AUTONOMOUS NETWORKING FOR ROBOTIC DEEP SPACE EXPLORATION

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ABSTRACT

Networked constellations of small spacecraft are emerging as novel ways to perform entirely new types of science observations that would not otherwise be possible [1], enable exploration of regions of high scientific value and that also could potentially be occupied by future human explorers (i.e., caves) [2], and demonstrate capabilities that will be useful for eventual human-robotic teams on the surface of the Moon or Mars [3]. In this paper, three mission concepts are presented and the resulting mission architectures are described. The first is a low radio frequency observatory involving tens of small spacecraft; the second is a multi-vehicle surface armada involving heterogeneous rovers (scouts, science rovers); and the third is a Lunar or Mars cave exploration scenario. Spacecraft networking architectures are determined by a unique combination of factors, including mission design constraints, mission objectives, autonomy capabilities, and networking capabilities. The combination of two technologies in particular, Disruption Tolerant Networking (DTN) [4, 5] and coordinated autonomy algorithms [6] can be enabling to these types of missions and are a focus for this paper. DTN can be thought of as the internet protocol for space and other critical applications where reliable and automated store-and-forward communications are needed. While particularly useful for long-haul links with large light time delays, DTN is also powerful for automating communication and maximizing throughput even when the communication delays are relatively short between the networked nodes. At the application layer, the ability to plan, replan, and coordinate autonomously among the nodes of the network can be important to achieve mission objectives, lower operations cost, and maximum data return.

1 INTRODUCTION

One aspect of this research is to evaluate the degree to which networked science mission concepts are both feasible and compelling. Towards that end, the development team includes planetary scientists, spacecraft design engineers, and technologists. The design exercises have required development of model-based system engineering models and optimization techniques for networked spacecraft. Two of the three mission concepts, the low frequency array and the cave exploration concept, were designed using these techniques along with simulations to evaluate operability, data return, and operations cost. The purpose of going to this level of depth was to gain more precise insights into feasibility, science value, and technology needs.

2 NETWORKED SCIENCE MISSIONS

Three mission concepts have been developed in detail. Space-based interferometer and cave exploration concepts were developed at much higher fidelity and over the course of roughly 1.5 years each. The study of surface exploration was shorter in duration since the technology needs are somewhat similar to the cave scenario.

2.1 Space-Based Radio Observatory

At decametric wavelengths, there are a number of high priority science observations to conduct, including tracking the radio emission generated by energetic particles in the inner heliosphere due to eruptions at the Sun; magnetospheric emissions generated by the planetary-scale magnetic fields of extrasolar planets, which may provide constraints on their interior structures; and, given adequate sensitivity and control of telescope systematics, the neutral hydrogen signal from the so-called “Cosmic Dawn" or the epoch of the formation of the first stars. Ground-based radio astronomy at some of the required frequencies cannot be done due to absorption from the Earth's ionosphere.

Several recent advancements have enabled a space-based low-frequency array or synthetic aperture telescope. These include small satellite technologies, increased onboard computational capabilities, advances in flight system autonomy, and the emergence of space networking technology. The mission architecture chosen for this study is one mothership with 32 daughterships and a single launch vehicle. The constellation is deployed in a 5000 km lunar orbit for minimal gravitational perturbations from Earth and to lower the radio interference as illustrated in Figure 1. The optimal mission duration is 1 year. This concept can be viewed as an extension to the RELIC mission concept [7].

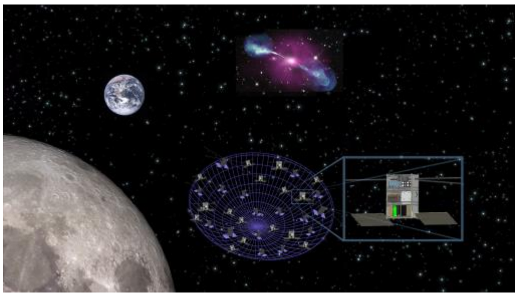


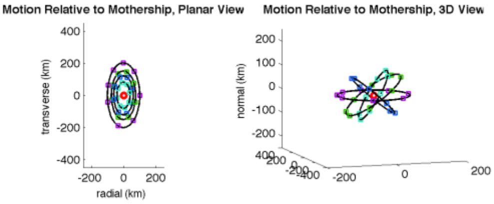
Figure 1: RELIC Constellation Concept.

