Distributed Spacecraft Mission (DSM) Plume Design Reference Mission (DRM) Inter-satellite link Modeling, Analysis and Simulation

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ABSTRACT

NASA Goddard Space Flight Center (GSFC) Radical Innovation Initiative (RI2) plans to focus intently on DSM capability advancements in FY22-24. A DSM mission involves multiple spacecraft, arranged in a constellation, to achieve one or more common goals via the use of inter-satellite links (ISL) between the satellites. Recently, the GSFC Internal Research & Development (IRAD) program established Enceladus as a design reference mission (DRM) for the current DSM effort to foster the conceptual development of communication architecture, requirements, and solutions for future DSM ISL, as well as being able to push other research areas of interest. Enceladus is an icy moon of the planet Saturn.

The DRM Enceladus mission concept involves a constellation of 24 small satellites, orbiting Enceladus around 100 km altitude in 3 planes, as observing nodes for science measurement. The mission science data will be sent back to Earth through a relay orbiting Saturn, using the constellation's inter-satellite links. A QualNet/STK simulation model of the Relay and constellation ISL optical and RF links is developed for the design and optimization of the link and orbital parameters, as well as the inter-networking protocols. Delay Tolerant Networking (DTN) is utilized in the application layer modeling.

This paper describes the plume DRM mission concept of an Enceladus constellation to relay science data to Earth and includes the proposed communication architecture and operation concepts. We present details of the QualNet/STK engineering model for this communication scenario to simulate the end-to-end data traffic through multiple layers (physical, data link, networking, transport and application). A link analysis for the constellation's ISL, constellation to Relay and Direct to Earth (DTE) optical link is provided and discussed. The results of end-to-end traffic simulation for the data throughout/latency evaluation and assessment of the communication architecture are presented. The investigation of the concept of optical multiple access (OMA) for the Plume DRM is discussed. The modeling and simulation methodology developed in this paper is applicable to other DSMs in near Earth and deep space such as Earth-Moon L1/L2 and Lunar regions.

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1.0 DISTRIBUTED SYSTEMS MISSION (DSM) ICY MOON PLUME OBSERVATION DESIGN REFERENCE MISSION (DRM) CONCEPT OVERVIEW

The Distributed Systems Missions effort is trying to advance technologies associated with the operation of larger constellations of satellites cooperatively acting towards some common objective.[1] Efforts are exploring the application of artificial intelligence to science sensing, event detection, and data prioritization for return. The goal is for on-board autonomy and automation to take on more roles from the spacecraft to either offload the ground operator burden for larger constellations, or to manage operations where the time to response does not allow for human-in-the-loop decisions. Deep Space missions observing transitive environmental responses may not allow time for the initial detection to be sent back to earth, have the science team make the appropriate decisions and then send the commands back. As such, the spacecraft will need means to make local decisions on prioritization of science observations and handling of on-board issues and faults. The Autonomous Navigation, Guidance and Control capabilities are looking for means to provide more onboard capabilities for orbit and attitude maintenance and event locating. Communications is working through the nuances of crosslink and relay communications as well as the tracking and pointing implications. Mission resilience is working towards more capabilities for on-board fault detection, recovery, prediction, and mitigation. Open Architectures is exploring means to handle coordination within a constellation or between federated observatories interested in common phenomena.

In an effort to allow different teams to focus on common goals so as to leverage each other's efforts, a common design reference mission was devised to maximize the challenges for the various teams. From the defined capabilities desired to be advanced, an icy moon mission was chosen attempting to observe transient plume ejecta whose duration may be shorter than the round-trip time requiring on-board task planning to enable multiple views of any detected plumes to maximize the science return.

