Optimizing SmallSat Scheduling for NASA's Deep Space Network

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Abstract

NASA's Deep Space Network (DSN) is a unique facility responsible for communication and navigation support for over forty NASA and international space missions, and ground-based science users. For many years, demand on the network has been greater than its capacity, and so a collaborative negotiation process has been developed among the network's users to resolve contention and come to agreement on the schedule. This process has become strained by increasing demand, and is threatened to be overwhelmed by the planned support for dozens of smaller satellites that will be carried as secondary payloads on future deep space missions. The first such mission is EM-1 in 2018, which will deploy about a dozen SmallSats during its flight. In this paper, we consider ways to incorporate these missions into the DSN scheduling process in a way that meets user requirements but minimizes the effort required of the SmallSat community, while maximizing the efficient use of DSN assets. We propose and evaluate two alternative strategies: one based on opportunistic gap fill, the other based on aggregating missions into blocks that can be manipulated and managed as single pseudo-spacecraft. The latter approach offers scalability and flexibility that strongly recommend it for implementation.

Fig. 1: A 34-meter antenna at the Goldstone Deep Space Communications Complex in California.

1. Introduction

NASA's Deep Space Network (DSN) consists of three communications complexes, located in Goldstone, California; Madrid, Spain; and Canberra, Australia. Each complex contains one 70-meter antenna and three or four 34-meter antennas. These ground antennas are responsible for communications and navigation support for a wide range of scientific space missions, from those in highly elliptical earth orbits, to some beyond the solar system. In future years, DSN will also support human missions to the moon and beyond. The placement of the three DSN complexes allows at least one of them to be in view of any distant spacecraft at all times (Imbriale, 2003).

In the past, most missions that use the DSN have been supported by relatively large US or international operations teams. These teams generally support dedicated schedulers who engage with DSN to define telemetry, tracking, and commanding requirements, and then ensure that the schedule reflects the ongoing needs of the mission. In recent years, the rise in popularity of smaller missions, generically called "SmallSats" have led to plans for a larger number of smaller missions with specialized science objectives, see e.g. (SpaceWorks Enterprises, Inc., 2017). These missions are much less expensive and are supported by smaller operations teams, such that dedicated DSN scheduling personnel may not be an option.

The first influx of deep space SmallSat missions into the DSN is planned for Exploration Mission 1 (EM-1), scheduled for launch in late 2018 as an uncrewed circumlunar flight of about three weeks duration. At several points ("bus stops") during the flight, the vehicle will eject groups of cubesats, for a total of 12 that will be supported by the DSN in S- and X-band. This one mission will increase the number of DSN-supported spacecraft by about 40%!

The current DSN scheduling process is lengthy (with a lead time of around four months) and labor intensive. It relies on peer-to-peer negotiation for changes, with frequent proposals and counter-proposals, and so it is a major challenge to add a large number of new missions without impacting the current mission users. This calls for new approaches for scheduling SmallSats that minimize the impact on the SmallSat teams, as well as on the missions and teams that are current and ongoing DSN users. At the same time, it is important to satisfy mission tracking and telecommunications requirements to the greatest extent possible. We have investigated two novel approaches to this problem:

- *opportunistic gap scheduling*: exploit the presence of unavoidable gaps in the schedule to insert SmallSat passes, potentially on very short notice relative to execution
- *block scheduling*: define and schedule one or more "pseudo-spacecraft" that are aggregates of multiple individual spacecraft, then decompose the blocks back into individual spacecraft activities

In the following (Section 2) we first briefly describe the DSN scheduling process, and then some of the factors that come into play as SmallSats are included in the DSN processes (Section 3). Investigations of two different approaches for scheduling SmallSats are then presented and discussed (Section 4), followed by conclusions and directions for future work (Section 5).

2. DSN Scheduling Process Overview

DSN scheduling differs from the other NASA networks in large part due to the operating characteristics of most of its supported missions. Deep space missions typically do extensive advance planning, to the point of building detailed command sequences that are uploaded days to weeks ahead of execution, reflecting a range of mission phases, science events, and engineering activities. Additionally, there are extensive checks on these plans and sequences, as an error can be catastrophic. Long light travel times preclude extensive real-time interaction. As a result, the DSN schedule is baselined months ahead of time, with changes occurring only when agreed to by all involved.