A range of mission designs were partially simulated with operational constraints in order to derive realistic results. The characterized science measurements were then used as a proxy for the mission science return to identify the most promising mission designs. The ASPEN/CASPER planning system [8, 9] was used to perform the data throughput analysis. For the geometric aspect of the problem of operations planning, the SPICE package [10] was used. Primary evaluation metrics were the Fourier-plane coverage, integration time, and target coverage. Excess unused capacity on some resources (e.g., unused power or bandwidth) was evaluated to detect which parts of a design may be over-engineered and which are the bottlenecks. The duration of crosslink, downlink, and observation activities were inputs to data throughput analysis.

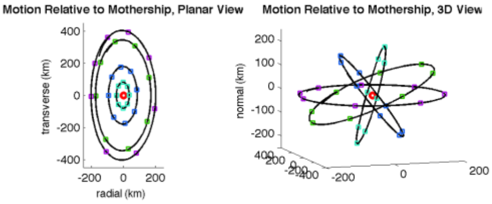
The Fourier-plane coverage also serves as the primary metric for orbit selection. The final design chosen for the orbits is four rings, each with 8 daughterships that have the same period in each ring. The mothership is at the center of the formation. The daughterships deploy from the mothership sequentially to the initial configuration (Figure 2a). After all the science data has been gathered and downlinked to Earth for a specific configuration, the daughterships reconfigure to provide additional Fourier-plane coverage. Such an aperture synthesis is possible due to the relatively static nature of the celestial objects being observed. A total of 20 reconfigurations provide sufficient Fourier-plane coverage. The final configuration is shown in Figure 2b.

A simulation of the instrument was created to analyze its radio image reconstruction capabilities. Figure 3-Left shows an image of a radio galaxy. The reconstructed image shown in Figure 3-Right demonstrates the telescope is capable of providing high-resolution images. The mission operates in an autonomous regime during most of its life. Each daughtership performs a series of maneuvers to achieve the correct orbit and orientation relative to the other assets and maintains that orientation, correcting itself if needed using ranging and telemetry from all other assets in the constellation. The majority of the computations are done at the mothership, leaving the daughterships the role of providing the necessary information and performing the actual maneuvers.

The system is capable of adapting the configuration to interesting transient events, like solar coronal mass ejections, which would require a higher level of autonomous decision making. DTN enables store-and-forward automated data return either direct to the mothership for automated relay to Earth or via-multiple-hops before arriving at the mothership for downlink to Earth. Both scenarios were studied.



(a) Initial Configuration



(b) Final Configuration

Figure 2: Simulated reconfiguration of the daughterships from their initial configuration to the final configuration. In all panels, the configurations are shown in a relative, rotating frame fixed at the mothership, which is represented by the red dot at the origin.

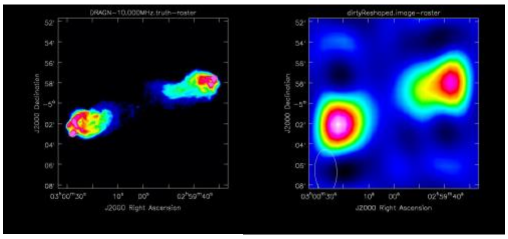


Figure 3: (Left) Input image of a radio galaxy. (Right) Smoothed recovered image (35 minutes of integration, 370km baseline, 15-20 arcsec resolution)

2.2 Surface "Walkabout" Exploration

Networked architectures could enhance the science return of landed planetary missions. Historically, surface rover missions to the Moon and Mars have provided a view of the surface that is restricted to a narrow swath along a lone rover's traverse. As such, these observations cannot be placed within the broader regional geologic context that is critical to interpreting the geologic history of the area. Although orbital data can provide some of this information, it cannot substitute for *in situ* observations. Networked assets synergistically exploring a single surface site could enable broader *in situ* geologic context mapping.

