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Autonomous Multi-Mission Orchestration for Small Satellite Constellations

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ABSTRACT

The accelerating proliferation of space vehicles in LEO presents a significant operational and security challenge in coordinating operations between vehicles and across constellations. The growing operational complexity demands a reliable automation approach capable of orchestrating multiple agents, potentially across different domains. No longer is it sufficient to automate a single vehicle in isolation since many of the tasks being conducted by these constellations require cross-schedule coordination. To address the current operational demands and limitations, the Multi-Mission Orchestrator, or MMO, provides a methodology and framework for coordinating space vehicle operations and secure data transfers across heterogeneous constellations and even multi-domain systems of systems. MMO removes the operational planning demand that would otherwise be placed on a team of operators and automates the day-to-day scheduling. It abstracts the detailed mission tasks into an intuitive framework while also leveraging quantitative mission utility and security assessments using a zero-trust approach. The optimization engine within MMO selects operations for every space vehicle within the system to result in an operationally feasible and secure constellation schedule. This paper describes the planning concept, outlines the underlying key elements enabling MMO, and analyzes the performance realized when using MMO to plan cross-schedule operations for collecting and ultimately, securely delivering mission critical data sets.

INTRODUCTION

Ongoing investment in proliferated satellite systems and the desire to conduct space operations across disparate constellations has introduced new complexities within the mission planning community. The challenges posed by operating hybrid space system architectures across military, civil, and commercial satellite constellations can be addressed with new and novel techniques of automation. Now the mission planning problem is not simply how to operate a collaborative group of satellites together but how to plan operations for a collaborative group of constellations. SDA, NASA and other government entities are currently looking for improved ways of performing missions using resources they own as well as utilizing additional capacity provided by other distinct constellation systems, which they can contract with.

Such an operating model can provide surge capacity in times of increased need as well as offload operations during times of system outages or other anomaly resolution activities. Furthermore, these systems can dramatically increase the overall survivability and sustained operations model during conflict. Within this paradigm, automation will be even more important to effectively conduct the mission and orchestrate the operations across the various systems and constellations.

This paper provides a framework for how to conduct such operations and proceeds by further defining the multi-mission orchestration problem (reference Figure 1), highlights Viasat's proposed solution framework, and then wraps up with an example scenario result and conclusion.

Related Work

A tremendous amount of research has been dedicated to various elements of the constellation planning problem. Some have developed methodologies for integrating multiple types of tasks into a single framework for situationally aware operations.[1-6] Others have focused on the data collection elements of the problem.[7-14] While still others focused on how to move data through the system for delivery to end users.[15-20]

Within all this research, a multi-mission planner is somewhat elusive in that a fully compatible methodology is not obvious. To address these limitations with planning operations across different constellations, as well as ensuring whole data set delivery, Viasat offers the Multi-Mission Orchestrator. The sections that follow will outline this planning methodology for various task types and then provide a realistic mission example to illustrate how it performs.