The DSN scheduling process (Johnston et al., 2014) operates on a rolling weekly basis: as the deadline for a week approaches (roughly four months before the start of the week), mission scheduling representatives enter the requirements for that mission into the Service Scheduling Software, or S^3 (Johnston et al., 2012). Once all inputs for a week are in, they are integrated into a single schedule and the DSN Scheduling Engine (DSE) (Johnston et al., 2010), is run to deconflict as much as possible, given any specified flexibilities in the input requirements from each mission. In practice, little flexibility is allowed, and the net oversubscription level means that many conflicts necessarily remain in the schedule.

Once the scheduling engine has been run, and conflicts reduced automatically as much as possible, a human scheduler called "Builder of Proposal", or BOP, starts to work on the schedule and makes further changes based on experience and background knowledge of each mission's requirements. These changes include: deleting some activities, shortening tracks below their specified minimums, splitting tracks flagged as unsplittable, and placing the (now shorter) segments into gaps in the schedule. This a time-consuming and labor-intensive process, requiring a great deal of familiarity with the entire DSN mission set and their typical requirement patterns and unstated flexibilities. The BOP can generally eliminate hundreds of conflicts, but at the end there usually remain 10-20 conflicting activities. At the conclusion of the BOP phase, the week is released to the full set of mission scheduling representatives to negotiate the remaining conflicts and to make any adjustments to changes introduced by the BOP. In this phase, individual mission representatives collaboratively negotiate peer-to-peer to reach a state where all users are agreed (Carruth et al., 2010). In this process, one user will propose a set of changes, to which all affected users must concur before it becomes the new baseline. If any user disagrees with the changes, it falls on him or her to counter-propose an alternative, with a justification (where just undoing a previous proposal is not allowed!). This process continues until the deadline is reached, at which point conflicts are either cleared or (rarely) waived, and the schedule is considered baselined and published. From the completion of the automated scheduling run to the baseline conflict-free schedule is typically 2-3 weeks. The overall duration of this process means that multiple weeks are being worked on in parallel, and about 18 weeks are in the pipeline in normal operations, with about 15 weeks negotiated and stable.

3. SmallSats in the DSN

The DSN is currently facing operational constraints that complicate the process of integrating SmallSats into the scheduling process. At present, the network supports approximately 35 missions and science users; this, combined with the limited number of available network assets and the need for antenna maintenance and calibration to ensure reliable service, has led to oversubscription of the network. As SmallSats extend into beyond geosynchronous orbit, they become a new customer base for DSN communications support. When tens of new SmallSat missions are deployed simultaneously, like those expected on EM-1's secondary payload, the load on the already oversubscribed network increases drastically, further complicating the iterative scheduling process.

The current scheduling paradigm is driven by peer-to-peer negotiation at a mission level, and is highly iterative, which poses interfacing concerns for SmallSat teams. Since larger class missions have the financial and personnel resources to plan and negotiate several weeks of DSN schedule at once, they are able to accommodate the long lead times and personnel-intensive nature of the scheduling process. SmallSats are generally very resource limited, and may lack the team members necessary to fully participate in the planning and negotiation of multiple weeks of DSN schedule.

Another concern for SmallSat integration into the network schedule is their relative mission priority. Since missions of all classes are supported by the DSN, SmallSats must compete and negotiate with larger missions in order to secure network time; due to their high-risk status, SmallSats may be seen as intrinsically lower priority, and therefore might struggle to obtain sufficient time to accomplish their science objectives if higher priority missions require network contacts during the same periods. Additionally, their lower priority may restrict SmallSats to use of a limited subset of 34-meter antennas, designated Beam Waveguide 1 (BWG-1), further limiting the available scheduling opportunities as there is only one such antenna per DSN complex. Although new antennas are planned for 2020 and later, they will not provide enough contention relief given the new large missions expected at that time.

SmallSat communication opportunities are also constrained by physical subsystem limitations. Since the spacecraft operate with restricted power, the system's recharge and discharge times will drive when the SmallSat is able to communicate with DSN assets. This characteristic necessitates careful track planning of both forward and return links.

