature

gs_i = Available ground station

gu_i = Available user ground station

h = Equality constraints

$\hbar$ = Planck's constant

J_i = Evaluation function for $i-th$ metric

k = Boltzmann constant

lat = Latency

L_{at} = Atmospheric losses

L_{fs} = Free space losses

L_{ms} = Miscellaneous link losses

M = Modulation levels

N_a = Number of antennas

N_c = Number of constellations

N_{gs} = Number of ground stations

N_{gu} = Number of user ground stations

I. Introduction

A. Background

Satellite communications system have been traditionally designed with the aid of several modeling capabilities. For instance, orbital propagators have been used to understand how relay satellites provide service to customers as they come in and out of sight (e.g [1]). Similarly, traffic models have been used to understand the required capacities for each link in the system, and how the RF bandwidth allocations can be optimally distributed across customers through multiple access and frequency reuse techniques (e.g [2], [3]). Finally, network simulators have been coupled with orbit propagators to precisely simulate the end-to-end performance of communication protocols when they are utilized in both space and ground-based links (e.g [4]).

Nevertheless, tools that help in the design of satellite communication systems at the architectural level (i.e. mapping between system functionality and elements of form) are scarce in the literature. The goal of this paper is to present an architectural tool that helps space network architects to rapidly explore trade-offs during the system architecting phase (rather than the design phase). The tool was originally developed to assist in the architectural studies conducted by NASA with respect to the 4^{th} generation of relay satellites for the Space Network (SN) .

B. Motivation

The SN has been successfully providing communication and navigation services to near Earth missions since its first satellite was launched in April 1983 [5] [6]. To date, three generations of satellites have been deployed, the last one consisting of two new spacecraft launched in January 2013 and 2014, and one more to be launched in 2015 [7]. The cost of operating and maintaining the network is approximately $\$1.9B$ every ten years, the typical replenishment cycle for the constellation. Of these, $\$1.1B$ account for procuring and launching new satellites (approximately $\$325M$ each), as well as upgrading the ground systems that support them [7], [8]. The rest, $\$80M$ per year, are used to fund the network operations [9].

Given that the SN is an expensive system, and that requirements from user missions are becoming more stringent, NASA is considering multiple alternatives to upgrade the current network capabilities [10], [11]. For instance, new RF and optical technology can be coupled with more powerful on-board processing capabilities to provide higher data rates with lower transmit power. Similarly, communication payloads can now be placed on-board commercial spacecraft as hosted payloads in order to reduce upfront costs [12].

As previously stated, the main goal of this research is to present a model and tool that assist system architects in the process of exhaustively evaluating, comparing and optimizing a large space of network architectures. In this context, the rest of the paper is organized as follows: Section II explores past approaches for architecting space networks and identifies their limitations. Section III describes the proposed model to architect space communication networks, while Sec. IV provides its implementation details. Finally, in Sec. V the model is exercised in order to provide recommendations for the architecture for the 4^{th} generation of the Tracking and Data Relay Satellite System (TDRSS).

II. Related literature

Studies related to the conceptual design and simulation of space communication networks abound in the literature. Depending on type of analysis required, four types of tools have been identified: Network simulators (Sec. II A), point designs (Sec. II B), architecture studies (Sec. II C) and tradespace exploration (Sec. II D). Next, a brief discussion of each of them is presented. Then, their limitations with respect to this paper's research objectives are discussed (Sec. II E).

A. Network simulators

Network simulators are composed of a discrete event simulator, a network model and an orbital propagator. The discrete event simulator generates notifications for events that replicate the real operations of the system (e.g. a spacecraft wants to start transmitting to a ground station). In turn, the network model specifies the stack of protocols used by each of the network nodes. Finally, the orbital propagator determines the position of the different network assets over time and their line-of-sight.

References [4], [13] and [14] are examples of space network simulators. They integrate two commercial pieces of software, STK [15] and QualNet [16], to obtain high precision simulations of the performance of the SN when supporting LEO spacecraft operations. Reference [1] introduces a similar tool, where the orbital propagator and line-of-sight analyses are based on custom developed modules, and the network simulator is implemented using NS-II [17]. Lastly, [18] presents a framework to assess the communication capabilities of small satellites given the engineering constraints of such platforms. The tool is then used to maximize the data downloaded for three paradigmatic missions given a predefined system schedule.

B. Point designs

Point designs typically propose a limited set of network architectures (≤ 10) and use qualitative and quantitative metrics to evaluate their desirability against a set of high-level needs from the network customers. For instance, six point designs for a Lunar-based relay network were presented in [19], one of which is then analyzed in detail (satellites in inclined polar circular orbit). Similarly, point designs to support Orion's exploration activities with end-to-end IP communication services are explored in [20]. Finally, the evolution of Ka-band space communications for near Earth spacecraft are introduced in [21], while [22] provides a point design for a commercial broadband mobile service system.

C. Architecture studies

Architecture studies provide a broader and more qualitative view of the network architecture than both network simulators and point designs. Their main goal is to frame the problem of architecting a space communications network based on the vision and needs for the system. For instance, [23] is the foundational document that identifies the need to upgrade the current NASA communication assets towards a unified near Earth and deep space network. It describes the future needs that will have to be addressed by such a network and provides high-level requirements for the different elements it will have to service. This work is further augmented by [24], [25] and [26], where specific requirements are specified and network protocols are suggested as appropriate.

D. Tradespace exploration

Tradespace exploration is often used to analyze the space of alternatives systems for large, complex and costly projects that need to satisfy the needs of several stakeholders with respect to multiple metrics [27]. For instance, references [28], [29] and [30] explore the application of tradespace exploration during the design of LEO commercial communication networks. They encode the network architecture as a set of design variables that can take a discrete set of values, and then produce valid architectures by choosing one alternative for each of them. For instance, [29] identifies 5 design variables to characterize an architecture: Orbital altitude, minimum elevation angle, transmit power, antenna diameter and presence of inter-satellite links. Based on the range of values that each of them can take, a space of 600 alternative architectures is analyzed to compare their performance (measured as the number of communication channels available) and life cycle cost. Then, the authors identify the set of non-dominated architectures, i.e. those for which the system capacity cannot be increased without increasing the cost of the system.

E. Literature discussion and research gap

Network simulators and *point designs* provide useful tools to evaluate a limited set of network architectures. These limitations come both from the amount of computational power they require per architecture evaluation, as well as from the assumptions they make on particular parts of network design. In contrast, *architecture studies* do not prescribe parts of the system design but are only able to provide qualitative assessments of desirable properties for the network. They can be used as framing studies that identify sensible possibilities for the network architecture but cannot be used to optimize the system architecture. Finally, the surveyed tradespace exploration techniques do not focus on the architecture of the system but rather on optimizing certain design variables once the architecture has been prescribed.

Therefore, there is currently an opportunity to create a tool that bridges the existing gap between tools used in the architecture phase (architecture studies), and tools used later in design (e.g. network simulators, constellation optimizers). It should be able to assess both the performance and the cost of the system, thus encompassing multiple tools previously used by the industry (e.g. link budget analyzers, network cost models), albeit at a lower level of fidelity. As a result, the research objectives of this paper are as follows:

- Develop an architectural model to optimize space communication networks.
- Implement and tailor the model to architect networks that provide communication services to

space missions in the near Earth domain.

- Exercise the model in order to provide recommendations to architect the next generations of the SN.

III. Model to architect space communication networks

A. Modeling the architecting problem

This section presents a model to architect space communication networks. The fundamental element of the model is the *Architecture*, and the main assumption is that the architecture can be represented as a set of decisions that largely determine the system performance and cost [27]. As a result, architecting a system is equivalent to a decision-making process [31].

From a mathematical standpoint, each decision can be modeled as a variable d whose value can be varied through a finite set of options $\{x_1, ..., x_N\}$. Therefore, an architecture can be viewed as the tuple $(\boldsymbol{d}, \boldsymbol{p})$, where $\boldsymbol{d}$ represents the decisions that the system architect has to make (i.e. variables that vary across architectures) and $\boldsymbol{p}$ contains the parameters that are constant across architectures. Finally, the process of architecting a system can be formulated as an optimization problem with respect to the architectural decisions:

$$\begin{gathered}
\{arch^*\} = \{(\boldsymbol{d^*}, \boldsymbol{p})\} = \arg\min_{\boldsymbol{d}} \boldsymbol{J}(\boldsymbol{d}, \boldsymbol{p}) \\
s.t. \\
\boldsymbol{g}(\boldsymbol{d}, \boldsymbol{p}) \leq \boldsymbol{0} \\
\boldsymbol{h}(\boldsymbol{d}, \boldsymbol{p}) = \boldsymbol{0} \\
\boldsymbol{d} \in \boldsymbol{D}
\end{gathered} \tag{1}$$

In this notation $\boldsymbol{J}(\boldsymbol{d}, \boldsymbol{p}) = [J_1(\boldsymbol{d}, \boldsymbol{p}) ... J_m(\boldsymbol{d}, \boldsymbol{p})]^T$ represents the evaluation function that computes the set of m metrics against which the architecture of the network is optimized. $\boldsymbol{D}$ is the matrix that encodes the set of options that are available for each decision, while $\boldsymbol{h}(\boldsymbol{d}, \boldsymbol{p})$ and $\boldsymbol{g}(\boldsymbol{d}, \boldsymbol{p})$ represent equality constraints and inequality constraints that all feasible architectures must satisfy. Note that, since in general the objective function is multi-dimensional, its solution is not unique but rather a set of non-dominated solutions [32].