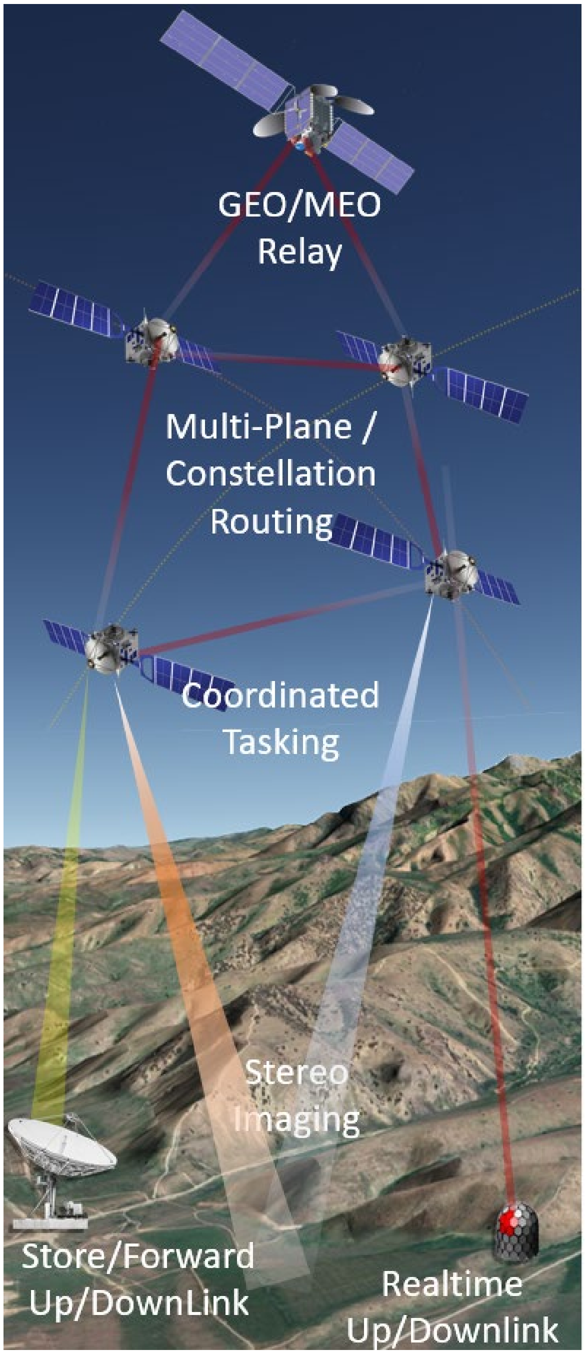

Figure 1: Multi-Mission Orchestrator Operations

AUTONOMOUS PLANNING FORMULATION

Viasat's MMO provides a tractable approach to solving the multi-mission planning problem and leverages experience and lessons learned in previous multi-agent constellation planning research. The base formulation is a re-invention of published works that dealt with in-schedule, and cross-schedule autonomous constellation planning.[1,2] The updated implementation removes the dynamic resource variable constraint to speed solution discovery without sacrificing ultimate performance and applies it to other agents within external constellations. The subsections that follow provide a brief description of the fundamental approach used in MMO.

Constellation Planning Approach

As the number of satellites within a constellation increases, the operational planning problem complexity compounds due to the spatial and temporal dependencies present within the constellation's operational environment and the limited resources onboard each vehicle. Ensuring a feasible, flight-worthy plan for every satellite within the system being planned is critical to sustained and autonomous mission operations.

As mentioned earlier, the Multi-Mission Orchestrator is built on previously proven constellation planning concepts that rely on a graph-based formulation where nodes in the graph represent discretized time steps within tasks and edges represent transitions between those tasks. If two nodes are connected with an edge, it means a feasible transition exists between that location in time. In-depth details regarding this graph-based formulation are provided in [2] and simplified in Figure 2 that shows two satellites traversing a graph.

At its core, the Multi-Mission Orchestrator finds optimal paths through the graph that maximize mission utility while not exceeding any specified vehicle or mission constraints. Utility in this case refers the difference between the score of performing a task relative to the cost associated with doing so. For instance, collecting an image of a high-priority target generates a large score that is then weighed against the cost of satellite resources like slew time, power consumption, or other factors. Mission constraints address both limitations within individual vehicles (e.g., slew rate) as well as constraints associated with preferred system behaviors. Some of these constraints guide the planner to avoid situations where multiple satellites perform the same operation (e.g., imaging the same target) or to limit the number of times a communications window can be assigned to a single satellite asset.

Additionally, the planner considers how one decision may affect subsequent decisions available to a satellite. This approach is applied constellation-wide to yield the best schedule possible for the mission. The output of the planner is a timed list of operations for every satellite involved within the planning horizon.

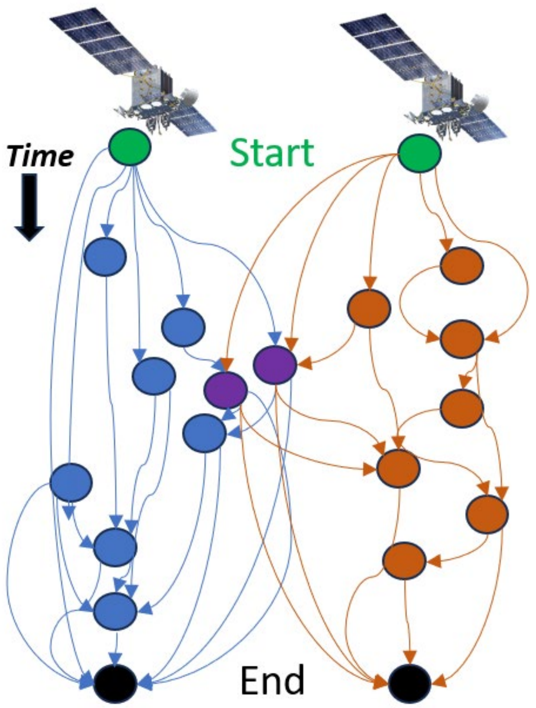

Figure 2: Graph-Based Planning Framework

Integer Linear Program Conversion

With a graph set for the constellation, it is then necessary to convert it into a linear program to facilitate solving a constellation level schedule of operations. During the conversion process, key constraints are applied to the nodes and edges to help realize specific behaviors within the system. These constraints include the following:

- **Flow Constraint** – this constraint ensures that each satellite begins at the start node and reached the end node. Applying this constraint ensures that every node entered is also exited until reaching the end node.
- **Resource Constraint** – this constraint was originally applied to ensure data storage was respected within each vehicle but can be used to track fuel or other consumables, depending on the mission and associated tasks.[2]
- **Cooperation Constraint** – this constraint applies to any task requiring more than one satellite to fulfill. For example, a crosslink operation requires coordinated pointing and communication compatibility settings. This constraint ensures if such a task is selected, then both vehicles properly operate in fulfillment.
- **Visit Constraint** – this constraint guides the planner to assign the correct number of satellites to a particular task. For example, the planner may want only a single satellite to be assigned to collect a particular ground target at one time, whereas a long communication window may allow for a single satellite to be assigned to use it multiple times in a very long access period (e.g., LEO to GEO for 60 minutes).

The mathematical definition of the Multi-Mission Orchestrator linear program is provided below as a maximization of mission utility (u) over the constrained optimization space:

$$
\begin{aligned}
&\max_{x} u^T z \\
&s.t.\ Dx = b \text{ (Flow)} \\
&\qquad A_{resource} z = b_{resource} \text{ (Resource)} \\
&\qquad A^{g-co} x = n^{co} \text{ (Cooperation)} \\
&\qquad A^{g-v} x \leq n^{v} \text{ (Visit)} \\
&\qquad x_i \epsilon \{0,1\}\ \forall i \\
&\qquad 0 \leq y_{l,k} \leq y_{l,max}\ \forall l,k \\
&\qquad z = [x^T, y^T]^T
\end{aligned}
\tag{1}
$$

The variables of optimization include two types. The first is a binary variable for each edge, x_i, denoting whether the solution uses edge i. The vector x combines all x_i values. The second type of variable represents the resource available onboard each satellite for each time step and is used to ensure the resource limits are never exceeded. The resource available for satellite 1 at time k is denoted as $y_{1,k}$, with the aggregate vector of all resource values (e.g., data stored) represented as y.

These variables of optimization directly impact mission utility based on the route selected through the graph. Mission utility is a quantitative assessment of the ultimate value of performing a task. This value factors the score of the task as well as the cost associated with its performance. Different scoring methodologies are supported by this implementation and allows targets to be scored based on lighting conditions, weather, last visit time, future opportunities, etc. Similarly, other task types such as communications support factoring the initial data storage on board the vehicle, the value of data onboard, the data rate supported during a particular link, and level of trust or security provided by the link. This flexibility in score and cost assessment provides users with a unique ability to tune performance and planning output based on unique mission preferences and as-planned operational conditions.

This conversion into a linear program provides the ability to specify the graph constraints into linear constraints while also providing unique capabilities when solving. For example, if the primary concern is speed of solution discovery, this approach allows for feasible solutions to be found exceptionally quickly. However, when time allows it also supports for full optimality within the problem space. A detailed development of the flow, resource, cooperation, and visit constraints is provided in previous works [1,2].

Application to the Multi-Mission Planning Problem

This same concept is leveraged when extending it into the multi-mission planning operation. When planning such operations, different levels of insight may exist within the operational systems. For example, some providers may allow users to generate flight commands for vehicles they do not own (e.g., MAXAR and their Direct Access Program) while others may simply allow time windows of availability for utilizing resources like communications (e.g., Viasat's GEO constellation). MMO accommodates both situations, with the detailed command generation being the more taxing situation.