4. Scheduling Approaches

Strategic incorporation of SmallSats into the current DSN scheduling paradigm requires the development and analysis of new process techniques, which can be categorized into tactics which implement new operational techniques or improvements that capitalize on current network inefficiencies. Ideally, integration of SmallSats would use a combination of operational upgrades and efficiency improvements in order to minimize strain on the network and on the SmallSat teams during the scheduling process. This paper explores the feasibility of using efficiency-based gap scheduling and geometry-based block scheduling to integrate SmallSats into the DSN scheduling process (Section 4). Other techniques that have been proposed and investigated include the following:

- Many proposed communications methods for SmallSats rely on convenient geometric alignment of spacecraft; these include the Multiple Spacecraft per Antenna (MSPA) and Opportunistic MSPA (OMSPA) capabilities, which allow simultaneous downlinking by two or more spacecraft that share a single antenna beam (Abraham et al., 2016). These techniques allow for practical communications with multiple SmallSats during deployment, but lose their efficacy once the spacecraft disperse and no longer lie within the beamwidth of a single antenna.
- Another technique that has been proposed to improve the efficiency and reactivity of DSN SmallSat scheduling is that of utilizing "beacon" mode, so that a spacecraft can transmit a tone indicating, for example, that it has science data to send back and that a telemetry pass needs to be scheduled (Wyatt et al., 2016). This has applicability for certain use cases, but will not available for the EM-1 missions.
- Finally, another proposed area that would improve SmallSat integration is based on reducing overhead times between passes. Currently, spacecraft tracks require setup and teardown time before and after each pass, to allow for re-pointing the antenna and reconfiguring and calibrating network assets. With a setup time allocation of 30-60 minutes, and a 15-minute teardown time, reconfiguration adds 45-75 minutes to the total antenna time scheduled for each spacecraft communication activity. However, this amount of time is rarely fully required to appropriately setup and teardown before and after a track, especially if the previous antenna pointing is very close to its new pointing. If reconfiguration times can be optimized, it would allow for more tracking time to be scheduled. While there are other approaches to reducing inter-track overheads, SmallSats with similar telecommunications configurations and small pointing adjustments are ideal candidates for routine reductions in overhead time.

General Tool Development and Interfacing and Test Case Formation

We built an exploratory software package to facilitate examination of the gap and block scheduling paradigms. Functionally, this package interfaces with existing in-house web-based tools, which process mission ephemerides into usable trajectory and link data.

The Geometry-telecom Web Applications Programming Interface (API) provides RESTful endpoints to characterize geometric information of spacecraft and link profiles for various transponders. In this study, we use endpoints that invoke asynchronous calls to programs that evaluate and store azimuth, elevation, and range information from trajectories for a set of lunar orbiters. These programs are executed using a protocol that relies on technologies from widely used web applications and hypertext transfer protocol (HTTP) requests (Johnston et al., 2014). The output of the software is returned in a JavaScript Object Notation (JSON) serialized geometric data are stored as documents in a database capable of storing and retrieving data with non-structured entries.

For demonstration purposes, we created a transponder profile for a radio transmitting at S-band with 7.71W of power and 20.5dB gain. For each trajectory, link profiles for this transponder were constructed at 5 minute intervals within view of each ground asset. When the RESTful endpoint is called to perform link analyses, the link profiles are also stored as documents in our database, and can then be retrieved using HTTP requests. In future studies the link performance results can be used to constrain opportunities for block scheduling.

Our SmallSat scheduling investigation software collects the geometric and link data, and applies them differently based on the desired scheduling paradigm. For gap scheduling, the spacecraft view periods are compared directly to the deconflicted DSN schedule in order to determine overlap between in-view times and unscheduled periods. Block schedule generation uses both the link and geometric information to determine blockable opportunities. This full tool package is ultimately intended to interface with the DSN scheduling engine, S^3 (Figure 2). After a user provides ephemeris data, characteristics of their spacecraft's transceiver, and mission tracking requirements to the tool package, the potential blocking opportunities would be calculated and passed into S^3 as "pseudo-spacecraft" blocks. Following negotiation, S^3 would translate this information into individual SmallSat schedules, which would be integrated into the full DSN schedule. There is also opportunity to integrate gap identification into S^3 to supplement to blocked schedules. Additional information on the gap and block identification process is discussed in further detail in the following sections.