B. Modeling the network

A space communication network can be modeled as a set of space and ground assets that carry communication payloads to establish wireless links between one another in order to exchange information.

1. *Network assets*

Figure 1 presents the decomposition structure used to model the different assets of the network. The network is composed of a space segment and a ground segment [33],[34]. The space segment contains N_c constellations, each one flying in a particular constellation pattern (e.g., a constellation in LEO with 6 evenly spaced planes and 11 evenly spaced "orbital positions" per plane). Each orbital position within that pattern can contain a single satellite or a cluster of satellites, an approach that renders the model flexible enough to capture monolithic, distributed and fractionated spacecraft [35],[36]. On the other hand, the ground segment is basically composed by a set of ground stations that are used to downlink information to the ground. Two types of ground stations are included in the model, *relay ground stations* and *user ground stations*. The former are used to support the space segment of the network, while the latter are used to provide communication and navigation services to the users.

Both satellites and ground stations carry antennas and communication payloads. The antennas are used to primarily model physical properties such as the orientation (zenith or nadir), field of view or aperture size. In turn, the communication payloads are used to model the RF and IF electronics, as well as any other digital signal processing that may occur to the data being relayed. They specify parameters such as frequency band, maximum supported data rate, preferred modulation and coding scheme. Additionally, they also specify the payloads' mass, power and dimensions. Note that some important parameters such as the gain of the payload are calculated using information from both the antenna (e.g. aperture) and the electronics (e.g. frequency).

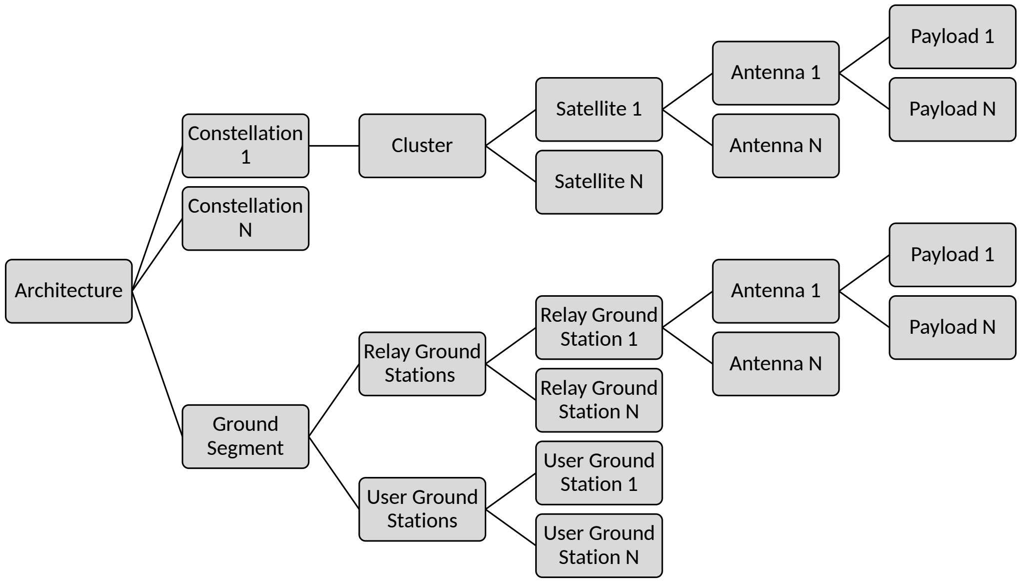


Fig. 1 Network formal decomposition

2. Network links

Four types of links are used to model all communication channels between assets that compose a space network:

- *Relay to user link (RUL)*: Bi-directional link between a relay spacecraft and a network customer. It is modeled and sized based on the return direction (from the customer to the relay) as it will typically support higher data rates.
- *Inter-satellite link (ISL)*: Bi-directional link between two relay spacecraft. It is assumed to be perfectly symmetrical with identical communication terminals are used at both ends.
- *Space to ground link (SGL)*: Bi-directional link between a relay spacecraft and a ground station. It is modeled and sized based on the donwlink (relay spacecraft to ground station) as it is assumed that the power transmission at the ground terminal can be easily adjusted to close the uplink.
- *Direct to Earth link (DTE)*: Bi-directional link between a network customer and a ground station. It is modeled and sized based on the donwlink direction as it will typically support

higher data rates.

Links in the network are said to be valid if the following constraints are met: First, assets have to be in line-of-sight of one another. This is mainly dictated by the orbital position of the satellites and ground stations, the field of view of the antennas they carry and their relative orientation with respect to the center of the Earth. Second, a link is valid if the link budget equation holds [37]. The model assumes that all RF links will utilize an $M-PSK$ modulation and, as a result, the link budget is expressed in terms of the bit energy to noise spectral density ratio.

$$\frac{E_b}{N_0} = EIRP + \frac{G_r}{T_s} - L_{fs} - L_{at} - L_{ms} - k - R_b \tag{2}$$

All terms in Eq. (2) are expressed in dB. $\frac{E_b}{N_0}$ refers to the bit energy per noise spectral density, $EIRP$ is the transmitter Equivalent Isotropically Radiated Power, $\frac{G_r}{T_s}$ is the receiver gain over noise temperature, L_{fs} are the free space losses, L_{at} are the atmospheric losses, L_{ms} are additional losses (e.g. cable losses, pointing losses), k is the Boltzmann constant ($-228.6dBJ/K$) and R_b is the link data rate. Therefore, the link is valid if

$$\frac{E_b}{N_0} \geq \frac{E_b}{N_0}^* \tag{3}$$

$$\frac{E_b}{N_0}^* = \frac{E_b}{N_0}_{min} + LM \tag{4}$$

where $\frac{E_b}{N_0}_{min}$ is the required energy bit per noise spectral density given desired the modulation, coding scheme and bit error rate and LM is a link margin set to $3dB$. Additionally, constraints on bandwidth (BW) availability for a given frequency band are taken into account through the spectral efficiency equation

$$M = 2^{\left\lceil \frac{1+\alpha}{\eta}\Gamma \right\rceil} \tag{5}$$

$$\Gamma = \frac{R_b}{BW} \tag{6}$$

where $\alpha = 0.25$ is the roll-off factor, Γ is the modulation spectral efficiency, η is the coding efficiency (number of information bits in a codeword) and M are the number of modulation levels to support the link data rate Rb with the available BW.

For optical links, the link budget equation is expressed in terms of the signal photons per symbol at the receiver n_s [38].

$$n_s = EIRP + G_r - L_{fs} - L_{at} - L_{ms} - R_s - E_{ph} \tag{7}$$

where G_r is the receiver telescope gain, $R_s = \frac{R_b}{\log_2 M}$ is the symbol rate, R_b is the bit data rate, M are the modulation levels and $E_{ph} = \hbar f$ is the photon energy. Note that some of the terms in both Eqs. (2) and (7) are highly dependent on the link frequency (e.g atmospheric losses). References [33], [38] have been used to obtain reasonable estimates for them.

C. Modeling the network customers

The customer base is used to model the set of missions that will connect to the network. It is organized as a hierarchical tree with four levels of decomposition: stakeholder, objective, user and service. Each node has an associated weight that represents the relative importance of that child for its parent node. Then, a weighted average function is used to aggregate metrics from the service to the stakeholder level, thus providing a mechanism to obtain a scalar metric for the architecture performance or benefit (Eq. (8)). Note that this approach is analogous to the value aggregation process in VASSAR [39].

$$\text{Architecture benefit} = \sum_{st=1}^{ST} w_{st} \sum_{ob=1}^{OB} w_{ob} \sum_{usr=1}^{USR} w_{usr} \sum_{sr=1}^{SR} w_{sr} sat_{sr} \tag{8}$$

The process for computing the satisfaction of a particular service starts by defining its concept of operations (conops) and requirements. The former are used together with the spacecraft orbit to compute the three figures of merit (FOMs) that are used to quantify the service quality of service:

- *Returned data volume (dv)*: Total data sent from the spacecraft to the ground over one day of operations.
- *Data latency (lat)*: Maximum gap between two consecutive contacts.
- *User burden (ub)*: EIRP that a network customer will have to provide in order to close the RUL link with the network relays and ground stations

Then, each FOM is run through a step-wise function that embodies the requirements and transforms the FOM objective value into a subjective normalized dimensionless satisfaction. Finally, the satisfactions of all requirements of the same service are aggregated with a weighted average function in order to obtain the service satisfaction sat_{sr}.

The concept of operations for a space communication service depends on the type of data being transmitted and the type of mission under consideration. For instance, Earth observation missions transmit two types of data: telemetry, tracking and command data (TT&C), and science data. They are usually downlinked directly to ground once or twice per orbit during relatively short contacts (e.g. $7min$). In contrast, the ISS returns science data and video through a high data rate link, while telemetry and voice run over an independent lower speed connection. Both links (science data and video) are always open to ensure immediate contact with the astronauts in case of emergency.