DETAILED DATA TRANSPORT PLANNING

Problem Definition

One key element of the planning methodology implemented by the Multi-Mission Orchestrator, is the ability to allocate communication resources to individual agents for use in data transport operations across constellations. This implementation generates a feasible constellation schedule but treats data (resource) as a continuous flow rather than discrete file-based storage that is implemented on today's satellite operating systems. A natural extension to the planning approach is to further optimize resource allocation by selecting unique files and assigning them to individual communication windows for transfer, thus further improving the utilization of the allocated communication resources, especially when sending data across multiple comm windows. The ultimate intent being to maximize the value of whole files delivered to the ground via downlink, while taking full advantage of the communication windows allocated by the planning system. This file selection problem closely resembles the classic knapsack problem where the files (knapsack items) have both a value and cost (weight) associated with them. The intent is to allocate as many prioritized files as possible to each available window while staying within the bounds of the window durations. The key differentiation of the downlink window file allocation problem relative to the classic knapsack problem is that downlink operations are often dependent on preceding crosslink decisions. The next section will describe our approach to this optimization problem and the solving method employed for the final file allocation strategy.

Transport Optimization Approach

With the communication windows established and assigned to individual vehicles, it is now possible to plan each downlink and crosslink window by identifying specific files to transfer during those time periods. The problem of identifying the optimal mix of files to transfer, and when to perform that transfer, is now examined. Due to dependencies between vehicles during crosslink windows, the problem of file allocation becomes more complicated than a typical downlink planning window where a knapsack problem approach would be valid. This is due to downlink planning being dependent on decisions made during crosslink window planning.

The objective in this transport optimization problem is to maximize the value of files downlinked to the ground while staying within the constraints of each communication window. These constraints include window duration: not exceeding the duration of each downlink and crosslink window and their associated transmission and receive data rates; single route: limiting each file to a single selected path in the network; and file existence: only transmitting a file after it is collected and onboard the satellite. Mathematically this is given by:

$$\begin{aligned} &\max_x v_f^t x \\ &s.t.\ A_{dur} \le b_{dur} \\ &\qquad A_{route} x \le b_{route} \\ &\qquad A_{exist} x \le b_{exist} \\ &\qquad x_i \epsilon \{0,1\} \end{aligned} \tag{2}$$

In the above formulation, v_f is the value to be realized in the optimization for each file downlinked via the decision variable x that specifies the selected route through the graph. The value is only realized when a file is planned for delivery to the ground via some combination of crosslinking and/or downlinking from the satellites. The matrix A_{dur} captures the required transfer duration for each file as it applies to each crosslink or downlink window opportunity and this transfer duration is determined by dividing the data file size by the data transfer rate of the communication link being considered. The matrix A_{route} requires a single transfer route to be selected for each file to avoid duplicative transfer in multiple windows. This constraint captures the relationship between edges of a graph that are mutually exclusive to prevent transferring a file via multiple paths from a single node. The matrix A_{exist} represents the existence constraint and ensures a file is onboard via collection or crosslink prior to being available for downlink to the ground. In this formulation b_{dur} is a vector of time values that represents the amount of time available in each crosslink or downlink window, b_{route} is a vector of 1's that ensures a particular file is transferred through no more than one path per source node, and b_{exist} is a vector of 0's that forces a file to be available onboard a satellite prior to downlinking the file to the ground. The decision variable x_i represents whether edge i is selected (value of 1) or not (value of 0). To fully solidify the concept and application of this formulation, a tractable example is provided in the next section.

Example Transport Plan

An example of the file ID transfer problem is now presented. Consider a total of 10 files, numbered 1 to 10 as illustrated by the green and blue circles labeled F_1 to F_{10} in Figure 1. Each file has an associated cost to transfer, represented as time, and an associated value if successfully planned for downlink. For this problem, the transfer time of a given file via either downlink or crosslink is the same since the data rate within each window is the same. This is done for example simplicity but is not required by the problem formulation. Table 1 summarizes the required transmit time and downlink value of each of the 10 files in this example.