2.0 *NOTIONAL DRM COMMUNICATION ARCHITECTURE, TOPOLOGY AND OPERATION CONCEPT*

The Enceladus mission concept, the notional DRM Enceladus communication architecture and topology, as shown in Figure 1, contains a Relay orbiting Saturn and 24 small satellites constellation (as observing nodes) orbiting Enceladus at around 100 km altitude in 3 planes. Enceladus orbits Saturn at about 238,000 km. The 24 small satellite constellation is using Walker Delta 24:3:1 orbits with 45 degrees inclination. The Relay will be in the Enceladus orbit separated by about 50,000 km from the observing nodes, and trailing Enceladus with true anomaly of 13.21 degrees. The mission data from the 24 small satellites constellation will be sent back to the Earth through the Relay. Optical communication will be utilized between the Relay, the constellation observing nodes, and Earth. The constellation 24 small satellites ISL supports the science and housekeeping data via optical links and coordination data with RF links. Notional JPL Deep Space Network (DSN) hybrid 8m equivalent optical ground stations are planned to be used for the Direct to Earth (DTE) link.

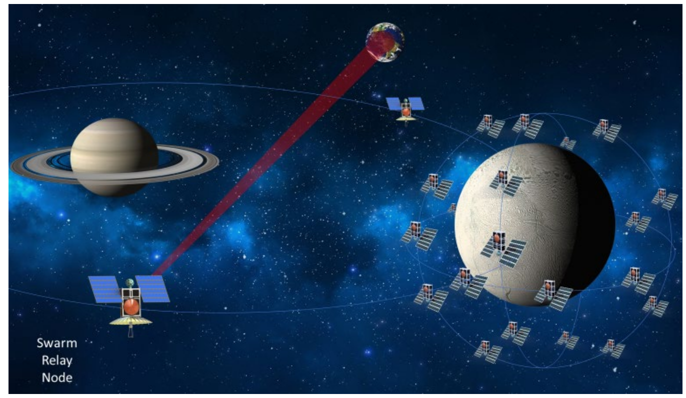

Figure 1. Notional DRM Communication Architecture and Topology

3.0 *QUALNET/STK SIMULATION MODEL TOOL OVERVIEW*

A system simulator was developed for the modelling and simulation of the constellation to relay to Earth inter-satellite link (ISL). It is based on a commercial tool: QualNet/STK.[2] The QualNet/STK, as shown in Figure 2, is a network simulator software tool that provides a comprehensive environment for designing protocols, creating and animating network scenarios, and analyzing their performance. STK simulates geometry configuration, communication system/link and propagation effect (orbit, antenna type, gain and orientation, attitude, propagation loss models, etc.). OSI Layers parameters and behaviors (Physical, Data Link, Network, Routing, etc.) are defined in QualNet. The MATLAB Simulink tool will be used to perform RF link trades analysis. Optical link budget analysis will be supported by Goddard Communication Link Analysis Simulation System (CLASS) tool. The STK plug-in SNT networks interface to QualNet models the flight communication and orbital parameters as well as network routing for the scenario configuration of the DRM. QualNet also models the DRM data transmission through the multi-layer to predict the behavior and performance of networks to optimize the design, operation, and management. The end-to-end data traffic network performance simulation run is performed by the STK SNT networks interface with QualNet. Table 1 lists the system simulator architecture elements.

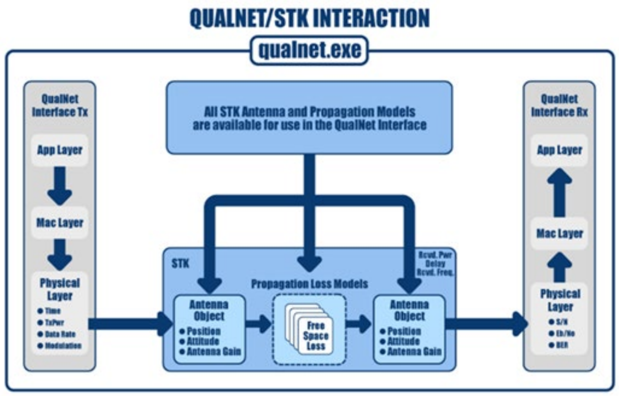

Figure 2. QualNet/STK Simulator

4.0 LINK ANALYSIS FOR CONSTELLATION INTER-SATELLITE LINK, CONSTELLATION TO RELAY AND DIRECT TO EARTH (DTE) OPTICAL LINK

Link budget analysis was performed for the design trades and optimization of the constellation intersatellite link (ISL), constellation nodes to Relay and Relay to Earth direct ground link.[3] Table 2 is summary of the DRM Enceladus optical ISL link design.