Networked surface missions may allow visits to multiple, high importance regions that may have otherwise been mutually exclusive in a single rover model. As a thought experiment, consider the case of the Mars Science Laboratory Curiosity rover. Curiosity landed ~400 meters to the east of an ancient lake bed named Yellowknife Bay and ~3 km to the north of Mt. Sharp, a ~5 km high layered sedimentary mound in the center of Gale Crater (Figure 4). While Mt. Sharp is the primary science target for the mission, the decision was made to initially drive east towards Yellowknife Bay before turning south. This decision was relatively straightforward because of Yellowknife Bay's proximity to the rover and perceived high science value. But what if Curiosity had landed closer to Mt. Sharp and further from Yellowknife Bay? The decision to visit Yellowknife Bay would have been less obvious, and if Curiosity instead headed straight for Mt. Sharp, some of the most significant discoveries from early in the mission may never have occurred. Exploration by networked assets would enable multipath exploration and limit similar decision-making scenarios in future missions.

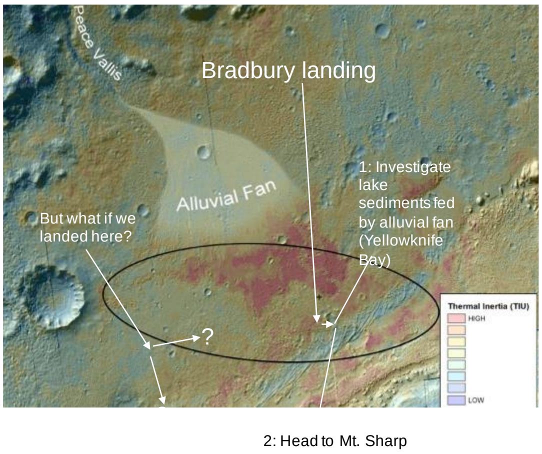


Figure 4: Ability to access multiple sites without a single path restriction.

Generally, the layers of Mt. Sharp were deposited from bottom to top, so the bottom of the mound is composed of older rocks than the top. As Curiosity climbs Mt. Sharp, the rover encounters younger and younger rocks and can therefore track temporal changes that are recorded in the rock record. Because of the high scientific interest in these temporal changes, Curiosity's exploration of Mt. Sharp has largely been vertical. However, orbital data suggest there is also significant lateral variability among some of Mt. Sharp's layers. These variations could reflect spatial changes in primary depositional environments, or they could result from post-depositional processes. Exploration of Mt. Sharp via multiple networked assets could enable simultaneous lateral and vertical exploration and would almost certainly enhance the science return of the mission.

Exploration of a surface site via networked architecture could improve mission efficiency and science decision making. A field geologist will often first perform a "walkabout", or coarse survey, of new a field site before returning to make more detailed investigations at key areas. This technique allows the geologist to efficiently locate regions for resource intensive measurements (e.g., sample collection, in situ instrument analyses, etc.) that will yield the best science results. Both Curiosity and the Mars Exploration Rover Opportunity rover used a walkabout strategy at Pahrump Hills (Figure 5) and Cape York (Figure 6), respectively. Field studies have determined walkabouts generate higher quality science decisions in shorter time frames. Small networked assets with minimal science capabilities could be deployed to perform initial surveys of an area. These would be followed-up by investigations at the best sites by a larger, more scientifically capable vehicle. This could be accomplished via ground control or autonomous coordination between rovers. Follow-up investigations could run in parallel with survey exploration of the next site, improving both mission efficiency and science return.

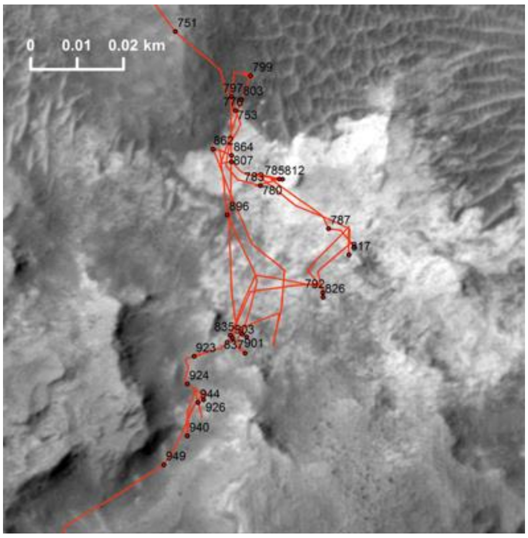


Figure 5: Curiosity at Pahrump Hills

Curiosity completed three walkabouts at Pahrump Hills. The first loop focused on collecting large scale imaging, the second loop concentrated on contact science locations identified during the first loop, and the third involved drilling. Multiple rovers could allow tasks from 2nd and 3rd loops to run in parallel with continuing exploration by reconnaissance rover.