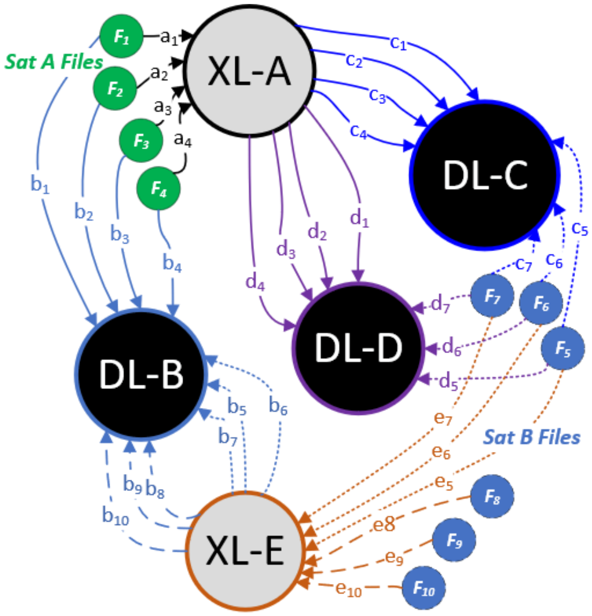

Figure 3: File Routing Example Graph

Table 1: Example File Transmit Time and Value

File ID	Transfer Time	Value (1-100)
1	3 mins	100
2	2 mins	50
3	4 mins	60
4	2 mins	70
5	1 min	100
6	3 mins	50
7	2 mins	60
8	2 mins	70
9	2 mins	100
10	2 mins	50

Constraints are now applied to ensure optimal use of resources. The first constraint is that of ensuring files scheduled for transfer do not exceed the time capacity of each communication window (window capacity). Windows are labeled XL-A, DL-B, DL-C, DL-D, and XL-E in Figure 1 and have time capacity of 8, 8, 6, 8, and 9 minutes, respectively. Using the time required to transfer each file, and ensuring the summation respects the capacity for every window, results in the following set of capacity constraints ($A_{dur} \leq b_{dur}$):

$$\begin{bmatrix} 3a_1 + 2a_2 + 4a_3 + 2a_4 \\ 3b_1 + 2b_2 + 4b_3 + 2b_4 + b_5 + 3b_6 + 2b_7 + 2b_8 + 2b_9 + 2b_{10} \\ 3c_1 + 2c_2 + 4c_3 + 2c_4 + c_5 + 3c_6 + 2c_7 \\ 3d_1 + 2d_2 + 4d_3 + 2d_4 + d_5 + 3d_6 + 2d_7 \\ e_5 + 3e_6 + 2e_7 + 2e_8 + 2e_9 + 2e_{10} \end{bmatrix} \leq \begin{bmatrix} 8 \\ 8 \\ 6 \\ 8 \\ 9 \end{bmatrix} \tag{3}$$

The next set of constraints considered is that a file may only be scheduled for downlink or crosslink at a single time (single transmission). For example, file F_1 should either be downlinked via node DL-B or crosslinked at node XL-A, but not both ($A_{route}x \leq b_{route}$). This constraint is formalized for the example as:

$$\begin{bmatrix} a_1 + b_1 \\ a_2 + b_2 \\ a_3 + b_3 \\ a_4 + b_4 \\ c_1 + d_1 \\ c_2 + d_2 \\ c_3 + d_3 \\ c_4 + d_4 \\ c_5 + d_5 + e_5 \\ c_6 + d_6 + e_6 \\ c_7 + d_7 + e_7 \end{bmatrix} \leq \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{4}$$

The requirement that a file must be onboard a given satellite prior to it being transmitted during a communication window (file precedence) is now specified. This constraint ensures that if a satellite plans to downlink a given file, but does not yet have it onboard, the planner schedules the file for crosslink prior to the downlink window occurring ($A_{exist}x \leq b_{exist}$). This constraint then creates a dependency of operations and is defined for this example as:

$$\begin{bmatrix} c_1 - a_1 \\ c_2 - a_2 \\ c_3 - a_3 \\ c_4 - a_4 \\ d_1 - a_1 \\ d_2 - a_2 \\ d_3 - a_3 \\ d_4 - a_4 \\ e_5 - b_5 \\ e_6 - b_6 \\ e_7 - b_7 \\ e_8 - b_8 \\ e_9 - b_9 \\ e_{10} - b_{10} \end{bmatrix} \leq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

Solving the example problem results in files 1 through 9 (F_1-F_9) being scheduled for downlink per the routing illustrated in Figure 2. Notice that files F_2, F_3, F_4, F_5, F_8, and F_9 were crosslinked prior to being downlinked.