Despite this heterogeneity, the model assumes that any service conops can be modeled through five different parameters: (1) Number of contacts in a day, (2) contact duration, (3) contact nominal data rate, (4) minimum time between contacts and (5) maximum allowable latency. They are used as inputs to a network scheduler to estimate the contacts c between the network and the customer. Then, the returned data volume dv data latency lat are computed as

$$dv = \sum_{c=1}^{C} T_c R_b \tag{9}$$

$$lat = \max_{\forall c} \{\Delta T_c\} \tag{10}$$

where C is the total number of contacts scheduled for a given service, R_b is the link data rate, T_c is the contact duration and ΔT_c is the gap between contact c and $c+1$. On the other hand, the estimation of the user burden FOM is based on the link budget equation (Eq. (2) and (7)) and normalized to a frequency of $2GHz$.

Once the three FOMs for each service have been estimated, its satisfaction sat_{sr} is computed as

$$sat_{sr} = w_{dv}U_{dv}(data\ volume) + w_{lat}U_{lat}(latency) + w_{ub}U_{ub}(user\ burden) \tag{11}$$

where w_{FOM} captures the relative weight of the FOM, and U_{FOM} represents its normalized utility function [39].

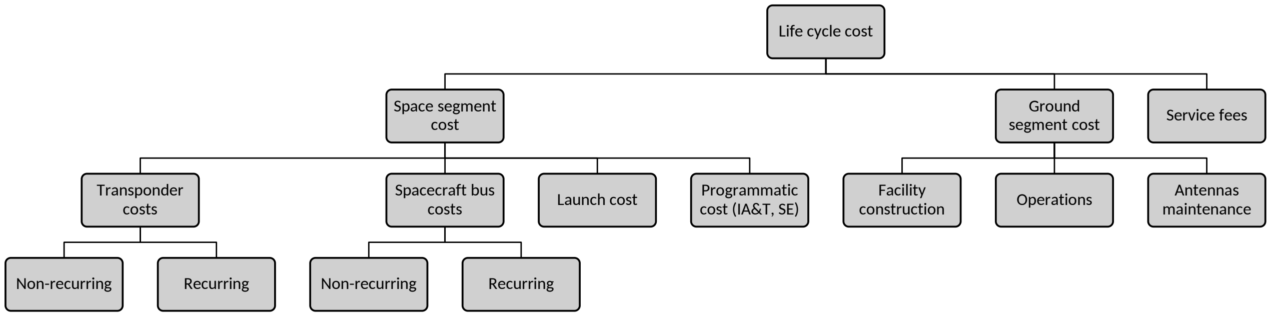


Fig. 2 Lifecycle cost breakdown

D. Modeling the network cost

Figure 2 presents the lifecycle cost breakdown for the different parts of the network. It comprises the following parts: transponder cost (antenna plus electronics), bus cost, launch cost, IA&T cost, operations cost, and program overhead. Some of these are further divided into non-recurring and recurring costs, as illustrated in figure 2.

IV. ITACA: Integrated Tradespace Analysis of Communications Architectures

A. Introduction

The Integrated Tradespace Analysis of Communications Architectures (ITACA) is the computational tool that implements the model to architect space communication networks presented in the previous section. The tool allows the user to perform the following tasks in an integrated environment: a) define the characteristics of the tradespace, b) enumerate thousands of architectures to explore using a selected search strategy, c) evaluate the performance and cost of the different network configurations and d) visualize and analyze the results. Its main modules are the Architecture Tradespace Explorer, the Architecture Evaluator, the Resource Manager and the Tradespace Viewer. Figure 3 shows a representation of the tool's workflow.

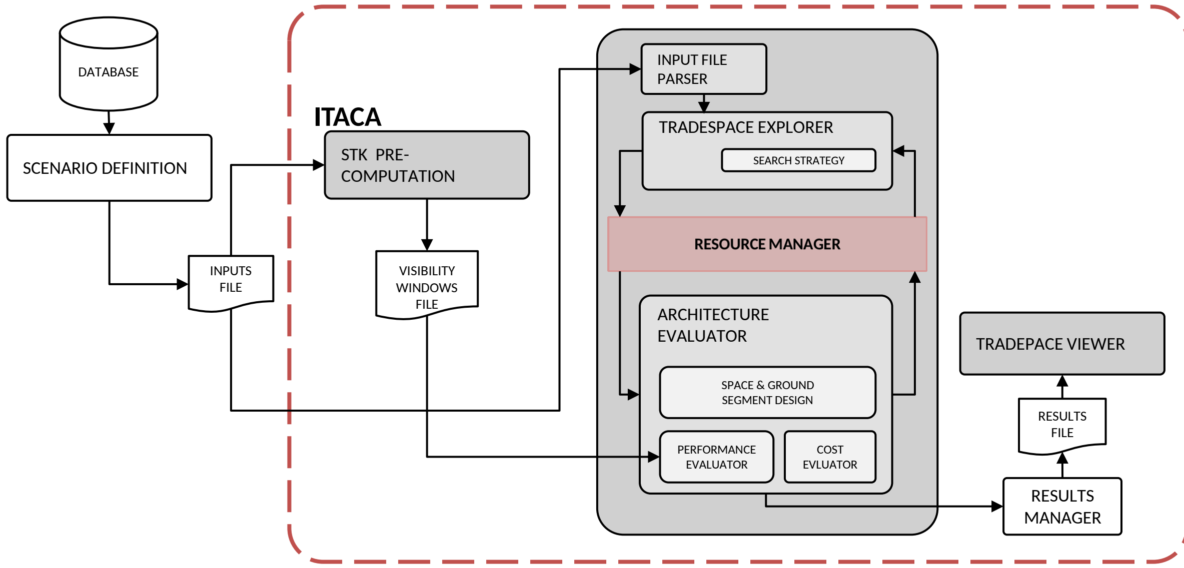


Fig. 3 ITACA Workflow

Initially, the user is provided with a database that contains part of the inputs of the tool. These include antennas and payloads characteristics, customers' properties, or orbits where the relay satellites will be located. Then, the user specifies the scenario that will be analyzed by selecting the decisions and options that will be used to generate network architectures. This file is parsed by the Architecture Tradespace Explorer and the resulting information is used to generate the set of architectures that the Architecture Evaluator will evaluate. Finally, the results created by the tool can be imported using the Tradespace Viewer, which helps the user analyze the tradespace, explore the information related to the cost, performance and design of the architectures, and evaluate the existing trade-offs among decisions.

The remainder of this section provides a description of the implementation details of each of the modules that constitute ITACA.

B. Architecture Tradespace Explorer

The Architecture Tradespace Explorer implements all the functionality that is needed in order to solve the optimization problem from Eq. (1). As such, it defines the specific decisions and parameters that are available to architect a network, as well as the search strategy that will be used to explore the space of alternative architectures.

1. Architecture

Based on the definitions from Sec. III A, an architecture is modeled as the tuple $(\boldsymbol{d}, \boldsymbol{p})$, where $\boldsymbol{d}$ represents the architectural decisions and $\boldsymbol{p}$ represents the set of input parameters that remain constant across architectures. Seven architectural decisions are used to define the entire tradespace of network architectures:

1. **Antenna assignment**: Given the set of *available antennas* $\{a_1, ...a_{N_a}\}$ and the set of N_c *available constellation patterns*, both defined as parameters in Table 2, assign subsets of antennas to each constellation pattern.

2. **Antenna allocation**: Given the set of antennas assigned to each constellation, choose to place them together on a single spacecraft or in a cluster of formation flying satellites.

3. **ISL antenna allocation**: Decide if each of the N_c constellations will use inter-satellite links.

4. **Contract modality**: Decide if each of the N_c constellations will be entirely procured or its antennas will be flown as hosted payloads.

5. **Relay ground stations**: Given the set of *available ground stations* from Table 2 $\{gs_1, ...gs_{N_{gs}}\}$, decide which ones will be operated to support the space segment.

6. **User ground stations**: Given the set of *available user ground stations* from Table 2 $\{gu_1, ...gu_{N_{gu}}\}$, decide which ones will be operated to support the network customers.

7. **Ground antennas**: Select how many antennas per ground station will be available to support network customers.

These decisions have been mathematically modeled using the classes of system architecting problems (SAPs) defined in [40]. Table 1 summarizes them along with the number of combinations they generate. Note that the first five decisions take place at the constellation level rather than at the architecture level. In other words, they affect each constellation independently, thus enabling the model to capture networks with multiple heterogeneous space segment configurations. Nevertheless, they also substantially increase the number of alternatives in the combinatorial space.