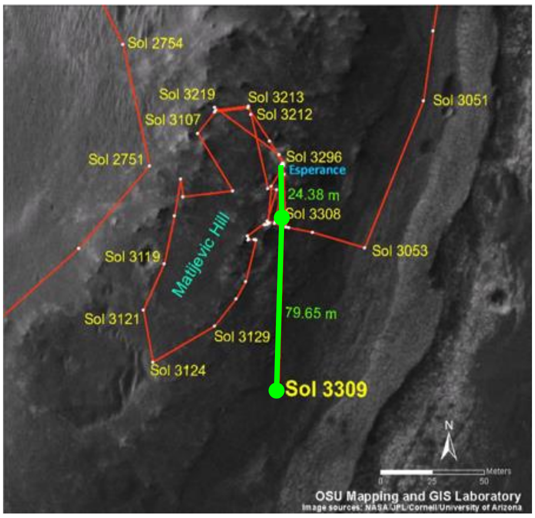


Figure 6: Opportunity at Cape York

During its exploration of the Cape York segment on the rim of Endeavour crater, Opportunity completed an imaging "walk about" to understand the geologic context of the rocks in the vicinity. Data analysis revealed several spots to revisit for detailed, time intensive contact science investigations. This could be made more efficient if one rover took detailed measurements, while second continued to survey.

2.3 Cave Exploration

Planetary cave exploration is a topic of growing interest in the planetary science community as well as for human exploration. More than 200 Lunar and 2000 Martian cave-related features have been identified. Vents and fissures associated with water ice plumes on Saturnian, Jovian, and Neptunian moons also represent possible cave systems [11]. Lunar and Martian caves are most commonly associated with lava tubes, although some are possibly present in karstic sulfate terrain (Mars) and cryovolcanic features (outer planet moons). Caves offer stable physio-chemical environments, may trap volatiles, enhance secondary mineral precipitation and microbial growth, are expected to preserve biosignatures, and provide record of past climate [12, 13, 14]. Investigation of petrological sequences on skylight and cave walls can provide critical constraints on lava temperature and cooling history, leading to insights into Martian magmatic processes and differentiation [15, 16]. Caves also represent potential environment for future human exploration: they are believed to offer a stable UV-shielding environment and can potentially act as volatile traps [17].

A future mission to Martian caves should provide reconnaissance both for scientific and human exploration. Key science objectives for this pathfinder mission would be to map the cave geometry (cave diameter/ceiling height from entrance to ~100 m depth), determine traversability challenges (boulder distribution, unconsolidated material), document the cave environment (spatial and temporal variations in temperature, humidity and radiation), and map the compositional and lithological diversity of the cave materials, in particular to look for mineralogy (e.g., hydration), volatiles, and organics. Science definition led to identification of possible instruments and resource requirements. The proposed payload leverages recent or emerging miniaturized instruments developed for CubeSat-class deep space missions. The mild radiation and thermal environment expected in caves justifies the use of CubeSat-class instruments while the multiple assets provide redundancy. Configuration of the instruments on the platforms and accommodation of special needs, such as illumination for imaging and attitude control for LiDAR, remain to be addressed in detail. Proposed objectives are presented in Table 1.

Objectives	Measurements	Payload
Map cave geometry	Cave diameter/ceiling height from entrance to ~100m depth	Stereo camera, Lidar
Determine traversability challenges	Boulder distribution	Camera telemetry
	Unconsolidated/loose material	
Document cave environment	Spatial and temporal variations in temperature and humidity	Temperature, humidity, and pressure sensors
	Spatial and temporal radiation energy spectrum	LET spectrometer
Map compositional diversity	Colors	Stereo camera (filters)
	Minerology	IR camera (point spectrometer OK)

Table 1. Example objectives, measurements, and payload for a cave reconnaissance mission

3 NETWORKED MISSION DESIGN

In previous work [18], an integrated approach to designing and optimizing mission concepts involving networked constellations of spacecraft was introduced. In this approach, a combination of generative graph grammars [19] and multi-objective evolutionary algorithms [20] is used to produce a set of Pareto-optimal mission concepts. The input graph grammar defines a series of variables, parameters and constraints. Only well-formed solutions (that is, solutions that meet all constraints) are considered. The optimizer explores a design space by generating solutions through the successive application of the grammar rules. A set of objective functions guide this exploration towards more and more favorable solutions. The approach is of an integrated nature since the design of the spacecraft vehicles, aspects of operations, the communications network, science merit, and the trajectory (if applicable) can all be considered simultaneously as part of a single optimization problem formulation.

