Architecture and CONOPS of Next-Generation Ground Network for Communications and Tracking of Interplanetary SmallSats

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Abstract

As small spacecraft venture out of Earth orbit, they will encounter challenges not experienced or addressed by the numerous low Earth orbit (LEO) CubeSat and Smallsat missions staged to date. The LEO CubeSats typically use low-cost, proven CubeSat radios, antennas, and university ground stations with small apertures. As more ambitious yet cost-constrained space mission concepts to the Moon and beyond are being developed, CubeSats and smallsats have the potential to provide a more affordable platform for exploring deep space and performing the associated science. Some of the challenges that have, so far, slowed the proliferation of small interplanetary spacecraft are those of communications and navigation.

In [23], we discussed the communications and tracking challenges facing interplanetary smallsats and CubeSats, and the next-generation ground network architecture being evolved to mitigate those challenges. In this paper we summarized the results in [23]. Based on our understanding on the mission set of interplanetary smallsats and ground network architecture, we discuss the preliminary thoughts on the operations concept that would transform the current DSN architecture to a federated network architecture that, in addition to traditional deep space missions, can also provide just-in-time communications and tracking services to a large number of interplanetary smallsats/CubeSats. We focus on the following topics:

1. DSN compatibility and interfaces.
2. Challenges on integrating heterogeneous non-DSN antennas into the DSN service management and service execution framework.
3. Cross-support with university antennas, with other space agencies, and with other research centers.
4. Network planning and scheduling concepts that maximize pass opportunities for smallsats and CubeSats.

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I. Introduction

Today, most CubeSats operate in low Earth orbit (LEO), typically using low-cost, proven CubeSat radios, antennas, and university ground stations with small aperture. As more ambitious yet cost-constrained space mission concepts are being developed, moving from LEO to the Moon and beyond, CubeSats and smallsats\(^3\) have the potential to provide the means to explore deep space and to perform science in a more affordable way. One of the bottlenecks for the proliferation of interplanetary CubeSats and smallsats is communication and tracking between the spacecraft and Earth over the vast distance of deep space.

This paper discusses the communications and tracking challenges of the interplanetary\(^4\) smallsats, and proposes a next-generation Deep Space Network (DSN) architecture and operation concept that would mitigate those challenges.

The DSN consists of Deep Space Communications Complexes (DSCCs) with ground stations located near Madrid, Spain; Canberra, Australia; and Goldstone, California. At each complex there are a variety of antennas, including 34-m beam-waveguide (BWG), 34-m high-efficiency (HEF), and 70-m antennas. In addition, the DSN supports radio frequency (RF) compatibility testing using the following facilities: the Development and Test Facility (DTF-21), located near NASA’s Jet Propulsion Laboratory (JPL); the Compatibility Test Trailer (CTT-22), which is able to come to the spacecraft builder site; and the DSN test facility (MIL-71) located at NASA’s Kennedy Space Center, Florida. The current DSN architecture is depicted in Figure 1\(^5\).

The current DSN ground network architecture is designed primarily to support deep-space missions that are characterized by good-size budget and long mission life cycle. These missions can afford the vigorous compatibility testing, meticulous engineering support, and high-end communication and tracking services offered by the DSN. Interplanetary smallsats and CubeSats, on the other hand, operate on a relatively smaller budget and have a much shorter life cycle. They typically piggyback as secondary payloads for launch opportunities, and there is high uncertainty in pinning down the launch window.

The major communications and tracking challenges of interplanetary smallsats are as follows:

1. **Link capabilities for data delivery.** Interplanetary CubeSats are constrained by the CubeSat form-factor, and are inherently limited in mass and power. Due to the sheer distance between the spacecraft and Earth, the data return must rely on the large aperture of the ground network infrastructure to compensate for the large space loss of interplanetary links.

2. **Accurate spacecraft tracking for navigation state vectors determination.** The position and velocity of a CubeSat in LEO can be measured by small onboard Global Positioning Satellite (GPS) receivers, and be expressed in the form of North American Aerospace Defense Command (NORAD) two-line element data. An interplanetary spacecraft must rely on deep-space tracking techniques like ranging, Doppler, and Delta Differential One-way Ranging (Delta-DOR) to derive precise information on range, angular, and velocity information.

3. **Precision timing and frequency references to ensure accurate determination of spacecraft position and velocity.** Accurate timing and frequency references are needed for the processing of tracking data.

4. **Accurate spacecraft and ground antenna pointing.** Ground and spacecraft directional antennas with higher gains have smaller beamwidths compared to their smaller-gain counterparts. In order to maintain communication with

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\(^3\) The term CubeSats refers to the class of spacecraft that conform to the CubeSat form-factor, and smallsats belong to the class of small spacecraft with low mass and size, usually under 500 kg, and that includes CubeSats.

\(^4\) In this article, the term interplanetary includes the Moon.

\(^5\) The DSN upgrade schedule is dependent on the planned budget.
a spacecraft in X- or Ka-band, the antennas must track with precision. This imposes challenging requirements on the structural design, instrumentation, and control system of the ground and spacecraft communication systems.

5. **Communications and tracking of multiple spacecraft.** In the era of interplanetary smallsats, there may be many occasions when the ground antenna will see multiple spacecraft in its beam. The ground network, in the interest of maximizing the antenna utilizations, will need the capability to communicate with and to track multiple spacecraft simultaneously.

6. **Spectrum coordination and utilization.** Another challenge resulting from multiple spacecraft in the vicinity of a target is spectrum availability. More effective and dynamic use of spectrum will be needed to support simultaneous communications and tracking of multiple spacecraft.

7. **Deep-space spacecraft commanding.** Due to the long light time delay, real-time commanding of spacecraft and instruments is not always feasible. A non-real-time planning approach that generates command sequences that control science and engineering activities is generally needed. These command sequences have to be constraint-checked, verified, and validated to ensure safe operation of the spacecraft.

In addition to the above technical challenges, we are considering the following efforts for current and future implementations to evolve the smallsat flight communications system and the DSN architecture:
1. Development of, and enabling industry capability to supply, a deep-space CubeSat/smallsat radio product line. Iris is a DSN-compatible navigation and communications transponder that, when used with the DSN, provides telemetry, commanding, Doppler, ranging, and delta differential one-way ranging (Delta-DOR) services.

2. Development of high-gain antennas compatible with the CubeSat form-factor to enable deep-space communication with limited power consumption. JPL is currently funding the development of at least three different types of antennas — deployable reflectors [1], deployable reflectarrays [2], and inflatable antennas [3] — with the goal of increasing the CubeSat equivalent isotropically radiated power (EIRP) with respect to the traditional LEO CubeSat missions, which are mostly equipped with monopole, dipole, and patch antennas.

3. Streamlining processes and upgrading the existing DSN capabilities. This includes modifying the DSN resource allocation to improve the antenna usage efficiency to better accommodate the smallsat missions, and reducing the testing and setup costs of using the DSN services as well as the Advanced Multi-Mission Operations System (AMMOS) services.