Table 1 Architectural decisions

Decision	*Parameters*	*SAP*	*Num. options*
Antenna assignment	$\{a_1, ...a_{N_a}\}$	Down-selecting problem	$2^{N_a N_c}$
Antenna allocation	$\{a_1, ...a_{N_a}\}$	Partitioning problem	$Bell(N_a)$
ISL antenna assignment	{yes, no}	Assigning problem	2^{N_c}
Contract modality	{Procurement, hosted payloads}	Assigning problem	2^{N_c}
Relay ground stations	$\{gs_1, ...gs_{N_{gs}}\}$	Down-selecting problem	$2^{N_{gs}}$
User ground stations	$\{gu_1, ...gu_{N_{gu}}\}$	Down-selecting problem	$2^{N_{gu}}$
Ground antennas	$\{1, ..., N_{max}\}$	Assigning problem	$2^{N_{gu}}$

Note also that these decisions are interrelated, i.e. the set of options available for a decision depends in general on the value of another decision. Therefore, dependencies among decisions must be captured in a structure that allows to a) make the decisions in the appropriate order and b) repair an architecture when an unfeasible combination occurs. ITACA models this inter-decision dependency using a hierarchical tree - called the Decision Tree - whose nodes correspond to decisions. Its root node is a void decision called the Root Decision; all decisions that do not depend on any other decisions are children of this Root Decision. In turn, if decision d_i depends on the options assigned to decision d_j then d_i appears as a child of d_j in the tree. Figure 4 shows a complete representation of the Decision Tree.

During the architecture generation process, assigning an option to each decision is done by descending through each branch in the Decision Tree until a leaf node (a node with no children) is reached. This ordered process ensures that the resulting architecture is consistent.

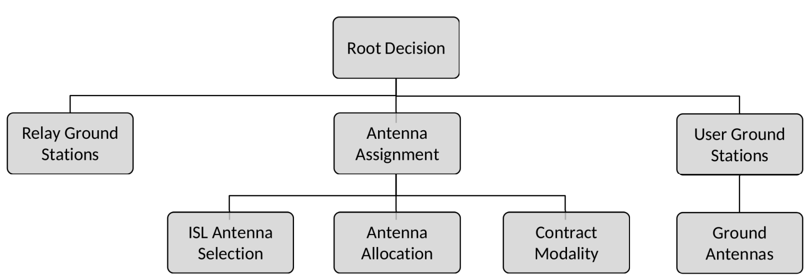


Fig. 4 ITACA's Decision Tree

Table 2 Input assumptions

Parameter	*Example*	*Explanation*
Lifetime	10 years	Design lifetime for the initial network (i.e. individual spacecraft)
Time horizon	30 years	Design lifetime for the network with satellite replenishment
Bus learning factor	95%	Doubling the number units (buses) reduces the total production cost by 5%
Payload learning factor	95%	Learning factor for identical payloads
Antenna learning factor	95%	Learning factor for identical antennas
Link distance CI	90%	Percentile of all distances between asset A and B used for link budget calculations
Maximum hops	3	Maximum number of hops between a network customer and a ground station
Number of steps	1440	Number of time steps in which the day of operations is discretized
Epoch	1 Jan 2015	Start date and time for the orbit propagation
Available antennas	SA1,SA2,SMA	Identifiers of the subset of antennas that can be placed on orbit. Each antenna may have one or more communication transponders attached to it as described in the database.
Available constellation patterns	MEO-1-1, GEO-1-3	Identifiers for the constellation patterns that can be used to generate a network. They are specified as "*orbit type*"-"*number of planes*"-"*number of slots per plane*", where one slot can contain one or multiple satellites. Each *orbit type* uniquely defines a semimajor axis, inclination, eccentricity and argument of perigee in the database.
Available ground stations	White Sands,Guam	Identifiers of the subset of ground stations that can be used to support the relay satellites.
Available user ground stations	Wallops	Identifiers of the subset of ground stations that can be used to support the network customers.

Finally, table 2 provides a comprehensive list of the set of input parameters $\boldsymbol{p}$ that ITACA uses for the network evaluation.

2. Search Strategy

Two search strategies are implemented in ITACA. Both of them have been tailored to work with the set of decisions presented in the previous section.

- **Full Factorial:** This search mode automatically lists and evaluates all the architectures existing in a tradespace. Hard constraints can be imposed to purge those architectures that are invalid, undesirable or whose study is considered worthless by the architect.

- **Genetic Algorithm:** A genetic algorithm (GA) is a population-based meta-heuristic optimization algorithm that uses heuristics inspired by natural evolution, such as crossover, mutation and selection. The GA implemented in ITACA follows the prescriptions of the Non-dominated Sorting Genetic Algorithm-II (NSGA-II), a Multi-Objective Genetic Algorithm (MOGA) [41]. This implementation presents advantages in terms of computation efficiency as compared to the original NSGA. The more recent version NSGA-III [42] was not used as it targets problems with many (more than two) objectives, which is not our case.

  Mutation and crossover operators for each of the architectural decisions have been specifically defined. They can act upon any of the decisions regardless of their dependencies. If an application of an operator leads to an inconsistent architecture, then the Decision Tree is used to trigger a recursive repair operation over all the dependent decisions. The repair operator starts by checking the coherence of the option assigned to a decision against the options assigned to other decisions. If the option resolves as invalid, specific rules fix it to be coherent with the rest of options. As an example, if the mutation operator changes the Antenna assignment by adding a new antenna to a constellation, the repair operation will act over antenna allocation and determine in which satellite it will be placed.

C. Architecture Evaluator

The Architecture Evaluator implements all the functionality needed to compute the performance and cost of a single architecture. In other words, it implements the function $\boldsymbol{J}(\boldsymbol{d}, \boldsymbol{p})$ from Eq. (1) that provides the set of metrics against which the system is optimized. This section presents a description of the different modules that compose the Architecture Evaluator.

1. *Introduction to RBES*

A RBES is a computer program that encapsulates human knowledge in the form of logical rules. It is designed to model the problem-solving ability of a human expert [43]. RBES are composed of three elements: a facts database that contains the information that describes the problem, a rule database that encodes the expert knowledge about how to solve the problem and an inference engine that executes the matching algorithm between rules and facts. As opposed to most common programming languages, which are procedural, RBES employ a declarative paradigm where rules are applied to facts in an order determined dynamically during execution time.

A rule can be thought of as an if-then statement. Rules *fire* (execute the *then* statement) when a match occurs (the pattern described in the *if* statement results in a logical true when applied to the data of some facts in the database). The inference engine implements the algorithm that allows to solve this many-to-many matching problem in an efficient way (usually some variation of Forgy's Rete algorithm [44]).

Most modules of the Architecture Evaluator were implemented using the Java Expert System Shell (Jess), a Java-based rules engine (i.e. a program to develop RBES). The reasons to choose Jess were, among others, the ease to integrate it with Java, its smart and efficient implementation of the Rete algorithm, its flexibility, and the quality of the available documentation. In ITACA, facts represent the architecture information, network assets, users, contacts, etc. whereas the procedures to design some elements as well as the model of the network are encoded using rules grouped in modules (e.g., there is a module to design antennas, another to estimate the satisfaction of the users, and so forth).

2. *Design space & ground segments*

The first step to evaluate a space communication network is to size the communication links between the different network assets, as well as their payloads and antennas (see Fig. 3). Then, these designs are used as an input to the spacecraft design algorithm that is used to size the bus of the the relay satellites. These two steps are described in more detail below.

Antenna design module

The objectives of the antenna design module are twofold. First, the module sizes the ISL and SGL for all the constellations in the network, as well as the communication payloads and antennas that support them. Then, the same algorithm is used to determine the frequency band that a user will have to use for a given service, and size the RUL in order to compute the user burden metric.

The main steps of the antenna design algorithm are as follows:

1. Find the bands were transmission is allowed given spectrum allocation restrictions (typically S, X, Ku and Ka-band) and sort them according to increasing bandwidth. The optical band is the last option since it is assumed that it has no bandwidth restrictions. It is further assumed that ISLs and SGLs can always use the optical band, whereas RULs and DTEs' band choice is also restricted by the bands supported through the payloads placed on-board the relay spacecraft and user ground stations.

2. If sizing an ISL or a SGL, estimate the nominal data rate R_b that the link has to support as a fraction of the total data rate provided to the customers (Eq. (12)). For bent-pipe and circuit switched schemes, ν can be viewed as a simultaneity factor, i.e., as an estimate of the worst case simultaneous traffic that could arrive to a relay from other relays, which in general will be less than 1. For store-and-forward technology, ν is a combination of the simultaneity factor and the multiplexing gain obtained when packetizing the information prior to its transmission. The values of the correction factor ν are presented in Table 3.

$$R_b = \nu \sum_{\forall i \in RUL} R_{b_i} \tag{12}$$

3. Retrieve the transmit frequency f and bandwidth BW for the first band in the list created in Step 1. If $BW = 0$, then there is no bandwidth allocation for that particular type of link (e.g.

Table 3 Correction factors for ISL and SGL data rates

Transponder technology	*ISL*	*SGL*
Bent-pipe	0.8	1
Circuit switched	0.8	1
Store and forward	0.6	0.75

NASA does not have frequency allocations at X-band for ISLs [?]) and therefore switch to the following frequency band.

4. Compute the number of modulation levels M required to provide data rate R_b with bandwidth BW, assuming that a phase-shift keying (M-PSK) modulation is used (see Eq. (5)).