Plotting performance attributes of the mission concepts (such as cost, mass, scientific merit, and amount of data returnable to Earth) for the set of generated Pareto-optimal mission concepts allows for deeper insight into the trade space. Generally, for networked constellations of spacecraft the trade-off between the cost of the constellation and its scientific merit is of primary interest. Constellation system cost is proportional to the number of spacecraft and their individual mass, as well as the homogeneity designs. Scientific merit is generally determined by considering a combination of instrument operations, temporal and/or spatial coverage of a particular set of measurements, and the amount of data that was collected, processed, and returned to Earth. For missions involving the communication of large quantities of data, trades involving the amount of power available for purposes of communication are also generally of interest. Devoting more power to communications allows for higher data rates or more prolonged communication periods, but reduces power available for other mission functions, such as the collection of science data or autonomy-related computations. Many trade-offs are often very specific to the particular mission concept being investigated.

Figure 7 illustrates example results from applying the design approach to the Mars cave exploration concept. Each dot represents one mission concept involving between 2 and 10 rovers. The mass of each rover can vary between 5 and 50kg. Rovers in the constellation with different mass are considered separate types of rovers for purposes of costing. It is assumed that rovers can only be equipped with primary batteries, giving them limited power to be used during the operational phase. The types of instruments each rover carries are variable, and their presence or absence in a rover is determined by the optimizer. Different instrument configurations are considered not to have an adverse effect on the cost, but do have an effect on resource usage. Resource consumption over the lifetime of a rover is determined by a parametric operations plan, in which power usage of different instrument operations is considered in combination with variable lengths of activities performed. The length of each rover activity is chosen by the optimizer. The amount of data transmitted by each rover is determined by (a) how much data is collected by the rover's instruments, and (b) how much data the rover receives from other rovers in the constellation. The total amount of data returned is the amount of data received by the base station. The optimization capability also can perform a trade-off between spending more power on either transmitting data (possibly via multiple hops) or traversing forward. Results clearly have shown that a higher number of rovers is required if the rovers can traverse long distances and return very large volumes of data.

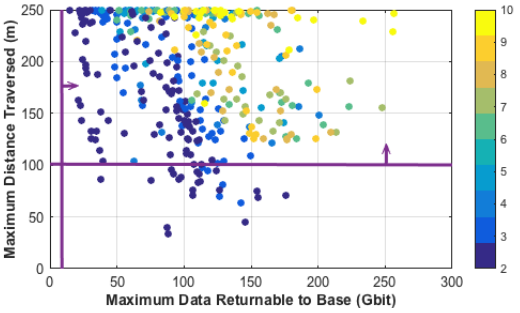


Figure 7: Example trade-off: data return vs. traversability. 9Gbit was the goal for data return and 100m was the goal for traversed distance. 250m was an artificial upper bound in the optimization. Colors represent the number of rovers as shown in the color key on the right. The data shown here is the capability for the given available resources and generated configurations. Generally, the trend shows heavier rovers or more rovers in the constellation towards the upper right (that's why there are some 2-rover constellations near where there are also 3- or even 5-rover constellations – capable of going further and returning more data).

4 SPACE NETWORKING

Unlike the indoor propagation environment where signals are attenuated and scattered substantially, for subterranean cave exploration the cave structure traps signal energy and can amplify both constructive and destructive multipath effects [21,22] (Figure 8), making it necessary to adapt transmission strategies based on real-time measurements instead of *a priori* scheduling. Link outages may occur with very small changes in the relative distance/positions of the transmitter and the receiver. For example, at 2.4 GHz a change of 10's of centimeters in position can make the difference between experiencing a 'null' where destructive interactions between multiple reflected signal components corrupts the signal beyond recovery or a 'hot-spot' where constructive combining of signal results in a substantially stronger signal than one would normally expect at that distance. Both phenomena have been observed in field experiments and are well known in terrestrial cellular networks, requiring "multiple access" technologies.