4. Enhancement of simultaneous tracking of multiple spacecraft within an antenna beam. The current operational multiple spacecraft per antenna (MSPA)⁶ approach can support two spacecraft downlinks within an antenna beam. An upgrade to support four spacecraft downlinks (4-MSPA) is being planned to support the near-term needs. A low-cost opportunistic MSPA (OMSPA) approach that tracks multiple spacecraft downlinks is also being considered. There is also a study on an enhanced version of MSPA that provides simultaneous uplink, downlink, and two-way tracking services for multiple spacecraft, such as could be the case around the Moon or at Mars.

5. Coordination with non-DSN antenna facilities to support interplanetary smallsats. It is likely that future growth of the interplanetary smallsat population would call for more antenna resources than the DSN alone can provide in some scenarios. The DSN plans to work with other academic and industrial ground antenna facility operators, and other national and international agencies, to standardize signal formats and data exchange interfaces, and to establish cross-support agreements so that it can request the use of these antennas in a timely manner. This would enable spacecraft operators, at their option, to move data and commands in a timely manner between their control/science centers and their interplanetary spacecraft, using ground aperture resources across the DSN and ground antenna facility operators affiliated with the DSN.

6. New network operation concept that maximizes pass opportunities for interplanetary smallsats. Link-capability-driven network planning and scheduling can help to create unused time gaps of reasonable length in the antenna-tracking schedule of the network. These gaps would be ideal to provide just-in-time demand access opportunities, so that the smallsat and CubeSat missions that have flexibility in subscribing DSN services can take advantage of the shorter passes in-between the adjacent longer passes of the traditional deep-space missions.

II. Summary of Architecture Study Results

In [23], we discussed the communications and tracking challenges facing interplanetary smallsats and CubeSats, and the next-generation ground network architecture being evolved to mitigate those challenges. The key findings are summarized in the following subsections.

A. Interplanetary SmallSat Mission Characteristics and Communications/Tracking Needs

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⁶ Sometimes MSPA is also known as multiple spacecraft per aperture.
After more than a decade of successful operations in LEO, opportunities for a new generation of smallsats are opening today. Smallsat missions are growing into real science missions and could support the space exploration program beyond LEO in the near future [4]. CubeSats and smallsat missions present unique advantages given by their nature, and these advantages have already been demonstrated in LEO:

- CubeSats are small, so they can benefit from multiple piggyback launches.
- CubeSats are cheap (compared to traditional satellites).
- CubeSats are suitable for distributed architecture — a mission can deploy many satellites instead of one big monolithic spacecraft.
- CubeSats have short development life cycles — fast development and deployment mean fast return of investment and science data.

These unique features are attractive for an increasing number of stakeholders, including universities, industries, and national space agencies.

There are other factors that directly or indirectly affect the communication and tracking capabilities from a mission and spacecraft perspective. They include:

- **Long mission duration.** Unlike many LEO CubeSat missions, which might last for hours or days, interplanetary smallsat missions are expected to last for years. This necessitates new capabilities, and imposes stringent reliability requirements on different spacecraft systems.

- **Harsh radiation environment.** Semiconductor electronic components onboard the spacecraft are susceptible to damage or malfunction as a result of the ionizing radiation of outer space. Extensive development and testing are required in the production of radiation-hardened versions of electronic components.

- **Power and thermal considerations.** An interplanetary smallsat needs renewable energy, thus requiring an advanced and well-regulated power system with solar panels and batteries. Also, the harsh thermal environment of space demands precise thermal control to ensure that the spacecraft electronics operate within their thermal limits.

## B. Interplanetary Smallsat Communication System Design

There are major differences in the design of smallsat communication systems between LEO missions and interplanetary missions. In the case of LEO CubeSat missions, the design depends mostly on the commercial-off-the-shelf (COTS) products available. This is because CubeSat developments are typically low-cost and fast-paced, and they do not allow customized antennas and transceivers. As a result, most of the current LEO CubeSats communicate at UHF or S-band [5], the two bands for which many of the communication products have been designed. In terms of components, CubeSat communication systems are mostly single-string, without an amplifier, and with only one antenna and transceiver. Antennas are generally monopole, dipole, or patches [5]. The transceivers are almost all COTS products; they typically receive serial data and perform packetization, error checking, and retransmission [6]. Most of the protocols implemented are device-specific, and they generally require the use of specific receivers on the ground. In addition, these COTS devices do not generally possess any tracking or navigation functionality. The ground receivers used for these missions are mostly operated in university stations or amateur radio stations, and the communication licenses used have mostly been amateur or experimental licenses.

The major differences in the design of smallsat communication systems between the LEO missions and the interplanetary missions are described in detail as follows:

- **Frequency.** While LEO CubeSats seem to mostly use UHF and S-band, interplanetary CubeSat designs seem...
mostly to use X-band [7-10]. To reduce spacecraft mass and power there is also an interest in using Ka-band [2], as it can be seen in the development of Ka-band antennas [1] and transceivers. However, the use of Ka-band for CubeSats is still limited by the current pointing capabilities.

- **Transceiver.** Instead of purchasing COTS products, interplanetary CubeSat missions need to rely on more customized radios that also implement several features required for deep-space navigation: Doppler, ranging, and delta-DOR. This necessity has driven the development at JPL of the Iris radio [11], which is described in details in [23].

- **Antennas.** Many of the antennas are custom-developed. For low data rates, patches [7] are generally used. As distance and data rate needs increase, arrays of patches are implemented [9], as well as reflectarrays [2], deployable antennas [1], and inflatable antennas [3].

- **Ground support.** As described in later sections, interplanetary CubeSat missions need more complex services than most of the LEO missions. As a result, most of the interplanetary CubeSat mission designs are currently baselined on the use of the DSN.

In addition to the aforementioned differences, for an interplanetary smallsat spacecraft there can be stronger dependencies and additional constraints between its flight communication system and the other flight subsystems.

The key dependencies are as follows:

- **Power system.** Smallsats, especially CubeSats, face limitations in the total onboard power that they can produce. This affects the communication system by limiting the power that can be allocated to the transceiver and by making it almost impossible for a CubeSat or smallsat to carry an amplifier. Another dependency between power and communication is that in many cases CubeSats and smallsats are equipped with deployable solar panels that can shade and/or limit the field of view of the antennas.

- **Pointing and control.** Almost all the directional antennas carried on CubeSats and smallsats do not have a gimbal and are body-mounted. As a result, the satellite control system needs to be able to adequately point the antenna, if required.

- **Navigation.** Interplanetary smallsats need frequent tracking measurements to allow precision navigation and pointing of spacecraft and ground antennas. As a result, the spacecraft radio needs to be equipped with additional capabilities to support navigation.

- **Instruments/payload.** There can be electromagnetic interference (EMI) between the communication system and the instruments. In addition, instruments may require a very high amount of data to be downloaded, which can influence the communication system design.

- **Structure.** Many CubeSats and smallsats have deployable solar panels and sometimes deployable instruments such as optical baffles. All these deployable components can obstruct the view for the antennas and create shading that can reduce the communication system performance.

- **Avionics.** The avionics characteristics (memory, processing power) can affect the amount of data transmitted versus what is processed onboard. In addition, many pc boards are packed together in a very closed space, and this can also generate undesired thermal effects and interferences that can affect the communication system.