We tested the fitness of the proposed scheduling paradigms by analyzing their application to a test set of lunar orbits, which included the Lunar Reconnaissance Orbiter (LRO), Themis B (THB), and Themis C (THC). These spacecraft were used in place of SmallSats due to the current lack of co-located SmallSat constellations. These spacecraft were analyzed using the aforementioned S-band radio characteristics. At the time of this study, the radio characteristics for interplanetary SmallSat missions were not fully defined; therefore, this model is not a complete representation of the link qualities of a lunar SmallSat. However, link characteristics are not used as a constraint in this analysis, which eliminates the impact of approximating SmallSat communication with this S-band radio model.

Opportunistic Gap Scheduling

The DSN scheduling process incorporates spacecraft communication, science observations, and network maintenance into weekly operational plans; following deconfliction, negotiation, and finalization of a week's schedule, there is invariably unused time available on network assets. These gaps vary in number and duration throughout the year, and are typically more frequent during those times of the year when active users line up predominantly in one part of the sky. The opportunistic gap scheduling method seeks to capitalize on this unused time by planning communication activities in the overlap between a spacecraft's in-view times and network free periods. It has been previously proposed that SmallSats could rely on gap scheduling as their only scheduling method; our analysis sought to determine if this is possible.

Gap scheduling presents multiple benefits to the SmallSat community and to the network: by planning communication activities during gaps in the finalized schedule, SmallSat teams could theoretically avoid the entire resource-intensive peer negotiation process while improving the network's overall efficiency through reduction of unused asset time.

In order to measure the feasibility of gap scheduling,

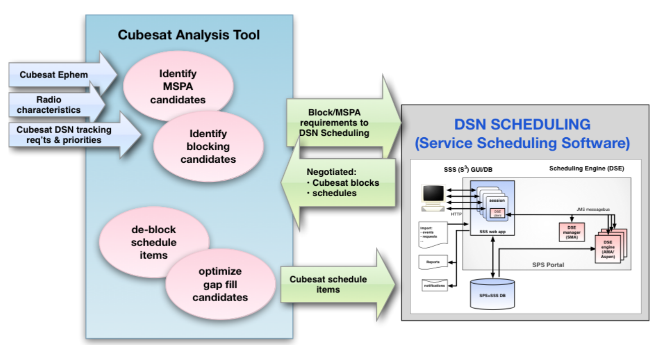


Fig. 2: Potential operational flow for block scheduling as part of a DSN SmallSat operations paradigm

weeks 32-35 of the 2016 DSN schedule were analyzed for gap coverage opportunities, and compared against in-view periods for the Themis B and C spacecraft (THB, THC), and the Lunar Reconnaissance Orbiter (LRO). These three missions are in lunar orbit and are good proxies for the lunar cubesats that will be deployed by EM-1. Schedules for weeks 32 and 34 are shown in Figure 3. Scheduled passes for THB/THC are dark purple, and those for LRO are light blue; other mission activities are shown as faded in the background, and indicate the loading on the network as a whole. Gaps in asset utilization that are also in lunar view are shown as gray boxes.

The entire network schedule was analyzed for gaps that lasted for a minimum of two hours, which would allow for a spacecraft track of one hour, along with reconfiguration time for uplink and downlink. On average, each week contained 4.5 gaps that met this criterion. When only BWG-1 assets were examined, the average gap duration was 1-1.8 hours, with an average number of gaps per week of 9.5. There was high variability observed in the total useable BWG-1 gap time per week, which ranged between 2.5-29.2 hours. The fluctuation in frequency and duration of gaps is evident when Weeks 32 and 34 are compared in Figure 3: although the weeks are proximal in the DSN schedule, communication requirements and view periods within the serviced mission set can change dramatically on a weekly basis, which contributes to gap variation.

To determine the feasibility of gap-only servicing, the resulting BWG-1 gaps were compared against an expected typical SmallSat communication requirement of three tracks per week, each with a two hour total track time. Since the average gap duration ranged from 1-1.8 hours with a total available time per week between 2.5-29.2 hours, it is infeasible to fully service even a single SmallSat in naturally occurring schedule gaps. If the SmallSat were to reduce their required tracks to two per week, or four total hours per week, then one SmallSat could be consistently scheduled, even during weeks that produced minimal gaps. Because of this, it is recommended that gap scheduling be utilized only as a supplemental scheduling strategy for the SmallSat community, since as a primary method it would not be able to service the required number of missions.