5. If $M \leq 8$ then select this band for the link. Use the link budget equations (Eq. 2 or Eq. 7) to design the payloads as follows: a) if the link is the ISL, size the antenna of the relay satellite assuming that an ISL has identical antennas at both ends; b) if the link is an SGL, assume that there is a 12 meter dish antenna on the ground terminal; c) if the link is a RUL, determine the EIRP the user needs to provide in order to close the link.

6. If $M > 8$ then move to the next frequency band on the list and go back to Step 3. If the current selected band is optical, then use Eq. (7) in conjunction with a 2-level Differential Phase Shift Keying (2-DPSK) or a 16-level Pulse Position Modulation (16-PPM) to size the diameter of the optical telescope. Finally, if there is no next frequency and $M > 8$, an 8-PSK modulation scheme is selected. In that case, the data rate is set to the maximum achievable data rate using the available bandwidth. The user burden is calculated using that data rate.

Inherent to this algorithm are both technical choices and regulatory limitations. For instance, the choice of PSK modulations comes from the fact that the current Space Network uses both BPSK and QPSK [5]. ITACA assumes that, in the future, at least 8-PSK will be available. Similarly, the choice of 2-DPSK or 16-PPM as baseline optical modulations is grounded on the optical technology that NASA is currently developing and demonstrating [45]. However, ITACA can easily integrate other technologies for link budget calculations should data on their performance become available.

Finally, the frequency and bandwidth allocations are based on the current NASA allocation for the SN [46].

Spacecraft segment design

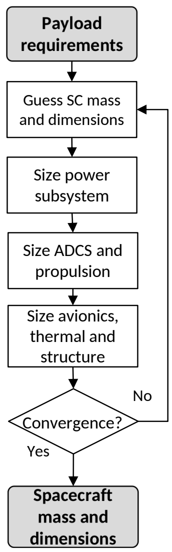


Fig. 5 Spacecraft design algorithm

The spacecraft design module consists in an iterative algorithm that provides a subsystem-level design of the spacecraft bus including a very rough configuration of the spacecraft from the payload requirements. Figure 5 presents a high-level functional flow diagram of the iterative algorithm. Based on the communication payloads requirements, an initial guess for the spacecraft mass, power and dimensions is obtained. Then, the different bus subsystems are progressively sized and compared to the initial guess until the algorithm has converged. A detailed description of the equations used to size each spacecraft subsystem can be found in [47].

3. Network performance evaluation

The Network Evaluator goal is to assess the performance of a space network architecture by simulating its operations on a typical day of operation. Its main output is a set of scheduled contacts for each of the services that the network customers requests. These are then processed in order to compute the returned data volume using Eq. (9) and the data latency using Eq. (10).

The Network Evaluator is implemented through a heuristic scheduler that assigns contact opportunities between network customers and assets. The capabilities of the scheduler algorithm include overlapping same-user different-band services, supporting multiple access (MA) contacts and simultaneous scheduling space and ground assets.

The network evaluation process is divided in 6 steps, as illustrated in Fig. 6. First, all visibility windows are computed off-line. For each architecture, after initialization, the highest priority service is identified and all viable visibility windows are identified. Visibility windows are allocated to services based on the heuristics described in the next subsection. Finally, those visibility windows that have been partially assigned are trimmed as required. The following subsections dissect each of the aforementioned steps.

Visibility Windows Computation

A *visibility window* defines a time-tagged contact opportunity between a user and a network asset. It is computed with STK taking into account the assets orbital movement and constraints on the antennas' FOV, orientation or elevation angle (for ground stations). Each visibility window is associated to a communication payload and therefore has a specified frequency band and maximum data rate.

Additionally, STK is also used to compute multiple hop paths between ground stations and relay satellites with and without the presence of ISLs. They are used to trim visibility windows that define contacts between a relay satellite and a network customer when the relay is not connected to a ground station.

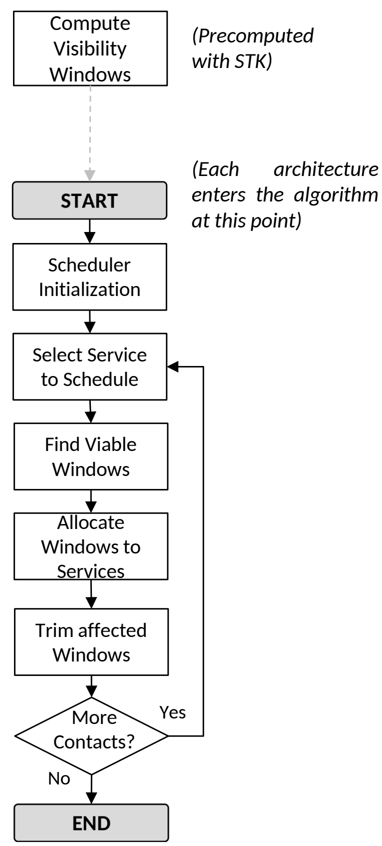


Fig. 6 Flow chart of the Network Evaluator Module

Variable Initialization

The Scheduler Initialization task performs two functions. First, it uses the pre-computed paths to certain discard visibility windows depending on the architecture. For example, paths that contain elements that are not present in the architecture, such as relays, ground stations, or ISL, are eliminated. Second, the priority of each service is calculated using the heuristic defined in reference [48]. Then, the scheduling process will proceed by progressively scheduling services in descending order of priority.

Viable Windows

Given a service to schedule, only a small subset of all the visibility windows can actually be used to grant contacts. We refer to them as the *viable windows* subset. The criteria that define the viability of a visibility window are as follows:

- **Same band criterion:** The service and the visibility window have the same frequency band.
- **Link capacity criterion:** The visibility window maximum data rate is higher than the service data rate.
- **Overlapping access criterion:** If the antenna is a Single Access (SA) antenna, this criterion is satisfied if there is no other contact scheduled in that visibility window in the same frequency band. If there is a scheduled contact in another band, the user of the scheduled contact and the selected contact must be the same and the antenna must support both bands.
- **Multiple access criterion:** If the antenna is a Multiple Access (MA) antenna, this criterion is satisfied if the number of scheduled contacts in that window is lower than the number of beams of the MA antenna.

Similar criteria apply to *user - user ground station* visibility windows.

Allocating Resources to Services

The allocation of resources to services consists in assigning viable windows to individual contacts. For a contact to be eligible for allocation, the following conditions must be met: a) it must be possible to place the contact at least *mtbc* seconds after the last contact scheduled for that service; b) there must exist a window (or a train of concatenated windows) such that its total duration is higher than the duration of the contact.

The criteria to decide which viable visibility window best suits each contact is based on heuristics that try to mimic the current daily schedules generated by the Network Control Center Data System (NCCDS) for the TDRSS constellation. These criteria, in order of importance, are:

- Windows where a contact already exists are always preferred to empty windows. In other words, overlapping contacts of different services for the same user is always desirable.

- If a window offers the possibility of overlapping a contact in the future, it is preferred to windows that do not offer this possibility. In other words, multi-band windows have preference over non-multiband windows.

- It is always preferable to schedule a contact through one single visibility window rather than concatenating several of them. This reduces the number of handovers in the network schedule.

- If concatenation is required, the window that creates the longest train of windows is preferred over the rest. In other words, the window that ends the latest is selected.

This part of the code was implemented in Java since the sequence of criteria to apply is constant and rule-based systems are known to be slower than traditional procedural languages in these circumstances.

Trimming Affected Visibility Windows

The assignment of contacts to certain visibility windows impacts the rest of visibility windows. For instance, if a visibility window is used by an SA antenna to provide a service to a certain user, no other user would be able to use that window during the duration of that contact. Hence, some visibility windows will need to be deleted, and others might need to be trimmed to update their starting and ending times. Similarly, in the case of MA antennas, the number of beams available during the contacts' periods must be decreased according to the number of contacts scheduled.

4. Network cost estimation

The model to evaluate the network cost has also been implemented in Jess. The different parametric functions and cost estimation relationships used to estimate the cost of the different parts of the network have been encoded as independent rules. Reference [47] provides a detailed description of these parametric functions. Reference [49] defines the cost model used for hosted payloads.

5. *Validation of the network evaluator*

The validation of ITACA has been conducted by comparing its communication and costing capabilities against the current implementation of the SN. To that end, twelve days of operational schedule were analyzed with respect to two metrics: Total network data volume and antenna utilization (fraction of time the antenna is pointed to a customer, either for transmission or tracking purposes). This information was used to differentiate between a "typical" day of operations for the system and a "high load" scenario.

Then, the set of users from both a "typical" and "high load" scenario were inputted into ITACA and the computed schedules were compared to the SN operations. Results indicate that the network capacity can be approximated to 10% of the actual SN capacity, measured both in terms of the returned data volume and the utilization of the network's space assets. A detailed discussion of this validation process and its results can be found in [48].

On the other hand, the space and ground segment design module and the network cost estimator were also benchmarked against the current NASA system. For the former, the design of a 2^{nd} generation TDRS was compared with the output of ITACA. Results indicate that the model is able to assess the mass and power of the satellite within a 10% error (see [50] for the details). Finally, cost estimates were validated against limited publicly available information, with sampled errors confined in the 15% range [50].