In the future when the network infrastructure needs to support a fleet of interplanetary CubeSats, more versatile and efficient communication schemes need to be considered, e.g. multiple access and multi-hop communications, to provide communications as well as navigation tracking capabilities.
C. Efforts to Streamline Existing DSN Operation Capabilities

To accommodate the communications and tracking needs of interplanetary smallsats, the DSN has been investigating different approaches to streamlining and updating the existing ground network capabilities, services, and processes. The next few subsections discuss the current status of the DSN resource allocation process, the spectrum assignment process, the multiple spacecraft per antenna (MSPA) enhancements, and the ground data system development.

C.1 DSN Resource Allocation Process

One important consideration is the availability of DSN resources to accommodate the interplanetary smallsat missions. The DSN currently makes available 13 antennas at its three Deep Space Communications Complexes located around the world. These 13 antennas are in high demand by the 35-40 missions they support. Due to the contending mission requests, almost all missions receive less tracking time than they request. In a typical week, approximately 300 hr of antenna time out of 1,500 requested goes unfulfilled due to contention with more than one mission requesting the same DSN resource. The current DSN scheduling process requires a large amount of time and effort to negotiate the resolution of conflicts in antenna time. The addition of multiple interplanetary CubeSats/smallsats is anticipated to exacerbate this contention.

The current DSN scheduling process is managed by the DSN’s Scheduling Process Office (SPO) located at JPL in Pasadena, California. The SPO provides the scheduling tools and end-to-end scheduling process for the scheduling community. The scheduling community comprises three scheduling teams that provide scheduling services to several dozen of the missions that use DSN antennas, plus a handful of individual missions that do their own scheduling. Together, the project/mission schedulers perform peer-to-peer negotiation for tracking time on the DSN antennas under the supervision of the SPO. The SPO and schedulers also receive assistance from DSN systems engineering and JPL navigation teams who provide support products and analysis. Time allocated for each user is based on the user’s requirements, spacecraft visibility, and the outcome of the negotiation process. The DSN does not allocate time based on priorities. However, there is an escalation process to resolve issues if a user is unsatisfied with the outcome of the negotiation process at lower levels of negotiation.

The future of the DSN scheduling process is currently under review and may comprise a hybrid approach of a peer-to-peer negotiation and a priority-based scheduling system. The priority system will be multidimensional, based on mission phase, mission events, spacecraft health and safety, and any other data necessary to meet user needs while maximizing the use of DSN assets. It is recognized that the DSN will be required to accommodate a more diverse mission set. Today, most DSN users have planning cycles greater than 8 weeks that adapt well to DSN scheduling. Future missions that have shorter planning cycles are less dependent on firm tracking schedules well in advance. The challenge for the DSN will be to meet all customers’ needs within the constraints imposed by DSN resource availability and operational rules.

C.2 Spectrum Assignment for Interplanetary SmallSats/CubeSats

Smallsats pose several challenges for spectrum management. The quick development cycle and opportunistic launches of smallsats often do not allow for the typical NASA frequency selection and spectrum coordination process, which can take several years to complete. This process includes spectrum consultations with the project, a frequency selection study with detailed RF interference analysis, hardware spectrum measurements, domestic and international frequency coordination, and regulatory filings with the appropriate spectrum authorities. This contrasts with the short development cycle of smallsats, which is sometimes a year or less. This creates difficulty for spectrum managers when doing frequency coordination and obtaining frequency licenses for smallsats. Furthermore, smallsats often request a frequency assignment before the launch date and trajectory have been determined in order to
facilitate procurement of transmitter hardware. This introduces uncertainty in the interference analysis needed to select the appropriate frequency channel, and it is not unusual to have to perform multiple frequency analyses for smallsats as their mission parameters change.

Due to power and size constraints, smallsats typically have an EIRP that is much lower than other interplanetary spacecraft. This renders smallsats especially susceptible to RF interference from higher-EIRP satellites when they are both in orbit around the same interplanetary body. There are several steps that can be taken from a spectrum management perspective to minimize RF interference for smallsats. The first is appropriate spectrum allocation and channel selection for both smallsats and other interplanetary spacecraft. In congested bands, the lower-EIRP and lower-data-rate missions should be placed on one end of the frequency band as much as possible, and the higher-EIRP and higher-bandwidth satellites on the other end of the band. This avoids the scenario where a high-EIRP spacecraft is placed on an adjacent frequency channel to a low-EIRP spacecraft, which could result in harmful interference to the lower-EIRP spacecraft if the two are spatially aligned.

Use of different antenna polarizations, bandwidth-efficient modulations, and transmitter filters are onboard hardware solutions recommended for reducing RF interference and simplifying frequency coordination. This should be done whenever practical, but it is recognized that these solutions are not always possible for smallsats due to hardware and cost constraints. Deep-space missions requiring large data rates and telemetry bandwidths are recommended to utilize the Ka-band deep-space allocation (31800–32300 MHz), which is much less congested.

If interference cannot be avoided through these methods, spectral analysis tools can be used to predict the time periods and expected signal-to-noise ratio (SNR) degradation of the RF interference. With this information, informed decisions can be made as to whether the interference is acceptable, and if not, then what operational workarounds are needed. Operational workarounds can include a temporary reduction in data rate for the interfering satellite, or scheduling alternate passes to avoid interference. A smallsat may have to operate on a non-interference basis if a late change in its trajectory invalidates the results of the frequency selection study, the mission cannot change its telecom parameters to minimize interference to other deep-space missions, and other operational workarounds are not practical.

C.3 Enhancements on Multiple Spacecraft Per Antenna (MSPA)

As alluded to near the beginning of this paper, the relatively low cost of developing smallsats and launching them as secondary payloads on trajectories that take them beyond geosynchronous orbit is leading to a veritable “explosion” of deep-space smallsat mission concepts. Each upcoming Space Launch System (SLS) launch, alone, has the capability to deploy as many as 17 6-U CubeSats from its interim cryogenic propulsion stage. Because these smallsats tend to be extremely mass-, power-, and volume-constrained, most of the telecom burden needs to be assumed by large antennas on the ground. But, such antennas are not in great abundance. In the case of the DSN, for instance, only 13 antennas7 are currently available to support roughly 35 spacecraft. But with just three SLS launches, including nothing else, the number of spacecraft needing support could more than double. And, because of their deployment as secondary payloads, many of these smallsats may require initial support at roughly the same time in the same portion of the sky. Hence, the DSN has been working to develop low-cost techniques to enable its antennas to support significantly more spacecraft simultaneously.

One technique that has been employed for over a decade is referred to as Multiple Spacecraft per Antenna (MSPA). In this technique, spacecraft that will be in view of the same ground antenna at the same time can share it for their downlink (see Figure 2). The number that can share the antenna tends to be constrained by the number of deep-space receivers affiliated with it. Currently, the DSN is constrained to configure two such receivers per antenna, limiting

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7 This number might change due to retiring of old antennas and deployment of new antennas.
MSPA’s applicability to only two spacecraft at a time. In this configuration, the uplink for spacecraft commanding and ranging measurement is shared between the two spacecraft via time multiplexing since the uplink equipment only supports one signal at a time. The downlinks that enable telemetry data return, as well as the return of ranging and Doppler radiometric data, are simultaneously supported with a different set of receiving equipment. The operation of the equipment, including the configuration setup at the start of the pass and the switching of the uplink in mid-pass between spacecraft, is automated and driven by the tracking schedule.