SmallSat Block Scheduling

Scheduling tactics that take advantage of geometric spacecraft alignment, like MSPA, are popular options for communicating with multiple spacecraft in a short amount of time. The block scheduling paradigm is an adaptation of this idea: if a group of spacecraft are in nearby areas of the sky, then it is efficient to communicate with all the members of the group in back to back "blocks" by slewing between them. Since the 0.077 degree (4.6 arc-minutes) half-power beamwidth of the 34-meter BWG-1 in X-band

Fig. 3: Lunar View Gaps in DSN Schedule: 2016 Week 32 (top) and Week 34 (bottom). Tracking activities for three DSN lunar missions (THB, THC, and LRO) are shown, as well as lunar gaps in view. Variations from week to week are very large.

(“DSN Telecommunications Link Design Handbook (810-005),” 2017) can encompass 15% of the Moon’s angular diameter (30 arc-minutes), and distant celestial bodies like Mars lie completely within the BWG-1 beamwidth, then opportunities exist to sequentially communicate with some or all of the orbiting spacecraft at one body. Since block scheduling does not require all of the target spacecraft to lie within a single beamwidth, the group’s relative closeness is dictated by the angular separation of the spacecraft from the centroid of the group relative to the ground asset. If a target spacecraft lies within a limited angular distance from the group centroid, then it may be considered “blockable” with other members of the group.

Functionally, the block scheduling algorithm interfaces with the aforementioned geometry and link calculation tools in order to examine the blocking potential of several target spacecraft. The blocking identification process begins when the tool is passed view period times, azimuth, elevation, range, and link parameters for all of the target spacecraft relative to a single ground antenna. The scheduling user also provides the desired schedule week for analysis, a maximum allowable angular distance for blocking, and any link parameter requirements, such as minimum data rates. The tool trims all geometric and link parameters to only include view periods that occur within the designated week and possess acceptable link characteristics. Next, the tool compares the remaining view periods for all of the candidate spacecraft, and identifies times when two or more spacecraft are in view of the ground asset. Spherical trigonometry techniques are applied to the geometric characteristics of the in-view spacecraft in order to find the centroid of the group relative to the ground asset, and subsequently determine if the all of the in-view spacecraft lie within the user-specified angular distance of the centroid. All spacecraft that meet the angular distance criterion are classified as “blockable”, and their data are saved into block-based structures and passed into the DSN scheduler. The flow diagram of this process is shown in Figure 4.