D. Resource Manager

ITACA takes advantage of all the computational power available by parallelizing the evaluation of architectures across multiple cores in the microprocessor. The number of threads used to evaluate architectures N_{th} is specified as an input of the tool.

The Resource Manager manages how threads cores are used to evaluate architectures. It contains a pool of N_{th} resources, where each resource has all the elements needed to completely evaluate an

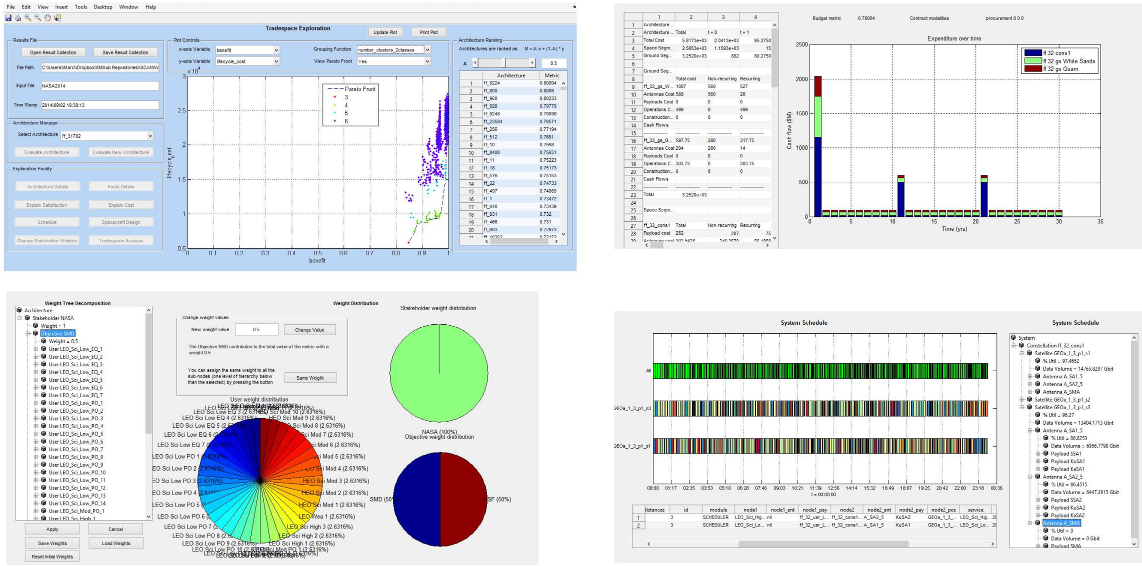


Fig. 7 Tradespace Viewer screenshots: Main Window (top-left), Cost details (top-right), Stakeholder Weight Selection (bottom-left) and Scheduling Results (bottom-right)

architecture. The Architecture Evaluator successively sends tasks to the Resource Manager, which executes them asynchronously and returns the evaluation metrics to the Architecture Evaluator. If no resources are available, the tasks are queued until a resources is freed and properly reset.

E. Tradespace Viewer

The Tradespace Viewer is a Graphical User Interface (GUI) developed to visualize the results produced by the tool. Its main window contains a scatter plot that shows all the architectures in the cost-performance space. Architectures can be color-coded according to the values of one or more architectural decisions $\boldsymbol{d}$ in order to easily identify structural features in the tradespace, such as clusters or stratification (see top left of Figure 7). In addition, detailed information about an architecture can be found by clicking on the corresponding point on the chart. This information includes the breakdown and time evolution of the life-cycle cost estimate (top right), breakdown of stakeholder satisfaction (bottom left), details of spacecraft design, and a detailed view of the network schedule (bottom right) among others. Finally, the Tradespace Viewer has several post-processing capabilities such as stakeholder-weight variation or further analysis of the tradespace using graph theory.

V. Results

The results herein presented are adapted from [48] and[50].

A. Tradespace Definition

We start with the assumption that NASA wants to maintain the core architecture of the existing SN: a set of geosynchronous satellites with bent-pipe technology commanded from two ground stations, White Sands and Guam. However, we wish to study the possibility of improving the current capabilities of the network by introducing two new high data rate payloads, one operating at Ka-band and another one at optical frequencies. Furthermore, we wish to study the option of flying some of these payloads as hosted payloads on commercial communication satellites.

Three decisions are used to model the resulting tradespace, *antenna selection*, *antenna allocation* and *contract modalities*. The constellation pattern is set to three different longitudes of the geostationary orbit (see tables 4 and 5). Additionally, four antennas are defined:

- *TDRS legacy antenna (SA)*: Supports communications in S, Ku and Ka-band with a maximum data rate of 300Mbps. The antenna is a 5m parabolic dish.
- *Low capacity antenna (SAL)*: Provides low data rate communications in S-band (up to 6Mbps) based on the current TDRS capabilities. The antenna is a 5m parabolic dish.
- *High capacity antenna (SAH)*: Supports Ku and Ka band and provides up to 600Mbps without extra bandwidth allocations. The antenna is a 5m parabolic dish.
- *Optical telescope (OPTel)*: Operates at 1550nm and its data transfer rate is 1Gbps. The telescope has an aperture size of 10cm.

Table 4 Case study architectural decisions

Decision	*Options*
Antenna selection	Any subset of SA (x2), SAL (x2), SAH (x2), OPTel (x1) can be assigned to any orbital slot
Antenna allocation	For each slot, all the possible partitions of N transponders into 1 or 2 satellites
Contract modality	Procurement or hosted payloads

Table 5 **Case study architectural parameters**

Parameter	*Value*
Orbit	Geostationary, 3 orbital positions
ISL	No
Network Type	Bent-pipe
Ground Stations	White-Sands and Guam
User GroundStations	None

The resulting tradespace contains a total of $4,450$ different architectures when using a full factorial enumeration. Nevertheless, this number is reduced to $1,440$ when two hard constraints are applied: a maximum of two antennas can be carried on any single satellite, and architectures with more than 9 satellites are considered unrealistic.

B. Customer base definition

Since this case study analyzes the architecture of the 4^{th} generation TDRSS, the customer base is based on a customer forecast for the 2020-2030 time frame. This forecast is grounded on two complementary studies: A stakeholder elicitation process conducted through expert interviews with different NASA communities (e.g. NASA Earth science missions, NASA astrophysics missions) [47]; and the analysis of two weeks of TDRSS operational data [48], [50].

The resulting scenario consists of a set of 15 missions from NASA, NOAA and USGS [51]. The NASA Earth observation community has eight missions using the network, two of which are major drivers ($> 10Tbit/day$). The NASA astrophysics and heliophysics communities are represented by three missions, one of which is considered to be a driver and the other two are medium-sized missions ($1Tbit/day <$ data volume $< 10Tbit/day$). On the other hand, two crewed missions are assumed, one similar to the International Space Station (ISS) and another one representative of a Multi-Purpose Crew Vehicle (MPCV) capsule. The former is a driver both in terms of data volume and requested contact time, while the latter only requires support for long continuous periods of time (5 hours approximately). Finally, all NOAA and USGS missions use the network as a backup option and only require sporadic 5 to 10 minute contacts at low data rates. The resulting customer base represents a 10% increase in the total scheduled time, and a 273% increase in data volume with respect to the current TDRSS operations.

C. Analysis

Figure 8 presents the results obtained when performing the constrained full factorial architecture enumeration previously described. Figures 8a and 8b only contain architectures where the *contract modality* decision is set to *procurement*. In turn, figures 8c and 8d contain the entire tradespace.

A few non-dominated architectures are highlighted and numbered on Figure 8. They have the following characteristics:

(1) Monolithic architecture with one SAL per satellite ($\leq 6Mbps$).

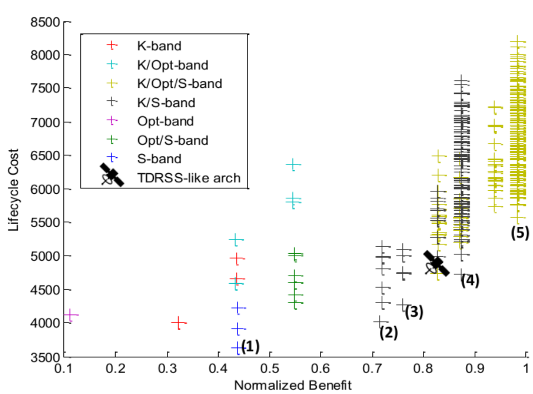
(2) Monolithic architecture with one SA ($\leq 300Mbps$).

(3) Monolithic architecture with two antennas per satellite, one SAL ($\leq 6Mbps$) and one SAH ($\leq 600Mbps$).

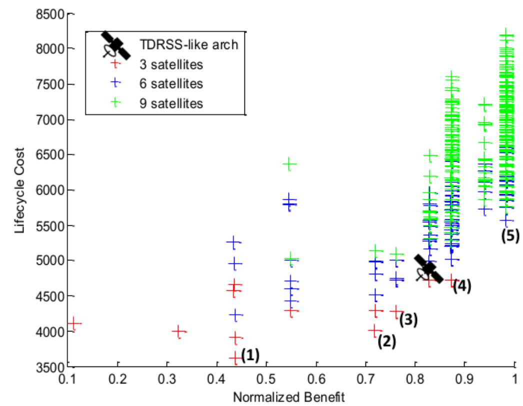
(4) Monolithic architecture with two antennas per satellite, one SA ($\leq 300Mbps$) and one SAH ($\leq 600Mbps$).