Figure 2. Traditional MSPA

In anticipation of the tracking demand from interplanetary smallsats, the DSN has recently been investigating different approaches to increase the number of simultaneous spacecraft that MSPA can support, and to enhance the tracking services for individual spacecraft. Three approaches are being considered: 4-MSPA and Opportunistic MSPA (OMSPA).

4-MSPA

4-MSPA is the extension of the current MSPA technique of tracking two spacecraft to four. This requires removing some legacy technical constraints in the equipment scheduling information processing, and upgrading the software for automated configuration. That would allow, for example, the uplink swapping done multiple times within a pass. Possible further improvement would be to increase the uplink capability by allowing for simultaneous generation and transmission of multiple uplinks — one for each spacecraft. This would increase the amount of two-way radiometric data and provide flexibility in mission operations with the sequence planning and command uplink.

OMSPA

In the OMSPA concept, a wideband recorder, rather than additional receivers, is added to the ground antenna and run 24/7, recording at IF whatever the ground antenna sees within the frequency bands of interest (Figure 3) [31]. While traditional links involving the antenna’s deep-space receiver still get scheduled, smallsats and other spacecraft that will be within the same beam of the antenna can opportunistically transmit open loop, with their signals getting captured on the recorder. Everything received through the antenna beam is digitally recorded. Smallsats transmit open loop when in the beam of the formally scheduled spacecraft. The appropriate time and frequency domain of the recording can then be retrieved and the appropriate signal processing performed to recover the data. The DSN delivers the digitized signals to the various smallsat Mission Operations Centers (MOCs), and each MOC retrieves relevant portions of the digital recording for subsequent demodulation and decoding (or they use a service that does
it for them).

**Figure 3. Overall diagram of OMSPA.**

Assuming adherence to proper frequency assignments, there is virtually no limit to the number of spacecraft that can be simultaneously accommodated within the same beam. And, adding one recorder per antenna and running multiple instantiations\(^8\) of software receivers to demodulate and decode the appropriate portions of the recordings is likely to be substantially cheaper than trying to add numerous strings of traditional receiving and telemetry processing equipment.

**D. Ground Data System for Interplanetary SmallSats**

The Advanced Multi-Mission Operations System (AMMOS) provides most of the ground data system functions needed to design, implement, and operate a mission operations system (MOS) for all mission types and classes (Figure 4). The development and maintenance of AMMOS is managed by the Multimission Ground Systems and Services (MGSS) Organization in JPL’s IND.

AMMOS consists of a core set of software products that can be readily integrated to meet specific needs of individual missions. These software products can be tailored for use by the deep-space CubeSat. The Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment (INSPIRE) mission is a recent example on tailoring and using AMMOS tools and services to great effect. INSPIRE consists of two spacecraft. AMMOS provided the AMMOS Multi-mission Data Processing and Control System (AMPCS) to command and monitor the spacecraft that are compatible with the DSN-supported interfaces and protocols. AMPCS is a reusable, multimission ground data processing, archival, visualization, and command system used for spacecraft testing and mission operations. The system was easy to configure and greatly aided in the flight system development and enabled testing with the same tools as will be used for operations. This effort was described in [12].

In working with INSPIRE, MGSS recognized the need for helping new missions getting into the deep-space regime with minimal costs. This led to the creation of the IND Customer Assistance Package (ICAP). The ICAP is intended

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\(^8\) An instantiation is the creation of a real instance or particular realization of an abstraction or template such as a class of objects or a computer process.
to be a support package designed to provide mission GDS engineers with a set of telemetry and command capabilities on the first day of the mission, with little or no involvement from MGSS. ICAP is a NASA AMMOS configuration (software and documentation) that will enable ground system engineers to quickly deploy, adapt, and operate a ground data system for their deep space small satellite with minimal custom development. In this way, the cost to the cost-constrained missions is minimized, as long as the missions use standard capabilities and features. In addition, the ICAP covers key aspects of working with the DSN and issues associated with getting ready for and executing operations in the deep-space environment that are not typically encountered in LEO.

Figure 4. AMMOS tools and services.
Before completing manuscript submission, submitters must also select the copyright statement that will appear on the paper, and complete other acknowledgments. It is also necessary to click both the “Accept” and “Save” buttons to complete a submission. No confirmation email will be sent upon completion of the manuscript submission. To confirm successful submission, submitters should reopen their manuscript submission pages and check the status of their submissions. A completed submission will have a status of “Accepted – Complete.” All files must be in pdf format. Please be sure that all security settings are removed from the pdf file before uploading to ensure proper processing of your manuscript file.

III. DSN Compatibility and Interfaces

The DSN provides standard services for spacecraft telemetry, tracking data (ranging and Doppler), ground station monitor data, and command services. In addition, there are other services that the DSN can provide. These services are listed in the published DSN Service Catalog.\(^9\) This service catalog describes the details of the different services as well as the DSN capabilities.

Most of the DSN standard services conform to the CCSDS standards. The CCSDS has published a series of documents on standards for spacecraft and ground communications. These standards cover modulation schemes, telemetry, and command formats as well as interfaces with ground stations.\(^10\)

For each of these services, there are interface options on how the services are provided to the customer (see Figure 15). The interface is dependent on the service type, requirements, and affiliations of customers, i.e., JPL missions or non-JPL missions. Generally speaking, the suite of interfaces for JPL missions is different from the suite of interfaces for non-JPL missions [16]. The exception is service management, for which the interface is the same for both cases [5]. Figure 5 summarizes the flow of requests and scheduling.

\(^9\) The DSN Service Catalog is publicly available on the DSN Commitments Office website at http://deepspace.jpl.nasa.gov/advmiss.

\(^10\) See http://public.ccsds.org/.
Service management of the DSN is used for scheduling the DSN resources (tracking antennas) used for supporting the mission. It includes providing the DSN mission general scheduling requirements such as minimum and desired tracking hours and contacts per week. The Spacecraft Ephemeris, usually captured in CCSDS-recommended format of a Spacecraft and Target Ephemeris Kernel (SPK) file, is also required by the DSN. This SPK file is used by the DSN for generating view periods when a certain ground station is in view of the spacecraft. The mission will provide a project scheduler representative who will interface with the DSN regarding specific requests for tracking stations and tracking passes that would be needed by the mission. This scheduler will also help negotiate requests and resolve conflicts as appropriate.

In addition, the mission will also provide a sequence of spacecraft events and network configurations for each of the requested DSN tracking supports. Tracking hours are limited by practical limits of total user demands and internal engineering and maintenance activities. The DSN and the deep-space user community work together to produce conflict-free schedules several weeks out. Advance DSN conflict-free schedules are important because deep-space missions operate primarily under sequence control (i.e., in response to a highly accurate model of predicted events). Late changes to the schedule are disruptive (and costly) to the user community in part because the schedule is typically packed very tightly. Demand scheduling of the DSN, in response to unplanned or ad hoc mission events, is not currently within the DSN operational concept. In addition to supporting the tracking of spacecraft, the DSN also serves the radio astronomy, radio science, and space radar communities with special products unique to those disciplines. These activities are also in competition with requests for spacecraft tracking supports to obtain the limited DSN resources. It should be noted that the DSN currently does not use a priority scheme in scheduling missions. DSN mediates schedule conflicts via the Resource Allocation Process (RAP).