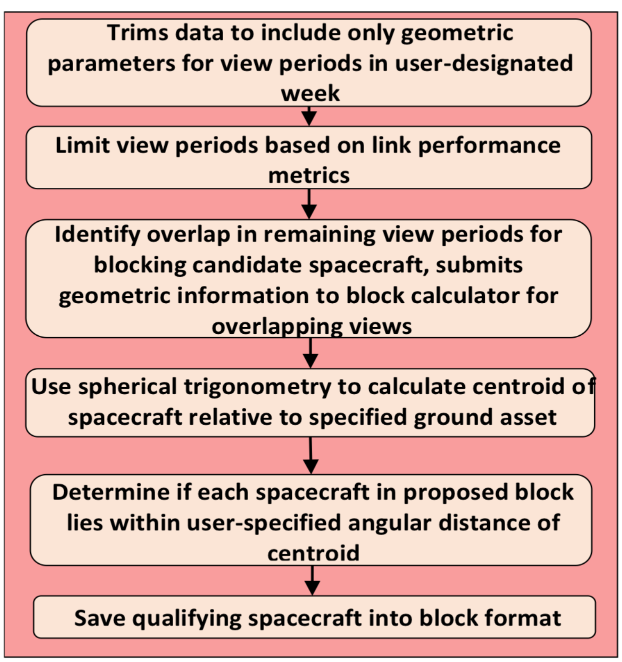


Fig. 4: Block Scheduler Algorithm Flow Chart

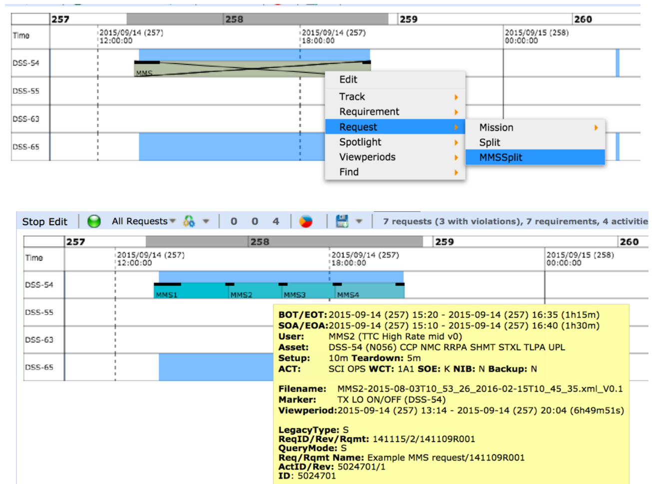
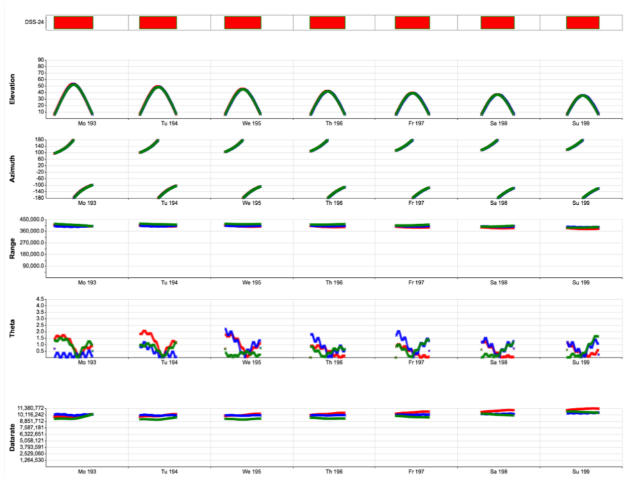


Fig. 5: MMS “Pseudo-Spacecraft” Track Splitting – before (top) and after (bottom) MMSSplit

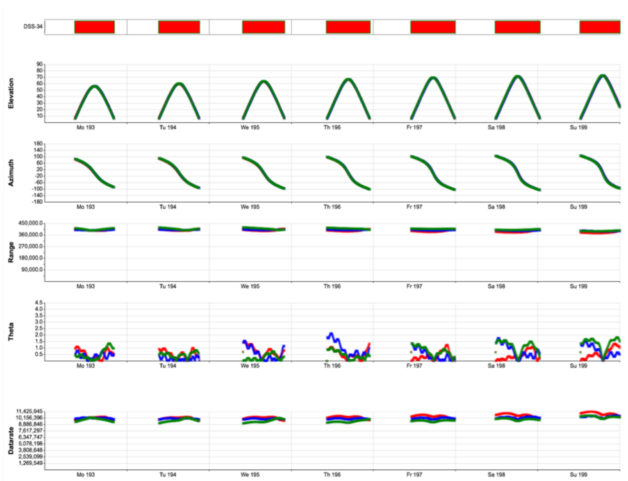
The block scheduling paradigm is of particular interest due to its potential to increase the efficiency of the network and streamline the integration of SmallSats into the current scheduling process. By scheduling back-to-back spacecraft tracks, the overall overhead time needed to reconfigure the network can decrease significantly. Initial setup times for the first spacecraft in the block would still lie between 30-60 minutes, and after tracking the first blocked spacecraft, only fifteen minutes would be necessary in order to slew and transition between each subsequent spacecraft. A blocked track would finish with the traditional 15-minute teardown time. If a SmallSat constellation of six spacecraft could be blocked together, then a total configuration time of 135 minutes would be needed for a 45-minute setup, five 15-minute transitions, and a 15-minute teardown; this blocked configuration time is equivalent to the current time necessary to reconfigure the network for two traditional spacecraft tracks and represents a reduction by a factor of 2-3 over the unblocked overhead time. This degree of reconfiguration time savings has the potential to significantly increase the overall efficiency of the network.