(5) Disaggregated architecture with two sets of 3 satellites. The first one carries a SAL and a SAH. The second set carries a SAH and an OPTel ($\leq 1Gbps$).

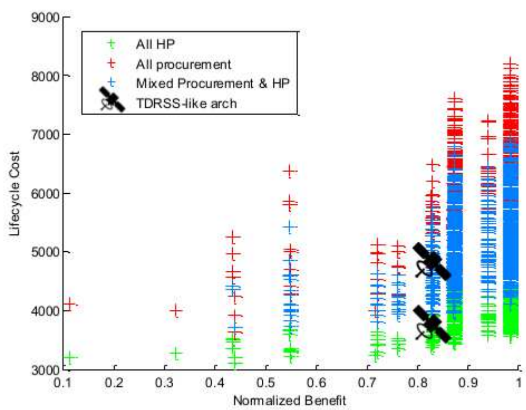
Given that architecture (3) is similar to the current TDRSS architecture, it is assumed that less performing architectures would never be chosen for the next generation. Therefore, a possible first step to improve the network performance is Architecture (4), characterized by replacing one of the legacy TDRS SA antennas for a new SAH that can provide communications up to 600Mbps. This increases the overall benefit of the system by 5% while slightly reducing its cost (-2%). This cost reduction is achieved thanks to the spacecraft mass reduction when fewer S-band transponder electronics are put into orbit. (Lower frequency transponders are usually more massive.) However, a network that is able to satisfy the requirements of the most demanding users requires optical communications. In Architecture (5), six satellites per generation have to be launched, three of them carrying an optical telescope. This alternative results in an 18% increase in the overall architecture score, but also incurs in an additional 25% cost.



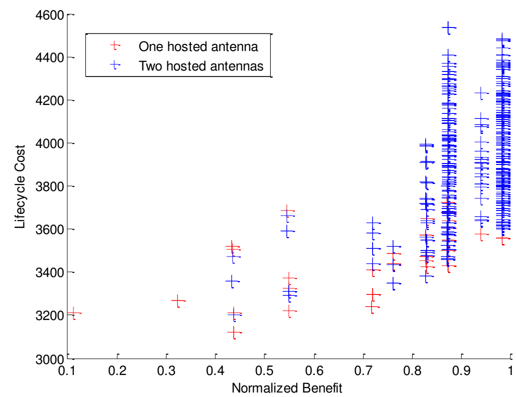
(a) Band selection



(b) Antenna allocation



(c) Procurement vs. Hosted payloads



(d) Procurement vs. Hosted payloads

Fig. 8 ITACA results

Further insight can be gained by analyzing the tradespace in more detail. The following premises resulted from this analysis:

- An all-optical architecture achieves a very low score in benefit (0.1 approximately) but is potentially less expensive than most RF and RF/optical architectures. This is due to the fact that the mission only included two missions with data volume requirements high enough to necessitate optical communications.

- All architectures that select one or two non-optical antennas to be flown rely on monolithic spacecraft (see architectures 1, 2, 3 or 4).

- The incremental benefit of having S-band for TT&C services is approximately 40%. Similarly, having Ku and Ka-band for science data return services provides an extra 50 to 55% of the benefit score.
- The current SN architecture is able to provide approximately 84% of the total benefit, although the same level of performance can be obtained with a less costly architecture, namely Architecture 4.
- Hosted payloads offer the possibility of significant cost reductions (between 15% and 30%). In fact, all non-dominated architectures are hosted payloads thus indicating the suitability of this alternative.
- By combining figures 8a and 8c one can assess the relative desirability of hosting certain types of payloads versus others. Results indicate that hosting an optical payload can potentially save up to 28% of the cost, while a low data rate payload (S-band) only obtains a 16% cost reduction. Therefore, it seems to be more advisable to put high data rate payloads like optical terminals in commercial satellites and retain control of S-band communications.

VI. Conclusions

A. Summary

This research presented a novel model to architect space communication networks. It formulated the network architecting problem as a combinatorial optimization problem over the set of decisions that define the system configuration, performance and cost. A system evaluation function that sizes the network space and ground segment, simulates its operations and estimates its cost was also proposed. Then, the model implementation details were described, with particular emphasis on the algorithms to size the communication payloads and schedule contacts between network assets and customers.

Once the model was presented, it was used to evaluate the tradespace of possible architectures for the 4^{th} generation TDRSS given the availability of new RF and optical technology, as well as the possibility of using hosted payloads to deploy the network. Results showed that in order to achieve maximum benefit optical telescopes were necessary, but an extra 25% cost was incurred in order to avoid placing three high data rate transponders in the same spacecraft. Furthermore, current costing models for hosted payloads predicted significant cost savings with respect to the current approach of procuring and operating the entire network, especially when placing the optical terminals on-board commercial satellites. Finally, the model demonstrated that in general monolithic architectures are cheaper than disaggregated ones due to the high cost of placing even small satellites in geosynchronous orbit.

B. Future Work

Several areas of potential future work have been identified during the development and utilization of ITACA. They are classified according to their nature: Modeling vs. Implementation.

In the modeling domain, three main areas of improvement can be proposed. First, the inclusion of deep space customers and Moon-based customers. This would allow ITACA to conduct architectural analyses that include both the SN and the Deep Space Network [52]. Similarly, improved network financial capabilities would allow the tool to capture trade-offs in the budgetary constraints of the SN fleet replenishment cycle. Finally, ITACA would also benefit from including a reliability module that assesses the probability of satellite or ground station degradation and failure. This would also result in improved modeling capabilities with respect to the network replenishment and maintenance.

In the implementation domain, areas of future work mainly include improvements in the tool computational performance and usability. Since the goal of ITACA is to explore large spaces of network architectures and conduct rapid what-if analyses, developing concise user interfaces that facilitate the traceability of the results can be largely beneficial for the tool's usefulness.

Appendix

Table 6 Acronyms

BPSK	Binary Phase-Shift Keying
BW	Bandwidth
DSN	Deep Space Network
DPSK	Differential Phase-Shift Keying
DTE	Direct to Earth
EIRP	Equivalent Isotropically Radiated Power
FOM	Figure of Merit
FOV	Field Of View
GA	Genetic Algorithm
GEO	Geosynchronous Orbit
GUI	Graphic User Interface
IA&T	Integration, Assembly & Testing
IF	Intermediate frequency
ISL	Inter-satellite Link
ISS	International Space Station
ITACA	Integrated Tradespace Analysis of Communications Architectures
LEO	Low Earth Orbi t
LOS	Line Of Sight
MA	Multiple Access
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
NCCDS	Network Control Center Data System
NEN	Near Earth Network
NOAA	National Oceanic and Atmospheric Administration
NSGA	Non-dominated Sorting Genetic Algorithm
OPTel	Optical telescope
PSK	Phase Shift Keying
PPM	Pulse Position Modulation
QPSK	Quadrature Phase-Shift Keying
RBES	Rule Based Expert System
RF	Radio Frequency
RUL	Relay-to-User Link
SA	Single Access
SAH	High Capacity Single Access
SAL	Low Capacity Single Access
SAP	System Architecting Problem
SCaN	Space Communication and Navigation
SGL	Space-to-Ground Link
SN	Space Network
STK	Systems ToolKit
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TT&C	Telemetry Tracking and Command
USGS	United States Geological Survey
VASSAR	Value Assessment of System Architectures using Rules

Acknowledgments

This project is funded by NASA under grant 6929366. The authors would also like to thank the Centre de Formacio Interdisciplinaria Superior, the Cellex Foundation and Banco Santander for partially funding this project.

References

[1] Yang, H., Wang, X., and Zhao, H., "The modeling, simulation and effectiveness evaluation for communication networks of multi-layer satellites constellation," *Computational Intelligence and Security, 2006 International Conference on*, Vol. 2, IEEE, Guangzhou, November 2006, pp. 1055–1060.

[2] Stoenescu, T. and Clare, L., "Traffic Modeling for NASA's Space Communications and Navigation (SCaN) Network," *Aerospace Conference, 2008 IEEE*, IEEE, 2008, pp. 1–14.

[3] Schorcht, G., Freund, U., Salzwedel, H., and Keller, H., "A hierarchical object-oriented global traffic model for simulation of mobile satellite communication networks," *Personal Wireless Communications, 1997 IEEE International Conference on*, IEEE, 1997, pp. 288–292.

[4] Jennings, E. and Heckman, D., "Performance characterization of Space Communications and Navigation (SCaN) network by simulation," *Aerospace Conference, 2008 IEEE*, IEEE, Big Sky, MT, March 2008, pp. 1–9.

[5] National Aeronautics and Space Administration, "Space Network Users' Guide (SNUG)," Tech. rep., Geenbelt, MD, August 2007.

[6] Center, G. S. F., "Space Communications and Navigation Network Service Catalog," Tech. rep., National Aeronautics and Space Administration, Washington, DC, September 2011.