Table 1. System Simulator Architecture Elements

Network Layer	Simulation Model Level	Description
Physical	Geometry Model	Using STK to model spacecraft trajectories and relative attitude to model the wireless communication link characteristics.
Physical	Flight Communication System/Multiple Access Model	Using MATLAB/CLASS to perform optical/S-band flight system modeling/analysis/design trades as well as the link quality of the chosen multiple access scheme. For example, estimating the BER/link margin performance of a CDMA network or the collision probability and associated back-off of a CSMA/CA transmission
Data Link	Flight Communication Link Performance Simulation	Coupled with the multiple access technique, model the time varying behavior of the inter-satellite link transceiver/optical terminal
Network	Switched Packet IP Network Simulation	Using industry standard simulation environment to model the actual activity within the switched packet IP network.
Network/ Application	Network Routing	Performance of the chosen cost-based routing protocol, as simulated by the switched packet IP network simulator.
Transport/ Application	User Data Flow Implementation	Using QualNet/STK SNT networks interface to simulate the end-to-end traffic data flow pattern that will ultimately 'load' the network,

Table 2. Summary of the DRM Enceladus optical ISL link design

Parameters	Constellation ISL Optical Link	Constellation Node to Relay Optical Link	Relay to Earth Direct to Earth (DTG) Optical Link
Wavelength	1550 nm	1550 nm	1550 nm
Distance	2000 km	50,000 km	1.4 billion km
Data Rate	100 Mbps	100 Mbps	50 Mbps/100Mbps
Modulation	PPM 8	PPM 8	PPM 256
Forward Error Correction Code	LDPC 1/2	LDPC 1/2	LDPC 1/2
Node or Relay transmit Power	1 W (Node)	10 W (Node)	20 W/40W (Relay)

Node or Relay Transmit/ Receive Telescope Aperture	5 cm (Node)	5 cm (Node and Relay)	2 m/1.5m (Relay)
Node or Relay Receive Detector	Pre-Amp + PIN diode	Pre-Amp + PIN diode	8 m (Earth)
Node or Relay Receiver Sensitivity	20.2 dBph/bit	10.3 dBph/bit	-4.2 dBph/bit
Implementation Loss	3 dB	3 dB	3.7 dB
Link Margin	11.22 dB	4.61 dB	2.75 dB

Note: Wavelength division multiplexing is used for the Constellation to Relay optical link for interference mitigation. BER = 10-5

Constellation ISL coordination link for housekeeping data will be at RF S-band: Data rate = 50 kbps, PA =2 W, Phased array antenna gain =8 dBi. BER = 10-5. Link margin: 12.4 dB.

For a DTE link of 50 Mbps, Table 3 lists the trades between the Relay telescope size and Relay transmitted power for the DTE link.

Table 3. DTE link Relay Telescope Size vs Tx Power Trades off

Relay Transmitted Power (Watt)	Relay Telescope Diameter Size (cm)
20	200
35.5	150
79.8	100
319	50
1995	20
7981	10

As indicated in the table, either the telescope size or the transmitted power values are not practical for realizing a relay in Saturn orbit. An alternate optical swarm arraying strategy to implement the relay is discussed in a later session.