Figure 6 summarizes the overall flow of data in the DSN. DSN tracking stations are located at Goldstone, California; near Canberra, Australia; and near Madrid, Spain. All data and interfaces from the tracking stations go to the JPL Deep Space Operations Center (DSOC) located at Pasadena, California. Missions use the DSOC no matter whether their interfaces with DSN are internal or external.
JPL missions that use navigation and tracking data services usually use specialized DSN equipment for processing and data conditioning prior to delivery. Telemetry and command services also employ customized equipment and processing, and the equipment is located at the DSOC. Thus, these missions have customized interfaces with the DSN that are not CCSDS-compliant. It should be noted that JPL internal missions could also use CCSDS interfaces as an option, but most do not.

For non-JPL missions, the DSN offers the use of the CCSDS Space Link Extension (SLE) [25,26] for both the forward link (command to the spacecraft) and return link (telemetry from the spacecraft). All telemetry data from the DSN tracking stations are sent to the DSOC. The mission then interfaces to the DSOC (the SLE telemetry server) for SLE frame service. Note that if a mission desires to retrieve telemetry files via File Transfer Protocol or similar protocol, it still interfaces with DSOC, and not with the DSN tracking station. For the SLE forward link (command), the mission still passively goes through DSOC, but actually interfaces directly to the DSN tracking station’s command system (command server). For tracking data services (i.e., Doppler and range data), the external mission also receives the data from DSOC via the DSN tracking station. For tracking data, the DSN offers external missions a DSN tracking interface (known as TRK-2-34) that is streamed in real time during the support. The DSN also offers the CCSDS tracking data message (TDM) from DSOC.

Using CCSDS standard interfaces can be the most cost-effective way for CubeSat missions. The CCSDS interfaces (SLE and TDM) that the DSN offers for telemetry, tracking, and command services have also been adopted by the Japan Aerospace Exploration Agency (JAXA) and the European Space Agency (ESA), and cross-support agreements are in place. In the near future, Goddard Space Flight Center’s NEN tracking facilities will also support the CCSDS standard interfaces. Also, university antennas, such as the antenna at Morehead State University in Kentucky, are considering supporting the CCSDS standard interfaces. By adhering to these CCSDS standards, a CubeSat mission can be compatible with a large number of ground stations around the globe, thus allowing quick and easy access to ground communications and tracking support during nominal and off-nominal operations.
IV. Challenges on Cross-Support with Non-DSN Antennas

In [13], the challenges and benefits of cross-support between ground stations for tracking LEO spacecraft were presented, and the concept of a federated ground network was proposed. The Near-Earth Network (NEN), which is composed of NASA-owned ground antennas and industry-owned antennas, is an example of a network leveraging on commercial capability to support LEO missions. Recent coordination and standardization efforts among space agencies have mitigated many of the challenges, as discussed in [13]. However, technical and nontechnical challenges still remain in the establishment of a federated ground network, especially in the area of deep space:

Standardization on signal and data formats. To ensure interoperability and cross-support among ground stations, consortia like Interagency Operations Advisory Group (IOAG) and CCSDS have been working towards a set of international standards in space communication signal formats and data formats. The standards are usually rather comprehensive, and ground stations do not typically implement every aspect of the standards. It is expected that all ground stations within the federated ground network are required to conform to a subset set of the IOAG and
CCSDS signal and data formats that ensure safe and reliable operations.

**Ground antenna diversity.** Different ground antennas consist of different hardware and software components. Standardized interfaces or proxy translations are needed in the seamless control and operation of the heterogeneous set of antennas. Also, the qualities of communications and tracking services can be different with respect to different antennas, and this creates complexity in the management and provision of services for a federated ground network. For example, the federated ground network needs to consider the aperture sizes in addition to missions’ communication and tracking requirements in the pairing of spacecraft and ground antennas in the planning and scheduling process.

**Security.** Unlike most LEO CubeSat missions, high-budget and high-profile interplanetary CubeSat missions as well as traditional deep-space missions levy stringent physical and cybersecurity requirements on the ground antennas that provide command and telemetry services to the missions. This can impose budgetary and technical challenges to many non-DSN ground antennas in installing physical security equipment at the antenna station premises and establishing trust for data transfer between two ground stations belonging to different institutions, and between the ground station and the mission.

**Different levels of participation from non-DSN ground antennas.** We expect that the non-DSN antennas would have their own business bases, and thus would offer different degree of participations in the federated ground network. In addition to different interfaces, different antenna stations might offer different access and control levels of their hardware and software. The availability of antenna resources must be well coordinated, so they can be provisioned for services in a timely manner. The federated ground network must mask the antenna idiosyncrasies to the extend possible, so mission users would experience consistent services offered by the federated ground network.

**Ground data transport.** Unlike a large commercial wide-area network (WAN) that shares diverse network resources among diverse users and has a complex topology that requires routing mechanism and flow control, the ground communication network of a space network operates under the assumption of a guaranteed dedicated bandwidth allocation between specific sparse endpoints in a star-like topology. To minimize the number of data interfaces and associated cost, a reasonable ground network topology would be that all ground antennas connect to a centralized network operation center (a.k.a. JPL Central), and from there data are distributed to the mission operation centers. Spacecraft data consist of different data types; each associated with an end-to-end latency requirement. The non-DSN antennas have to establish ground link connectivity with JPL Central, with sufficient bandwidths that would meet the data latency requirements of the spacecraft users.

**V. DSN Cross-Support Approaches with Other Ground Antennas**

In this section, we discuss the preliminary thoughts and/or ongoing efforts on DSN cross-support approaches with non-DSN ground antennas.

**A. University Stations — Case Study: Morehead State University**

The number of CubeSat missions planned for beyond LEO poses a challenge for mission operations and for DSN ground operations. A potential solution lies in the implementation of high-gain ground stations operated by universities and other astronomical research centers. One example is the 21-m Space Tracking Antenna operated by the Space Science Center at Morehead State University (MSU). The antenna (Figure 7) was brought online in 2006 and provides telemetry, tracking, and command (TT&C) services for a wide variety of space missions, but it is particularly well suited for supporting smallsats. The 21-m is a multipurpose instrument, serving also as a radio telescope for astronomical research and as an experimental station for communications systems development. The
instrument is a unique educational tool that provides an active laboratory for students to have hands-on learning experiences with the intricacies of satellite telecommunications and radio astronomy. The 21-m antenna supports undergraduate research in astrophysics, satellite telecommunications, RF, electrical engineering, and software development. From its inception, it was anticipated that the 21-m antenna would provide telemetry, command, and tracking services for small, low-power satellites performing research in the lunar vicinity, at Earth–Sun Lagrange points, at Near Earth Asteroids, and potentially out to Mars at low data rates. It was not envisioned that these small satellites would be CubeSats since the form-factor was evolving simultaneously with the planning and design of the 21-m antenna. The MSU team received significant guidance from NASA’s NEN (Ground Network at the time) and from Mike Moore Engineering Enterprises, who assisted in developing performance criteria and requirements anticipated to support spacecraft operations into the 21st century. One of the primary uses of the 21-m system is to provide ground operations services for small satellite missions operated by MSU and its partners. The students and staff of MSU have gained valuable experience in space operations and the 21-m antenna’s performance has been vetted through these activities. Dynamical and mechanical properties of the antenna can be found in [14,15].