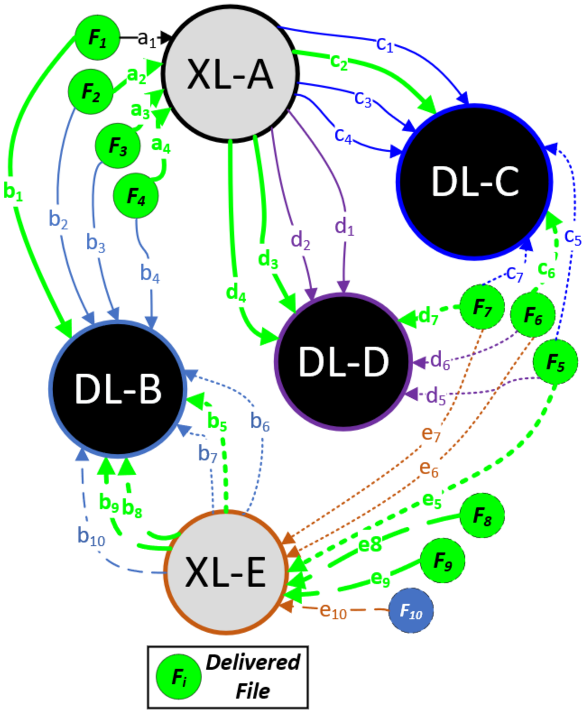

Figure 4: Optimized Transport Plan

This example shows the mechanics of how the transport plan optimization would occur within the assumptions stated while also providing context for how a more sophisticated scoring approach would be leveraged in altering the outcome. For example, if a file had security requirements that prohibited transport to certain nodes or geographic areas, this formulation would route around those nodes to yield an acceptable plan, while still optimizing the objective function specified.

With the multi-mission planning formulation and detailed transport planning approach now defined, we turn our attention to an applied multi-mission planning scenario in the next section.

MULTI-MISSION SCENARIO

Scenario Configuration

To illustrate the capability of MMO, we now introduce a relatively complex mission planning scenario of two (2) sun synchronous Earth sensing satellites and a two-plane configuration of seven (7) satellites, over a period of 194 minutes. The sun synchronous satellites fly in a circular orbit at an altitude of 600 km and have ascending nodes at approximately 11 AM and 2 PM, local time. The other planes are circular orbits inclined at 45 degrees and have altitudes of 810 km (plane 1; 3 satellites) and 600 km (plane 2; 4 satellites). The altitude difference was used to create a noticeable difference in periodicity between the two planes and demonstrate MMO's ability to plan accordingly. Interplane spacing is set at 30 degrees of true anomaly for both planes with the RAAN of plane 1 being 0° and the RAAN of plane 2 set at 60°. The epoch for this scenario is 1 May 2024 18:00:00. A summary of these orbital parameters is provided in Table 2 and an illustration of the scenario is provided in Figure 5. Only two (2) ground terminals are available for use by a single satellite at a time and targets are sporadically located across the Earth's landmass. The modeled downlink antennas are located in Logan, UT, USA and Kingsbridge, UK. All nine (9) satellites in this scenario are capable of both Earth sensing operations, intersatellite optical crosslinking, and direct to Earth data downlink.

Table 2: Example Scenario Orbital Parameters

	Comm Plane 1	Comm Plane 2	SS1	SS2
Semi-Major Axis (km)	6978	7188	6978	6978
Eccentricity	0	0	0	0
Inclination	45°	45°	97.8°	97.8°
Arg of Perigee	0°	0°	0°	0°
True Anomaly	[0, 30, 60, 90]°	[30, 60, 90]°	0°	60°
RAAN	0°	60°	25°	65°

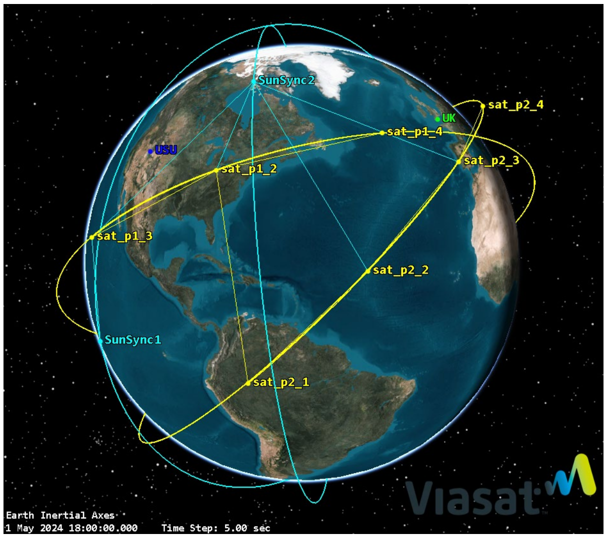

Figure 5: Example Scenario Planned with MMO

Planning Considerations

As previously discussed, MMO attempts to maximize mission utility – a quantifiable measure of task score relative to its cost. Within the scenario discussed, performing Earth sensing operations with high elevation angles, acceptable lighting conditions, and when not competing with ground terminal operations is best. Similarly, crosslink and downlink operations are preferred when not competing with imaging operations, which tends to occur when a satellite is in eclipse. These types of behaviors are encoded into the very flexible utility function of the tasks. This approach to scoring and cost evaluation was implemented for the planning period starting at the orbit epoch and running for just over 3 hours, or two orbital revolutions for the longest orbital period. The next section provides a short explanation of the results observed after running MMO on this scenario.