5.0 DRM ENCELADUS TO RELAY TO EARTH END-TO-END TRAFFIC PATTERN MULTI-LAYER SIMULATION FOR THE DATA THROUGHOUT/LATENCY EVALUATION AND ASSESSMENT

A QualNet/STK engineering model was developed to simulate the end-to-end data traffic through a multi-layer (physical, data link, networking, transport, and application) for the data throughout/latency evaluation and assessment. Delay Tolerant Networking (DTN) is utilized in the application layer modeling. Each satellite in the constellation is considered a routable node in the network with an identical inter-satellite link transceiver and a space router. Each node is assigned a single IPv4 address that is routable over all its inter-satellite links, including the Relay. The simulation results will support inter-networking protocols design specification for control and data transmission management.

Observing Node to Relay Traffic Simulation Over 24 hours: Static Routing

Simulations were performed for observing node to relay traffic simulation over 24 hours.[4] Note that due to the huge simulation time for 24 satellites over 24 hours, only an 8-satellite case were simulated. It is expected that the results will be similar for the 24 satellites case.

Each node sends 81000 packets (512 bytes each) to the Relay continually via broadcast, static routing protocol, whenever in view. The Total packet received at the Relay is 452306 out of 648000 packets sent from 8 satellites (in 81000 seconds). The data throughput is 69.8%. When the observing nodes are behind Enceladus, the view to the Relay is blocked, hence the throughout is reduced.

Simulation also was performed with store and forward Disruption Tolerant Networking (DTN) in the application layer. The total amount of packets received at relay is 613008 out of 648000 sent from 8 satellites (in 81000 seconds). The data throughput is 94.6%. DTN is applied if the network layer path to the next forwarder/destination is active and available, otherwise, the forwarder will store the message.

Simulation results of the static routing without and with DTN are shown in Figures 3 & 4, respectively.

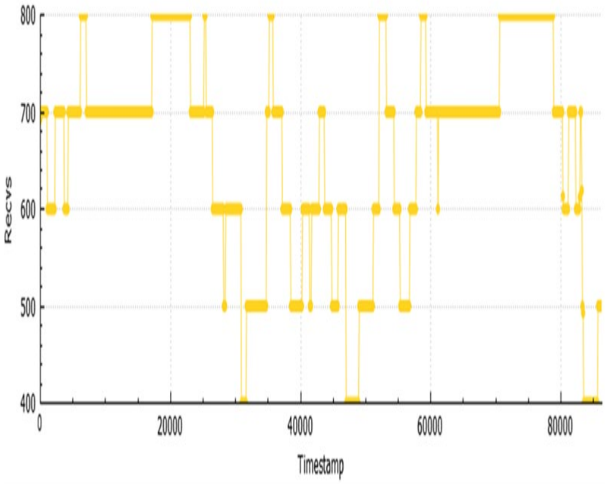

Figure 3. Static Routing Simulation Traffic with No DTN

Recvs: receive data (packet). Timestamp: second

Observing Node to Relay to JPL Goldstone Station End-to-End Traffic Simulation: Static Routing

Simulation results of the observing node to relay to Earth End-to-End Traffic at JPL Goldstone station, without and with DTN are shown in Figures 5 & 6.