A block diagram of the standard 21-m feed configuration is shown in Figure 8. Feeds typically consist of a horn, coupler, orthomode transducer (OMT), low-noise amplifier (LNA), and noise control source or test inject with heater that is encased in insulation. Downconversions are accomplished using frequency-specific, interchangeable tuners. RF performance characteristics are provided in [16,17].

The 21-m system incorporates back-end (digital front-end) technologies that include complete automation and control systems (for remote autonomous operation of the 21-m), software-defined radio/digital signal processor (DSP) front-end (including an Amergint SoftFEP 200 Telemetry receiver, an RT Logic T400 modem, a National Instrument digitizer for experimental purposes, a version of the NASA NEN operating software [HWCNTRL], and a high-performance S-band feed). The 21-m is currently an effective system at S-band, X-band, and Ku-band. The system also supports remote operation by off-site operators, and it is capable of supporting the SLE data formatting and processing protocol. Figure 9 shows the back-end architecture for the MSU 21-m antenna.
Figure 7. The MSU 21-m antenna (Lat: 38° 11' 30.773 N, Long: 83° 26' 19.948 W).

Figure 8. Standard configuration of the RF systems of the MSU 21-m antenna.
Figure 9. MSU 21-m antenna telemetry and signal processing architecture.

The MSU 21-m antenna currently has the capacity to track satellites in LEO, the geostationary arc, and the lunar vicinity (with high transmission power), owing to a combination of antenna gain and relatively low-noise feed systems. The system currently operates at UHF, L-, S-, C-, X-, and Ku-band. The 21-m has extremely good surface (0.0166" root-mean-square [RMS]) and tracking accuracies (0.005 deg RMS at Ku-band), and excellent pointing (≤ 0.01 deg RMS). While the 21-m has been successfully used to service (uplink commands and downlink data) small satellite LEO missions, the potential exists to evolve the system into an instrument capable of supporting deep-space small satellite missions. When combined with the 21-m aperture area gain, and improved performance characteristics owing to planned upgrades (cryogenic low-noise amplifiers, improved back-end digital signal processing, and improved time synchronization), the antenna is poised to support low-power small satellite missions beyond LEO.

Currently there is a three-year plan to upgrade the MSU 21-m antenna. The three-year timeline for implementation was chosen to allow adequate time for hardware and software development, to assess performance on benchmark activities, and to train university personnel and students. The timeline was also selected to implement an additional vetted DSN node in time for the 2018 launch of the NASA EM-1 mission that will include as many as 11 6U CubeSats headed to lunar destinations and beyond.

B. Cross-Support with Other Space Agencies — Case Study: European Space Agency

ESA has a strong heritage in the development and operation of near-Earth and interplanetary missions for advances in science and space exploration. The ground segment of all ESA missions is designed and operated by the ESA Operations Centre (ESOC) located in Darmstadt, Germany, and it allows mission operations during all phases, from listen-in during system validation tests at satellite integration facilities and at launch pad, until end of mission,
passing through launch and separation, insertion into the final orbit, orbit correction maneuvers, interplanetary cruise, and planetary insertion or landing. A typical ESA ground segment includes a Mission Control System (MCS) responsible for the processing and visualization of housekeeping telemetry and generation of telecommands, a Flight Dynamics System (FDS) in charge of orbit determination and prediction, maneuver control and optimization, and attitude determination, as well as other subsystems used for mission planning, data dissemination, and testing.

Access to space is ensured by a world-wide distributed multimission network of antennas of different diameters called ESTRACK\(^{11}\) (European Space Tracking network) connected to the above ESOC-located subsystems through a wide-area network (WAN). ESTRACK includes (among other terminals):

- A 5-m terminal located on Santa Maria Island, Azores, is used for launcher S-band tracking.
- Two 13-m and 15-m antennas located in Kiruna, Sweden, are used for near-Earth and Earth-observation missions.
- Three 15-m antennas located in Perth, Western Australia (this antenna will not be available starting in 2016); Maspalomas, Spain; and Kourou, French Guyana, supporting launch and early orbit phase (LEOP) operations in S-band and X-band as well as S-band routine operations for near-Earth missions.
- Three deep-space 35-m antennas located in New Norcia (DS1, Western Australia), Cebreros (DS2, Spain), and Malargüe (DS3, Argentina), ensuring uninterrupted coverage for interplanetary missions, supporting routine operations in S-/X-/Ka-band.

A typical ESA ground segment data flow is shown in Figure 10.

The design and main specifications of the deep-space antennas are reported in [18]. The actual performance of DS1, DS2, and DS3 exceed the specifications. The downlink performance in X-band, and especially in Ka-band, is affected by the presence of the atmosphere, which introduces signal attenuation and increase of the antenna system temperature. Guaranteed figures (for a given percentage of time) can be computed according to the relevant ITU-R recommendation [19].

\(^{11}\) [http://www.esa.int/Our_Activities/Operations/Estrack_tracking_stations](http://www.esa.int/Our_Activities/Operations/Estrack_tracking_stations)
The ESA antennas support most modulations, coding schemes, and SLE services recommended by the CCSDS, with specific technical constraints that must be verified when negotiating a cross-support. As far as deep-space tracking is concerned, ESA antennas can perform Doppler measurement on signals with suppressed and remnant carrier, with accuracy on the order of 0.1 mm/s with 1-min integration, and ranging on signals with remnant carrier with jitter accuracy in the meter region. Due to the large baselines between its deep-space antennas, ESA can perform $\Delta$-DOR [20] for precise angular measurement of the spacecraft in the plane of sky, with angular accuracy in the order of 15 nanoradians.

Due to increasingly demanding requirements in terms of return data volume, spacecraft operability and deep-space navigation, ESA is studying various enhancements of the 35-m antenna systems that are related to near-Earth and interplanetary missions:

- Enhanced X-band and Ka-band G/T
- Enhanced X-band EIRP
- Implementation of simultaneous Gaussian minimum-shift keying (GMSK) and pseudo-noise (PN) ranging
- Implementation of Ka-band uplink in DS3
- Enhanced $\Delta$-DOR

The enhancement of X-band and Ka-band G/T can be achieved by extending the cryo cooling (currently limited to the low-noise amplifiers) to the feed assembly, as studied and implemented by NASA/JPL [21]. The expected G/T improvement from such implementation is on the order of 2 dB at Ka-band and 1 dB at X-band in clear sky conditions, bringing the downlink performance of the ESA antennas to essentially equivalent performance of comparable-diameter antennas of the NASA/JPL DSN.

The motivation for enhanced uplink performance is linked to the capability of recovering deep-space missions, in those scenarios where correct spacecraft attitude cannot be ensured and communications have to be established through the onboard low-gain antenna. The enhancement under consideration is for an uplink power of 80 kW at
antenna aperture, versus the current 20 kW, leading to an overall 6 dB increase in the current EIRP.

The implementation of simultaneous GMSK and PN ranging, following the related publication CCSDS Blue Book [23], will remove the constraint of not performing ranging during downlink operation with (band-efficient) GMSK modulation, simplifying mission operations.