Another possible benefit is the ability to reduce the team personnel resources required for SmallSats to participate in the DSN scheduling process. All of the SmallSats that are “blockable” can be included into the scheduling process as a single “pseudo-spacecraft”, which would allow for a single “pseudo-mission” to represent the aggregate communication requirements of multiple SmallSats during initial formation of each week’s schedule. This “pseudo-mission” scheduling paradigm is currently supported for the

DSS-24:



DSS-34:



DSS-54:

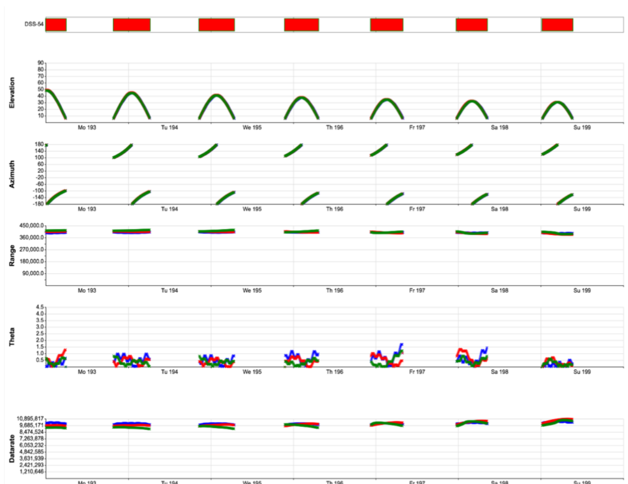


Fig. 6: Lunar mission blocks for BWG-1 antennas at Goldstone (DSS-24), Canberra (DSS-34) and Madrid (DSS-54)

Magnetosphere Multiscale (MMS) team, who plan and negotiate tracks for the four MMS spacecraft as a single chunk of time. The current DSN scheduling engine employs the MMSSplit funtion to split these "pseudo-spacecraft" time blocks into individual tracks based on the requirements of the spacecraft within the "pseudo-mission", as seen in Figure 5. Since this technology is already implemented within the scheduling engine, it is straightforward to apply the "pseudo-mission" paradigm to blockable SmallSats. Because only a single mission representative is necessary to engage in scheduling, implementing "pseudo-mission" blocks decreases the number of missions that have to fully participate in the iterative scheduling process, which will reduce the logistical strain while encouraging SmallSat teams to strategically pool their resources and efficiently negotiate for DSN time.

Potential drawbacks of the block scheduling approach stem from the technique's reliance on geometric proximity. Since the spacecraft must be co-located for block scheduling to be affective, this tactic is best suited for scheduling SmallSat constellations, or those that orbit the same celestial body.

The block scheduling algorithm was used to examine the blocking potential of the same lunar orbiter set using a BWG-1 at each DSN complex during Week 28 of 2016 (July 11^{th} – 17^{th}). This analysis assumed a maximum slew distance of 10 degrees, which is a conservative limit given the 0.8 degrees per second slew rate of the 34 m BWG antennas ("DSN Telecommunications Link Design Handbook (810-005)," 2017) and the desired 15-minute transition time. Operationally, this corresponds to a maximum angular separation of 5 degrees between a spacecraft and the blocking group centroid. For this analysis, no additional link parameter constraints were imposed. Finally, the tool creates blocks with a start/stop time accuracy of ±2.5 minutes; this moderate fidelity approach is acceptable for proof of concept testing.

Figure 6 illustrates the blocking opportunities and related information for LRO (in blue), THB (in red), and THC (in green) for DSS-24 at Goldstone, DSS-34 at Canberra, and DSS-54 at Madrid. Within each chart series, the first plot visualizes the duration of the blockable time period per day, and is similar to what would appear in the DSN schedule before the "pseudo-mission" was split into individual spacecraft activities. For DSS-24, the lunar orbiters present daily blocking opportunities with durations of between ten to eleven hours. The next three plots show the elevation, azimuth, and range of the three spacecraft over the course of the week. Since these spacecraft remain in similar positions relative to DSS-24, azimuth and elevation remain consistent for all three orbiters throughout the week, while range exhibits small variation due to the differences in trajectory. The angular separation of each orbiter from the group's centroid is given below the range data, and shows substantially more variability, which is again attributed to the different orbital periods of the three spacecraft. Although the angular separation for each spacecraft varies significantly with time, it does not exceed 2.5 degrees; the maximum observed angular separation of approximately 2.4 degrees is generated by LRO at the beginning of Wednesday's block. This 2.4-degree angular separation indicates the potential for less slewing between tracks within the block, and further reduction in necessary transition time. Data rate is shown on the last plot, and demonstrates the tool's ability to limit block formation by constraining link parameters (not used in this example).