[7] Center, G. S. F., "TDRS-L Media Kit," Tech. rep., National Aeronautics and Space Administration, Greenbelt, MD, 2014.

[8] http://www.spacenews.com/article/launch-report/32141tdrs-k-launch-caught-up-in-cascade-of-fla-delays.

[9] http://www.spacenews.com/article/launch-report/39228atlas-5-delivers-nasas-newest-tdrs-satellite-to-geo-transfer-orbit.

[10] Communications, S. and Program, N., "Space Communications and Navigation (SCaN) Network Architecture Definition Document (ADD) Volume 1: Executive Summary," Tech. rep., NASA, Washington, DC, October 2011.

[11] Communications, S. and Program, N., "NASAs Space-Based Relay Study: Overview and Direction," Tech. rep., NASA, March 2013.

[12] Andraschko, M., Antol, J., Horan, S., and Neil, D., "Commercially hosted government payloads: Lessons from recent programs," *Aerospace Conference, 2011 IEEE*, IEEE, Big Sky, MT, March 2011, pp. 1–15.

[13] Barritt, B., Bhasin, K., Eddy, W., and Matthews, S., "Unified approach to modeling and simulation of space communication networks and systems," *Systems Conference, 2010 4th Annual IEEE*, IEEE, San Diego, CA, April 2010, pp. 133–136.

[14] Baranyai, L., Cuevas, E. G., Davidow, S., Demaree, C., and DiCaprio, P., "End-to-end network modeling and simulation of integrated terrestrial, airborne and space environments," *Aerospace Conference, 2005 IEEE*, IEEE, Big Sky, MT, March 2005, pp. 1348–1353.

[15] http://www.agi.com/products/stk/.

[16] http://web.scalable-networks.com/content/qualnet.

[17] http://www.isi.edu/nsnam/ns/.

[18] Spangelo, S., , and Cutler, J., "Analytical Modeling Framework and Applications for Space Communication Networks," *Journal of Aerospace Information Systems*, Vol. 10, No. 10, October 2013, pp. 452–466.

[19] Bhasin, K., Hackenberg, A. W., Slywczak, R., B., P., Bergamo, M., and Hayden, J., "Lunar relay satellite network for space exploration: architecture, technologies and challenges," *Proceedings 24nd AIAA International Communications Satellite Systems Conference*, San Diego, CA, June 2006, pp. 12–14.

[20] Bhasin, K., Hayden, J., Sartwell, T., Miller, R., and Hudiburg, J., "Integrated Network Architecture for NASAs Orion Missions," *SpaceOps 2008 Conference*, Heidelberg, GE, May 2008, pp. 1–16.

[21] McCarthy, K., Stocklin, F., Geldzahler, B., Friedman, D., and Celeste, P., "NASAâĂŹs Evolution to Ka-Band Space Communications for Near-Earth Spacecraft," *Proceedings of the SpaceOps 2010 Conference*, Huntsville, AL, April 2010, pp. 1–12.

[22] Andersen, B. R., Gangaas, O., and Andenæs, J., "A DVB/Inmarsat hybrid architecture for asymmetrical broadband mobile satellite services," *International Journal of Satellite Communications and Networking*, Vol. 24, No. 2, March 2006, pp. 119–136.

[23] NASA, "Space Communications and Navigation (SCaN) Network Architecture Definition Document (ADD)," Tech. rep., NASA, Washington, DC, October 2011.

[24] Bhasin, K. and Hayden, J. L., "Space Internet architectures and technologies for NASA enterprises," *Aerospace Conference, 2001, IEEE Proceedings.*, Vol. 2, IEEE, Big Sky, MT, March 2001, pp. 2–931.

[25] Schier, J. S., Rush, J. J., Williams, W. D., and Vrotsos, P., "Space communication architecture supporting exploration and science: Plans and studies for 2010-2030," *1st Space Exploration Conference: Continuing the Voyage of Discovery*, Vol. 30, Orlando, FL, February 2005, pp. 1–33.

[26] Bhasin, K. B., Putt, C., Hayden, J., Tseng, S., Biswas, A., Kennedy, B., Jennings, E., Miller, R., Hudiburg, J., Miller, D., et al., "Architecting the Communication and Navigation Networks for NASA's Space Exploration Systems," *System of Systems Engineering, 2007. SoSE'07. IEEE International Conference on*, IEEE, San Antonio, TX, April 2007, pp. 1–6.

[27] Crawley, E. F., Cameron, B., and Selva, D., *System Architecture*, Pearson, 2015.

[28] de Weck, O., de Neufville, R., and Chaize, M., "Enhancing the economics of communications satellites via orbital reconfigurations and staged deployment," *American Institute of Aeronautics and Astronautics*, September 2003.

[29] De Weck, O., Neufville, R. D., and Chaize, M., "Staged deployment of communications satellite constellations in low earth orbit," *Journal of Aerospace Computing, Information, and Communication*, Vol. 1, No. 3, March 2004, pp. 119–136.

[30] Siddiqi, A., Mellein, J., and De Weck, O., "Optimal Reconfigurations for Increasing Capacity of Communication Satellite Constellations," *46 th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Austin, TX, April 2005, pp. 1–13.

[31] Simmons, W. L., *A framework for decision support in systems architecting*, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, February 2008.

[32] Deb, K., "Multi-objective optimization," *Search methodologies*, chap. 10, Springer, 2014, pp. 273–316.

[33] Wertz, J. R., Everett, D. F., , and Puschell, J. J., *Space Mission Engineering: The New SMAD*, Space technology library, Microcosm Press, 2011.

[34] Maral, G. and Bousquet, M., *Satellite communications systems: systems, techniques and technology*, John Wiley and Sons, Surrey, UK, February 2011.

[35] Brown, O. and Eremenko, P., "Fractionated space architectures: a vision for responsive space," Tech. rep., DTIC Document, Arlington, VA, April 2006.

[36] Brown, O. Eremenko, P. and Roberts, C., "Cost-benefit analysis of a notional fractionated SATCOM architecture," *Proceedings of the 24th AIAA International Communications Satellite Systems Conference (ICSSC), AIAA-2006-5328,*, San Diego, CA, June 2006, pp. 1–17.

[37] Jo, K. Y., *Satellite Communications. Network Design and Analysis*, Artech House, October 2011.

[38] Hemmati, H., *Deep space optical communications*, Vol. 11, John Wiley and Sons, April 2006.

[39] Selva, D., Cameron, B., and Crawley, E., "A rule-based method for scalable and traceable evaluation of system architectures," *Research in Engineering Design*, Vol. 25, No. 4, June 2014, pp. 325–349.

[40] Selva Valero, D., *Rule-based system architecting of Earth observation satellite systems*, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, May 2012.

[41] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., "A fast and elitist multiobjective genetic algorithm: NSGA-II," *Evolutionary Computation, IEEE Transactions on*, Vol. 6, No. 2, April 2002, pp. 182–197.

[42] Deb, K. and Jain, H., "An Evolutionary Many-Objective Optimization Algorithm Using Reference-Point-Based Nondominated Sorting Approach, Part I: Solving Problems With Box Constraints," *Evolutionary Computation, IEEE Transactions on*, Vol. 18, No. 4, August 2014, pp. 577–601.

[43] Durkin, J., *Expert Systems: Design and Development*, Macmillan Publishing, New York, 1994.

[44] Forgy, C. L., "Rete: A Fast Algorithm for the Many Pattern/Many Object Pattern Match Problem," *Expert Systems*, edited by P. G. Raeth, IEEE Computer Society Press, Los Alamitos, CA, USA, 1990, pp. 324–341.

[45] Optical Link Study, "Final Report," Tech. rep., Interagency Operations Advisory Group, 2012.

[46] http://classwww.gsfc.nasa.gov/gsamsgreet_spectrumAllocationSummary.htm.htm.

[47] Sanchez, M., Selva, D., Cameron, B., Crawley, E., Seas, A., and Seery, B., "Exploring the architectural trade space of NASAs Space Communication and Navigation Program," *Aerospace Conference, 2013 IEEE*, IEEE, Big Sky, MT, March 2013, pp. 1–16.

[48] Sanchez, M., Selva, D., Cameron, B., Crawley, E., Seas, A., and Seery, B., "Results of the MIT Space Communication and Navigation Architecture Study," *2014 IEEE Aerospace Conference*, IEEE, Big Sky, MT, March 2014, pp. 1–14.

[49] Davidson, A., Kwon, D., and Shannon, P., "Pricing a hosted payload," *Aerospace Conference, 2012 IEEE*, IEEE, March 2012, pp. 1–12.

[50] Sanchez, M., *Architecting Space Communications Networks*, Master's thesis, Massachusetts Institute of Technology Department of Aeronautics and Astronautics, Cambridge, MA, June 2014.

[51] Sutherland, T. A., Cameron, B. G., and Crawley, E. F., "Program goals for the NASA/NOAA Earth Observation Program derived from a stakeholder value network analysis," *Space Policy*, Vol. 28, No. 4, November 2012, pp. 259 – 269.

[52] Laboratory, J. P., "DSN Telecommunications Link Design Handbook," Tech. rep., Pasadena, CA, 2012.