Results

The results show satellites performing both Earth sensing, crosslink, and downlink operations within the set planning horizon. These operations maximize the mission utility based on the specified scenario conditions, scoring specifications, and associated costs. The resulting mission graph and selected plan for the sun synchronous satellite #1 is provided in Figure 6 while the constellation summary schedule is illustrated in Figure 7. This figure shows the operations being conducted by each of the nine satellites, with correlated crosslink operations lining up in time with the partner spacecraft. The different operations are color coded to identify Earth sensing, crosslink, and downlink. Notice that the ground station terminal usage is deconflicted as part of the MMO planning process due to only a single satellite being able to use that resource at any time. Finally, the resulting file delivery optimization is illustrated in Figure 8 and Figure 9. Any path highlighted red in these figures means that the associated file was transferred over that link, during the associated communication window.

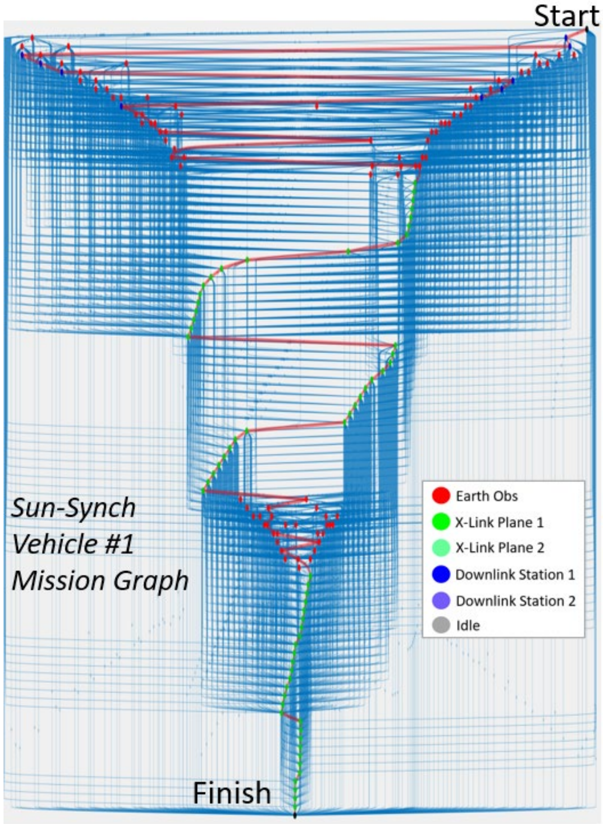

Figure 6: Sun Synch #1 Mission Graph and Schedule

CONCLUSION

Planning complex space vehicle operations across disparate systems of systems presents new challenges to the mission planning community and requires unique approaches to properly orchestrate. Viasat's Multi-Mission Orchestrator can address many of these challenges using a flexible and extensible framework that ensures a feasible schedule can be generated across the participating assets. This paper has illustrated the basic formulation upon which MMO is built and demonstrated the effectiveness of the planner itself in scheduling nine satellites across unique orbital configurations. MMO shows tremendous promise in its ability to leverage the capabilities of heterogeneous constellations and yield a reliable schedule that helps realize the full capability of these systems.