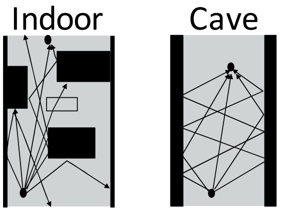


Figure 8: Notional differences between propagation indoor vs. in a cave

In such high-uncertainty communications environments, the network must be able to adapt and automate the process by which lost/disrupted communication is recovered/resumed seamlessly. The surface armada, for example, must be designed to cope with link quality fluctuations due to near-ground propagation loss over long distance and fading caused by nearby and distant terrain features. Figure 9 shows the total radio frequency propagation loss consists of measurable and strongly distance-dependent average loss, a variation that occurred over longer (large-scale) distance, and a variation that occurred over shorter (small-scale) distance. Since it is not possible, nor desirable, to acquire the full geometry of the operational environment ahead of time, a statistical understanding of the communications environment and the resulting communications strategy is critical to mission success.

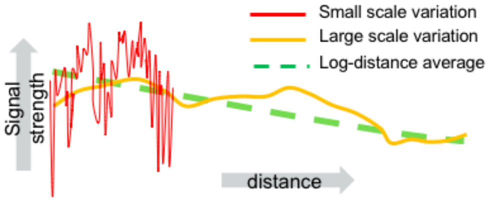


Figure 9: Signal Propagation and Variations

Finally, for all deep space missions, the long-haul link from the spacecraft to Earth is highly constrained by propagation losses and occultations due to planetary motion and antenna availability. This further builds the case for adopting a disruption tolerant networking architecture that is integrated with mission operations.

4.1 Delay/Disruption Tolerant Networking

Delay/Disruption Tolerant Networking (DTN) is a networking paradigm developed for deep space communications characterized by episodic connectivity between nodes, long propagation delay, and the absence an end-to-end data path consisting of multiple contemporaneously available links. Traditional terrestrial networking technologies, specifically those based on TCP/IP protocol suite, do not apply in deep space due to the requirement for end-to-end handshaking, which is only feasible when all links have very high availability and short propagation delay. In deep space, planetary motion, occultations, and very long propagation delays on the order of minutes or hours makes it necessary to break away from the Internet's 'end-to-end' networking paradigm and adopt a 'hop-by-hop' approach. At the core of DTN is a set of networking functionality that executes hop-by-hop store-and-forwarding, routing, and reliability based on a priori network information captured in the form of a Contact Graph (CG). The CG is a database containing the full communications schedule between any two end-points in the network. For missions with pre-planned activities and highly predictable orbital geometries, a static CG is sufficient information for automating store-and-forward communications without any coordination between networks and mission operators, as demonstrated by the EPOXI mission [23]. However, for a networked constellation of highly autonomous spacecraft, the CG will require constant update to reflect real-time topology changes and facilitate routing decisions that continuously adapt to the operational goals of the mission.

4.2 Integrated DTN Architecture

In an integrated DTN architecture for cave exploration (Figure 10), autonomy software, DTN, and the communications subsystem must coordinate and exchange updates regarding link/network state (i.e. data rates and connectivity) as well as operational constraints, such as energy, storage, and traffic loading.

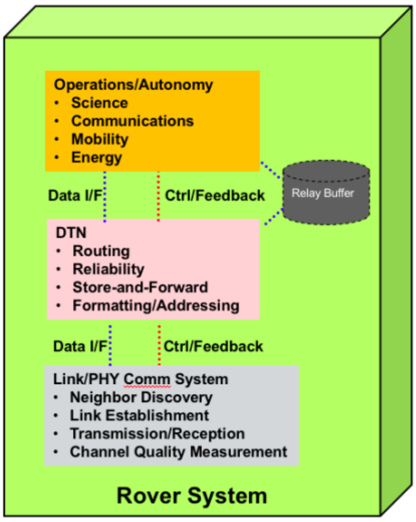
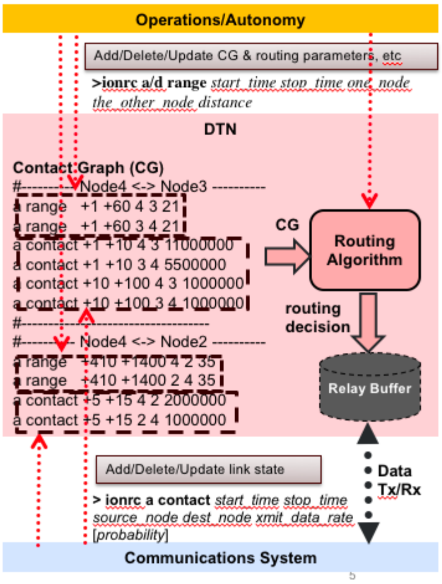