Week 28 lunar orbiter blocks were also generated for DSS-34 at Canberra and DSS-54 at Madrid. The blocking opportunities for DSS-34 are very similar to those observed at Goldstone, with average block durations of 12 and 14 hours. The angular separation reaches a maximum of 2.2 degrees, which corresponds to a maximum slew of 4.4 degrees. Madrid's DSS-54 also presents blocking opportunities in every lunar view period, with an average block duration of 11 hours, and a maximum angular separation of 2 degrees.

These blocking results present powerful opportunities for decreased calibration time and increased network efficiency. If only a single BWG-1 was used, the three lunar orbiters would have approximately 11 hours available for blocking; if a total calibration time of 1.75 hours, which facilitates setup, transition between the three spacecraft, and teardown, is assumed, then 9.25 hours remain for communication activities. This allows for approximately 3 hours of tracking per spacecraft, which would nearly fulfill the 3.5 hour tracking requirements for THB and THC and the 1-6 hour tracking requests for LRO. Due to their power constraints, it is estimated that SmallSat track requests will lie between 1-3 hours, which will be easily accommodated at the Moon given the observed blocking opportunities.

These block durations facilitate reasonable track times when shared between multiple missions, and occur with enough frequency for lunar orbiters that it is possible to meet the weekly tracking requirements of multiple missions through blocking alone.

As noted above, the regular DSN user MMS, a constellations of four spacecraft that traverse the Earth's magnetosphere, already has the capability to block schedule. Future constellation missions (whether SmallSats or not) could also make use of this, and such blocks could facilitate the entire scheduling process by providing flexibility in time, asset assignment, and the efficient splitting of shared time among limited resources.

Operational Recommendations

Based on analysis of four weeks of the DSN schedule, gaps do not occur with enough duration, frequency, and consistency to sustainably service multiple SmallSat missions. However, the gap scheduling process may provide a useful supplement to the conventional scheduling process if last-minute tracking activities are necessary.

Due to the frequency and duration of calculated lunar blocking opportunities, it is recommended that block scheduling is pursued as an operational paradigm for SmallSat scheduling. This method has proven applicable for lunar orbit, and will translate naturally to SmallSat constellations located at other celestial bodies. Block scheduling also possesses the potential to substantially decrease the configuration overhead currently experienced by the network, which will benefit the entire DSN community through increased efficiencies. Blocking also facilitates the rapid integration of multiple missions into the scheduling process through use of the "pseudo-mission" configuration; this allows the SmallSat community to participate in iterative schedule negotiation with fewer resources, and to micro-optimize the placement of SmallSat activities within the allocated blocks.

5. Conclusions

In this paper we have explored two potential options for adapting the DSN scheduling process for the coming wave of SmallSats that will use the DSN large aperture antennas for communication and tracking. We have shown that a *gap filling* strategy has the potential to support late-breaking non-impacting changes, but it does not scale to the levels needed. In contrast, a *blocking* approach, while more complicated, could be used to make a large efficiency improvement for co-located spacecraft, and ensure that adequate service time is included in the schedule. It would further allow for flexibility among the SmallSats as a group.

Further work is needed before either of these approaches is ready for operations:

- gap fill requirements, interfaces, and processes need to be defined and implemented
- blocking criteria and tools need to be developed that can be used routinely to include as requirements in the DSN schedule, and processes and policies for negotiation and priorities need to be defined (Fig. 2)
- de-blocking strategies and tools need to be further developed, to partition the negotiated time and allocate back to the individual spacecraft

- SmallSat communication system models need to be tested and link constraints need to be implemented to refine blocking opportunities

Further investigations will address how best to combine these approaches in a flexible but effective manner.

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