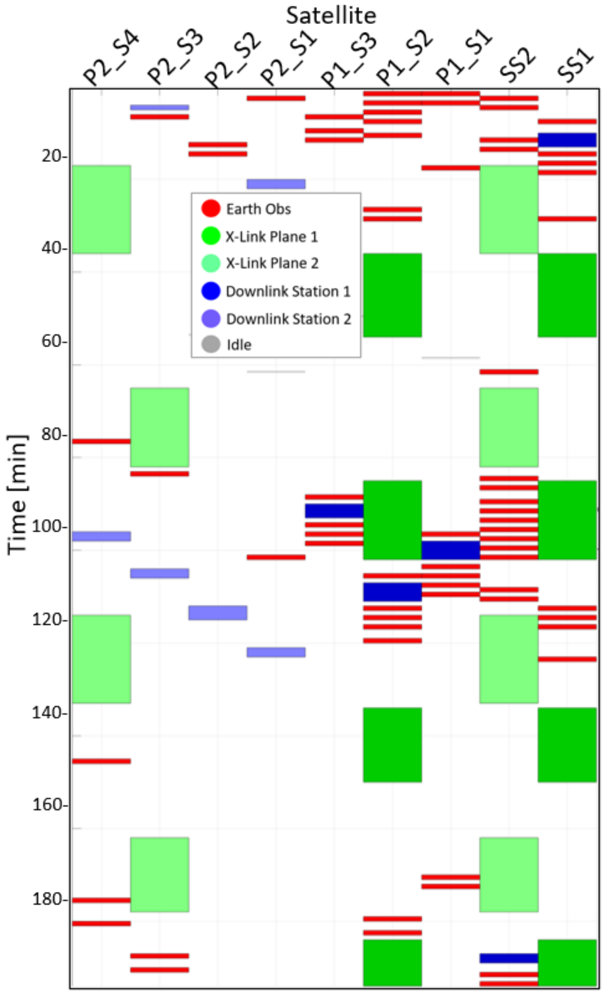

Figure 7: Constellation Schedule Created by MMO

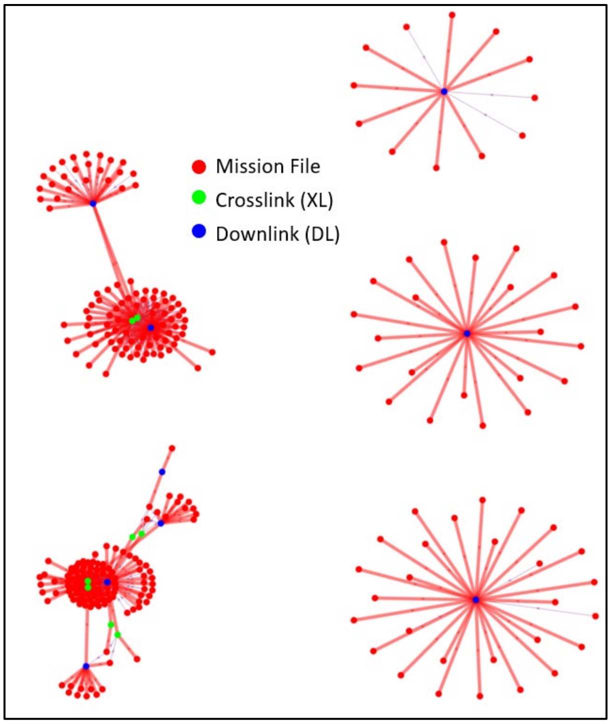

Figure 8: File Delivery Optimization Results

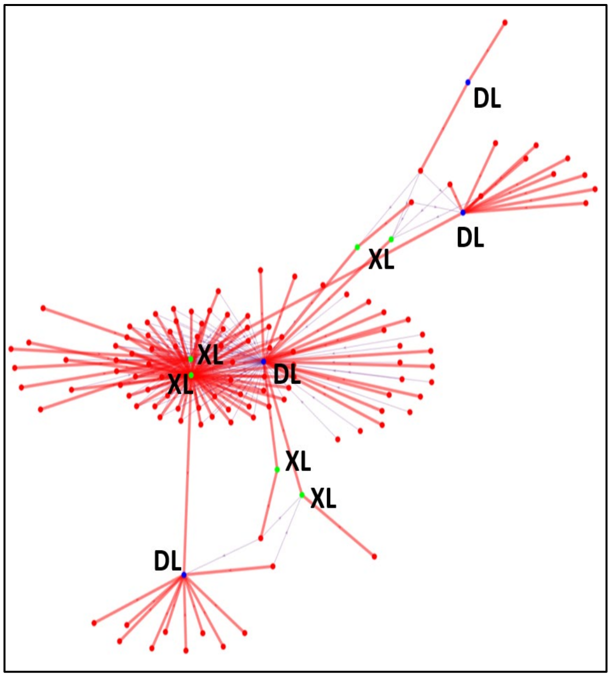

Figure 9: Chained Crosslink (XL) and Downlink (DL) Opportunities for Secure File Delivery

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