The implementation (already partially completed) of Ka-band uplink in DS3 is part of a broader ESA objective to achieve full radio science capabilities. The link will indeed allow establishing three coherent links (X-/X-band X-/Ka-band, and Ka-/Ka-band) with deep-space satellites equipped with a Ka-/Ka-band translator on top of the X-/X-/Ka-band transponder, thus allowing full removal of plasma disturbances, which are the dominant error source for tracking observables during superior solar conjunctions. The use of Ka-band uplink could also be considered for telecommand transmission in the future, especially for critical operations performed during superior solar conjunctions at low separation angle with the Sun.

Finally, ESA plans to improve its delta-DOR system for accuracy as good as down to 1 nanoradian, for enhanced deep-space navigation.

The above enhancements may be considered in feasibility studies involving the ESA ground segment in the long term, even though the actual implementation is still to be confirmed, taking into account programmatic constraints.

The long-term plan for the S-/X-band 15-m antennas is under evaluation by ESA, taking into account cost and utilization aspects. At present, a very limited evolution of the terminals is planned, the focus being on sustaining actions to extend the lifetime for support to flying missions.

D. Cross-Support with Other Research Centers — Case Study: Applied Physics Laboratory

Many missions, particularly those not affiliated with a space agency, have had to develop their own ground stations to support their communications and tracking operations. These stations are often idle for a large percentage of the time, especially those whose primary missions are over. Some of these stations have large aperture, and have potential and excess capacity to support a significant portion of an interplanetary smallsat/CubeSat mission. One example is the 18-m antenna of the Applied Physics Laboratory (APL). Figure 11 illustrates the 18-m antenna (APL-18) and its specifications.

The APL-18 ground station has a rich history and excellent track record of providing highly reliable ground station support for orbiting spacecraft, dating back to the early 1960s. The original VHF/UHF system became operational in 1963 and used for the U.S. Navy’s Transit Program. Throughout its more than 50-year existence, the APL-18 has undergone numerous upgrades to enhance the capabilities far beyond its original design specifications.
As space-to-ground communications evolved, APL engineers followed suit with upgrading the APL-18 ground station capabilities. In its current configuration, the APL-18 supports both S- and X-band communications. Transmit capabilities include a dual redundant S-band 2000-watt uplink with “on-the-fly” selectable polarization (LHCP or RHCP). The downlink consists of four simultaneous S-band downlink chains (two each at LHCP and RHCP) as well as two simultaneous X-band downlink chains (one each at LHCP and RHCP). The APL-18 uses three Cortex-DS command ranging and telemetry units (CRTs) to provide CCSDS-compliant uplink, downlink, ranging, Doppler, and Space Link Extension (FWD CLTU, RCF, RCF) services. The station is fully automated and configurable using a customized version of the NASA NEN operating software (HWCNTRL) enabling both attended and unattended “lights-out” operations. The setup and teardown times are on the order of three minutes or less. The scheduling software (HWSCHED) is extremely flexible for remote scheduling of the station, utilizing both web-based and TCP/IP interfaces. APL’s network infrastructure enables connections between the APL-18 and the NASA restricted IONet. Figures 12 and 13 illustrate the APL-18 station block diagram and the feed block diagram, respectively.
In summary, the highly capable APL-18 station and experienced engineering staff make this an excellent choice for providing cross-support for interplanetary smallsat/CubeSat missions.

VI. Network Scheduling Concepts that Maximize Pass Opportunities for SmallSats

Current deep-space planning and operation are based mainly on spacecraft-ground-in-view periods and other criteria such as mission priority and science returns. Traditional network planning and scheduling involves individual missions performing their own link analysis and submitting network support requests. The “horse-trading” among missions is done, by and large, based on antenna tracking time metrics. Due to the iterative nature of the resource allocation negotiation, missions are generally very conservative in their requests for coverage time, reducing the overall effectiveness in using the network.

In the era of interplanetary CubeSats, it is important to improve the communications and tracking efficiency between the spacecraft and the ground network, so that missions can fulfill their communications and tracking needs but with shorter passes. This would help to create “wedges” or gaps of reasonable length in the antenna-tracking schedule of the network. These gaps would be ideal to provide scheduling opportunities and demand access opportunities for interplanetary smallsats/CubeSats. This concept can be illustrated pictorially in Figure 14. Consider a ground station that is in view with three spacecraft along a given timeline. A conservative planning approach based on view periods only typically schedules a pass based on worst-case data rate at minimum elevation angle. This approach results in poor network utilization and the antenna can support two tracks of one spacecraft. If the planning takes into account the link capability and the data return requirement, shorter passes can be used to return the same amount of data. This approach results in good network utilization and the antenna can support two tracks of two spacecraft.

Similarly, using advanced communication strategy like adaptive data rate can further improve the link usage efficiency, and the same antenna timeline can support two tracks of three spacecraft.

To achieve higher efficiency, we investigated a network planning and scheduling concept that integrates link capabilities and telecom performances with scheduling. This approach in general provides better link configuration and schedule timing information, which results in more favorable elevation angles and higher supportable data rates,
thus requiring lesser track time per spacecraft on the average and enabling the network to support more spacecraft. This approach would require missions to provide more information on their pass-by-pass data delivery and tracking requirements and their operation constraints, and to allow flexibility in the scheduling of the passes.

To realize the aforementioned network efficiency, network planning and scheduling needs to take into account the pair-wise link capabilities between network antennas and spacecraft when they are in-view with each other. The above network planning and scheduling concept was studied extensively in [24] and [25]. In this paper, the network planning and scheduling scenario is cast into a constrained-optimization problem that minimizes antenna tracking time of the network, and at the same time meets the data delivery and tracking requirements and the science and operation constraints of the spacecraft.

**Case 1: One antenna per site**

In [24], we consider the simple case of including only one antenna in each of the three DSN sites, and each antenna only supports one spacecraft at a time. This problem formulation optimizes the start-time and end-time of each pass, which are all continuous variables. In this case, straightforward constrained-optimization scheme like sequential quadratic programming (SQP) can be employed to solve the problem. The mathematical formulation and analysis details can be found in [24].

![Ground antenna usage efficiency](image)

**Figure 14. Ground antenna usage efficiency.**
We use the following example to illustrate the above analysis method. We consider a communication network consisting of three ground tracking stations and six orbiting satellites for demonstrating purposes. One could assume any other communications network of various sizes. The satellites move in three-dimensional elliptical orbits. Positions of the ground stations and the satellites are then simulated using our orbital mechanics tool, which is built upon the Keplerian framework. Based on their geometry and communications configurations, a set of time-dependent supportable data rates are generated for a period of 24 hours and are displayed in Figure 15.

By assuming each pass must constitute at least 20 minutes in length, there are exactly 31 passes. As a result, due to different constraints discussed in [24], there are 67 overlapping passes. For simplicity, we assume the data volume required for satellites 1 through 6 are as follows:

<table>
<thead>
<tr>
<th>Sat1</th>
<th>Sat2</th>
<th>Sat3</th>
<th>Sat4</th>
<th>Sat5</th>
<th>Sat6</th>
</tr>
</thead>
<tbody>
<tr>
<td>16200</td>
<td>26420</td>
<td>39880</td>
<td>28560</td>
<td>65080</td>
<td>48880</td>
</tr>
</tbody>
</table>

Numerical results are displayed in Figure 16, where the darkened areas signify the optimal scheduling to meet the all objectives. In this example, we demonstrate that by using the aforementioned link-driven network planning approach, we achieve the following goals:

1. Meeting or exceeding the required data volume requirements.
2. Minimizing communication time and thus making full use of all the passes.
3. Satisfying the one-to-one-basis communication constraint between ground station and spacecraft.
Figure 16. Supportable data rate for a communications network of three ground stations and six satellite orbits.