Figure 10: Integrated Networking Architecture

Figure 11 shows in more detail how near-real time updates can be applied to the CG in order to optimize routing decisions based on performance criteria set by the autonomy software. The figure illustrates the CG implementation in ION, NASA's implementation of DTN protocol suite, and the associated function calls that facilitate CG updates by external systems. ION is open source software that can be enhanced as required. The autonomy functional element, having visibility to all rover subsystem states and resources, can provide additional inputs to the routing functions in order to optimize communications.



```
>ionrc a/d range start_time stop_time one_node the_other_node distance
```

```
#---------Node4 <-> Node3 ----------
a range   +1 +60 4 3 21
a range   +1 +60 3 4 21
a contact +1 +10 4 3 11000000
a contact +1 +10 3 4 5500000
a contact +10 +100 4 3 1000000
a contact +10 +100 3 4 1000000
#----------------------------------
#--------- Node4 <-> Node2 ----------
a range   +410 +1400 4 2 35
a range   +410 +1400 2 4 35
a contact +5 +15 4 2 2000000
a contact +5 +15 2 4 1000000
```

```
> ionrc a contact start_time stop_time source_node dest_node xmit_data_rate [probability]
```

Figure 11: Contact Graph update API with ION

4.3 An End-to-end Network Overlay

From the end-to-end prospective, a cave exploration mission is a concatenation of two very distinct segments (Figure 12). The first segment, the 'in-cave' segment, is a highly autonomous network of rovers (or other platforms) that coordinate operations *in situ* in an uncertain communication and mobility environment. The other segment, the 'deep space' segment, consisting of the surface rover, orbiter, DSN, and the scientists on Earth, is very similar to current Mars exploration mission configuration, which is predominantly executed under a pre-scheduled paradigm – meaning all communications and operations decisions are made days/weeks in advance and executed by stored time-triggered commands. Hence there is a combination of both prescheduled operation and autonomous operation in this single end-to-end mission. The DTN functional element provides an overlay across these two distinct operational environments and delivers a consistent framework for communications and data delivery.

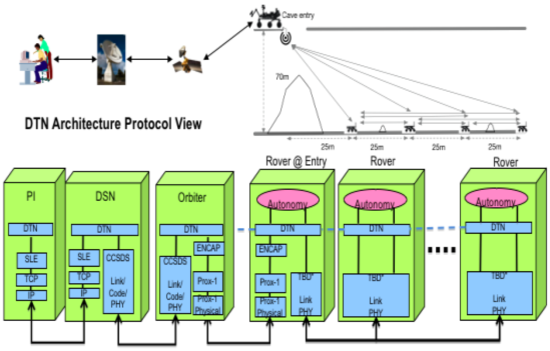


Figure 12: *End-to-end Network Overlay*

5 NETWORKED AUTONOMY

5.1 Multi-rover Coordination

For Mars cave exploration, multi-rover coordination is a key mission enabler due to limited communication, power, and mission duration (just days), as well as impractical humans-in-the-loop operations. Autonomy helps rovers to resiliently communicate in the cave environment and to map and characterize as much of the cave as efficiently as possible within this limited lifetime.

5.1.1 Algorithm

Onboard autonomy provides the network of rovers resiliency to communication disruption. Moreover, given the limited rover lifetime, the onboard exploration strategy leverages the networking capabilities to cover the cave and collect science data. The proposed *Dynamic Zonal Relay with Sneakernet Relay Algorithm* is a two-step algorithm designed with the assumption of a fixed, limited communication range between rovers. The algorithm identifies zones for each rover, which are based on the maximum communication range, as shown in Figure 13.

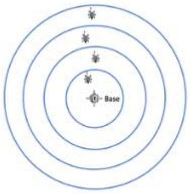


Figure 13: Rovers in their assigned Zones as determined by the Dynamic Zonal algorithm

The first step (Dynamic Zonal) distributes the rovers such that they always maintain communication distance with neighboring rovers. Each rover drives to a designated zone along the length of the cave and only takes science data while in its designated zone. The data is then transmitted to the neighboring rover in the direction of the lander. If network connectivity is lost due to a null link or to a rover not being operational, the rovers would re-establish communication by driving towards their respective neighbors in the direction of the mouth of the cave. In the case of a rover failure, the other rovers would re-distribute the zones to maintain communication, characterization of the environment, and science data flowing out of the cave to the lander. The next step (Sneakernet Relay) allows the rovers to acquire science data further in the cave by driving beyond the communication distance. Figure 14 outlines the difference phases of lead and relay rovers in the two steps of the algorithm.

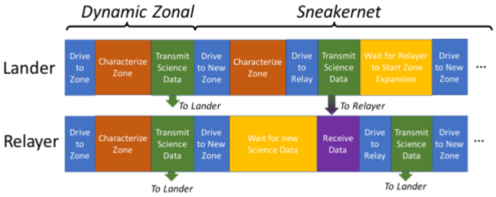


Figure 14: Phases of the Dynamic Zonal Relay with Sneakernet Relay Algorithm

5.1.2 Simulation

Simulation is essential to evaluating rover performance, robustness, operability, science return, and a spectrum of mission parameters, network topologies, and environmental settings. The simulation framework uses the Robot Operating System (ROS) to test the aforementioned algorithm. The framework allows different multi-rover mission configurations and supports the measurement, evaluation, visualization (Figure 15) and analysis of rover performance and science utility. A configuration with four identical rovers and a base station was used in the simulations. This configuration is based on the preliminary cost and payload analysis described in previous sections. The cave model used is a model of the Cassone Cave [24], scaled approximately twelve times so that the width is around 70 m to be in the range of the expected dimension of Martian lava tubes.

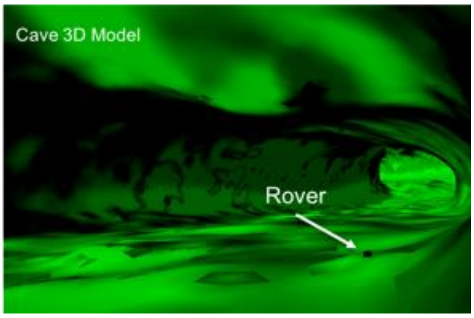


Figure 15: Cassone Cave simulation

Each rover is assumed to have an identical suite of instruments, including: LiDAR (used to characterize the cave walls, facets and structure), color camera, spectrometer, thermometer, radiation detector, and hygrometer. A baseline experiment was performed with four rovers, zero obstacles, and no random dying of the rovers. Two further experiments were performed, again with no random death but with randomly placed obstacles with densities of 10% and 20%. Figure 16 illustrates the progression of the depth position in the cave using the algorithm while Figure 17 illustrates the trajectories of the rovers in different obstacle densities. In order to show the robustness of the algorithm to loss of rovers, another experiment was run with zero obstacles and a random chance of rovers dying during the run. The results also show that the sneakernet algorithm, while endeavoring to maintain communication isn't currently robust at greater obstacle densities. Additional algorithms are needed to handle greater obstacle densities.

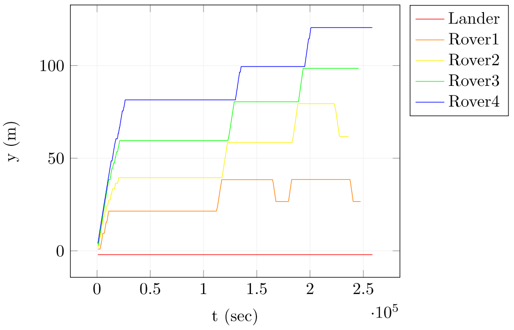


Figure 16: Rover depth with no obstacles.

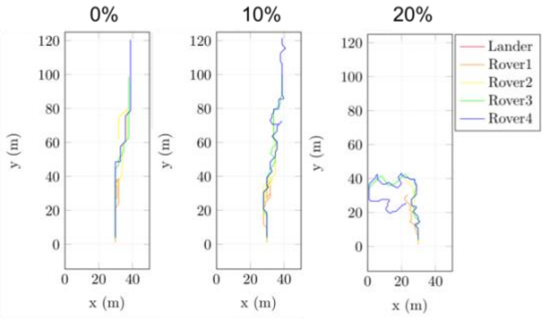


Figure 17: Rover trajectories vs. obstacle densities

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