Case 2: Multiple antennas per site

In [25], we tackle the general problem of a network with multiple antennas within a site. This scenario is more in-line with the current configuration of the DSN. The problem formulation for this scenario is more challenging than the “one antenna per site” scenario in Case 1, as each antenna-“spacecraft pass” pair defines a tracking pass and contributes two dimensions in the search space, one for the start-time and one for the end-time. In addition, we need to define an integer variable that is an identifier of the ground antenna at the DSN site. This leads to a mathematical formulation based on Mixed-Integer Programming (MIP), and the analysis details can be found in [25].

We introduce a two-step approach to solve the constrained optimization problem. An analytical method like sequential quadratic programming (SQP), which is implemented in the FMINCON function in MATLAB, is a deterministic optimization process that requires updating the Hessian of the Lagrangian at every iteration. Like all gradient schemes, depending on the objective function of the problem and the initial guess, the iterative solution could converge to a locally optimal solution (a sub-optimal solution). Moreover, the SQP process can be time-consuming; therefore, it is important that the initial guess is selected cautiously. In this paper, we propose to use the Particle Swarming Optimization (PSO) method to construct the best possible initial guess before feeding it to the FMINCON algorithm. The PSO method starts by using the Monte Carlo method to generate randomly a set of $n$ feasible solutions (called particles) with uniform distribution between the upper and lower bounds. One can imagine that every particle in the PSO scheme is a bird soaring over the feasible domain. As it flies, each bird keeps track of its personal best (local) solution as well as the flock’s best (global) solution, and tends to gear towards those directions. Thus the next iterative solution is constructed by perturbing its current location and velocity plus two small, but random (uniform distribution) pushes, one towards its personal best and the other towards the flock’s best. The PSO method provides an efficient and yet easy-to-use approach that heuristically constructs a feasible starting guess (the best among the locations the flock have been through).

PSO shares many commonalities with the Genetic Algorithm (GA), such as generating random initial guesses, and searching for the optimal solution by computing and comparing the values of the objective function. While all chromosomes in the GA share the search information with each other (with $O(n^2)$ complexity), each PSO particle shares only its personal best and the flock’s best (with $O(n)$ complexity).

In most cases, the schedule attained by the PSO algorithm is very close to the global optimal and thus the SQP process converges effortlessly. The PSO method is extremely fast because it requires only the evaluation of the objective function (no gradient approximation). Figure 17 illustrates pictorially the update process of the PSO algorithm.
Figure 17. Particle swarm optimization (PSO) concept.

For the proof of concept, we consider 20 spacecraft passes that are in view with a DSN site with three antennas over a period of 72 hours. As shown in Figure 18, the ground stations typically see multiple spacecraft at any one time. The supportable data rate profiles of the spacecraft-ground station pairs can vary greatly due to the different link configuration, range, and weather condition as seen by each pair. The dotted vertical lines over any view periods signify the regions where overlapping view periods occur. Our objective in this simulation is to optimally assign for each view period the optimal start time and end time so that (i) the achieved network data throughput is maximized, (ii) the individual mission data volume requirements are met, (iii) each ground station supports one spacecraft at any one time (non-overlapping pass), (iv) each pass must be sufficiently long to ensure efficient usage of a ground station, and (v) each pass must start and end within its bounds. The dimension for the search space is 60 in this scenario. There are 20 linear bounds, 60 upper bounds, 60 low bounds, and 23 nonlinear constraints (3 non-overlapping and 20 mission data volume). In seeking an optimal solution, the PSO algorithm is used with 200 randomly generated particle elements. The process for both PSO and FMINCON with 200 iterations takes about 2482 seconds.¹² Note that the computation of the nonlinear constraints is time consuming. The results of the optimal schedule for the three ground stations are displayed in the lower plots of Figure 31. The blue lines indicate the view periods and the red lines indicate assigned passes after the scheduling. The achieved data volume for each scheduled pass is also shown. The optimal results contain passes that includes the entire view-period with respect to a single spacecraft, as well as passes generated by the constrained optimization scheme that de-conflicts and splits the overlapping view periods into disjointed time intervals, each assigns to a spacecraft.

¹² Using a laptop in 2011.
As observed in the lower plots of Figure 18, the network is able to support all 20 spacecraft passes and meet their data return requirements. There are a number of sizable time gaps available within the 72-hour timeline to support other spacecraft.

VII. Concluding Remarks and Future Trends

In this paper, we discuss the next-generation ground network architecture and its evolutionary path for communications and tracking of interplanetary smallsats (which includes CubeSats). We describe the unique characteristics and needs of interplanetary smallsat missions, and detail the ongoing development in CubeSat-compatible radios and high-gain antennas. We then outline various approaches to streamline and to upgrade the current DSN capabilities and processes, and describe new techniques for simultaneous tracking of multiple spacecraft by a ground antenna. We also provide preliminary thoughts on the DSN operation concept and its interfaces with non-DSN antenna facilities and missions, and we discuss the multimission ground data system for interplanetary smallsats. An interim version of this paper was published in [23].

Moving forward starting with the planned 2018 SLS launch to the Moon, we expect a large number of interplanetary smallsats that piggyback on and deploy from lunar and deep-space launch vehicles. As the science goals of interplanetary smallsat missions become more challenging, we anticipate the following advances in communications and tracking technologies that would help to fulfill smallsat mission needs:

• **Miniaturization of flight system components.** Traditional flight components will be miniaturized, and this includes software-defined radio transceivers, antennas, and atomic clocks. Recent advances in flight hardware allow the use of complex and stable signaling schemes for efficient deep-space communications and tracking [11] as well as enabling telecommunication science [42]. High-precision, miniaturized attitude control systems will also be
needed to point the high-gain antenna and instruments.

- **Migration to higher frequency.** Instead of the UHF-band and S-band frequencies that are commonly used in today’s LEO CubeSat missions, Ka-band and optical links are being considered for use in interplanetary smallsat missions [2,26] to increase the data rate and to alleviate the spectrum congestion problem.

- **Deep-space multiple access schemes.** The variety of MSPA schemes discussed in this article can be considered as the near-term solution that provides simultaneous tracking of multiple spacecraft. In the longer-term future, more versatile and efficient multiple access schemes would be needed. One consideration is to upgrade the current code-division multiple access (CDMA) scheme that is technically mature in the terrestrial wireless environment to operate in the deep-space environment, which is characterized by low signal-to-noise ratio, high dynamics, and a requirement for navigation tracking support. Recent studies indicate that this approach is promising [27,28].

- **Multi-hop communications.** Some recent interplanetary smallsat mission concepts call for a fleet of smallsats, with one or more mother ships that serve as in situ communication nodes that relay data to and from Earth [4,29,30]. This necessitates the development of novel protocols and routing schemes for a dynamic space network to ensure reliability and efficient data delivery from the smallsats to Earth.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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