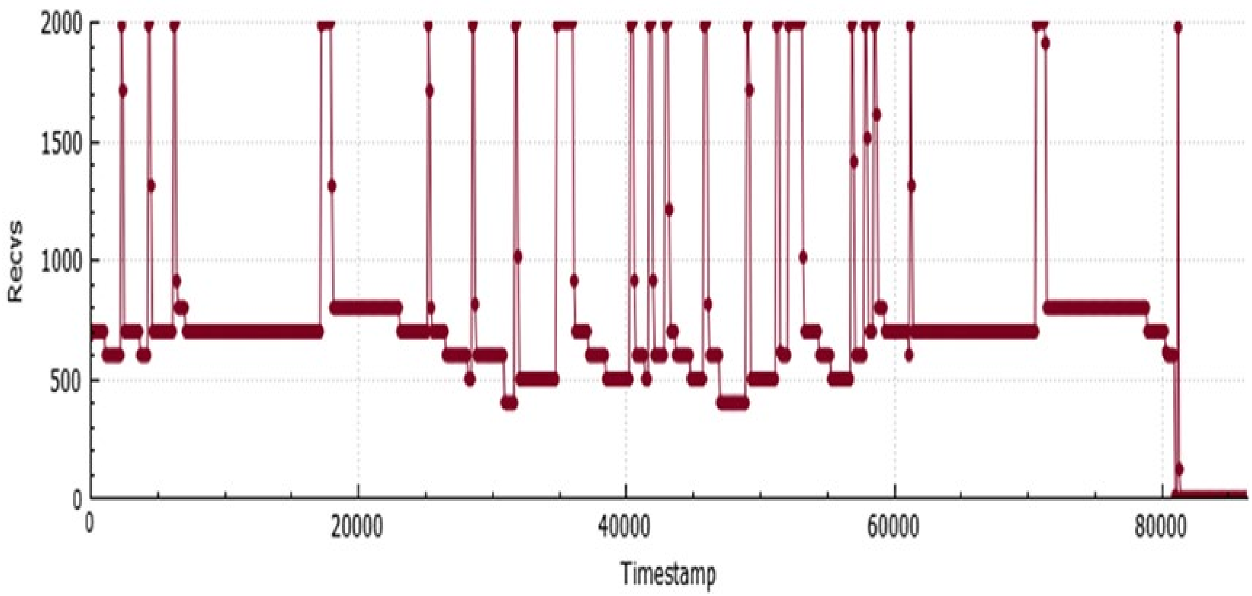

Figure 4. Observing node to Relay traffic simulation over 24 hours: Static Routing, With DTN

Recvs: receive data (packet). Timestamp: second

As shown in Figure 5 & 6, the total packet received at Goldstone as a percentage of data sent by the Satellites is 185182 out of 351993, without DTN. The total receive packets at Goldstone as a percentage of data sent by the satellites is 310297 out of 351993, with DTN. (12.22 hours in view over 24 hours)

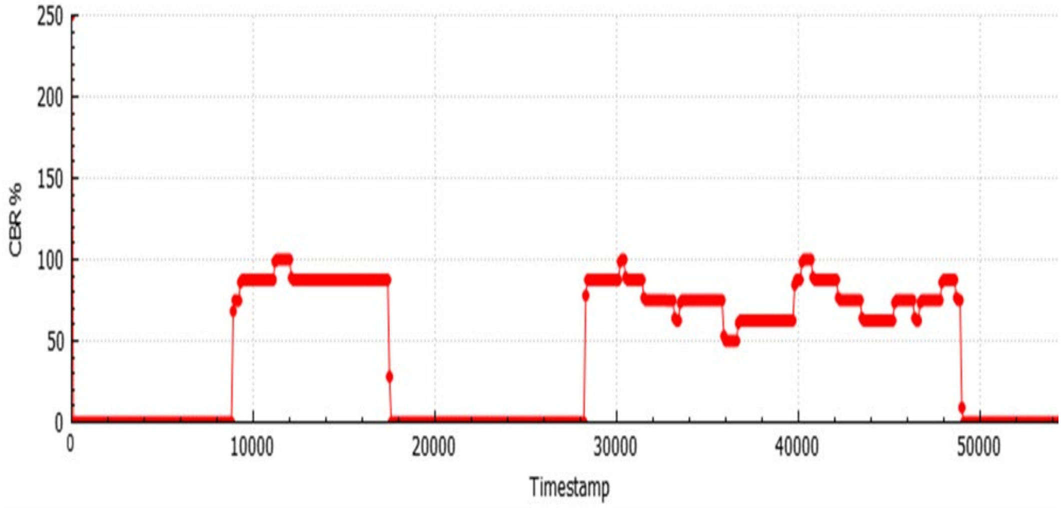

Figure 5. Observing Node to Relay Traffic Simulation through Multi-layer over 24 hours, Static Routing. No DTN. CBR: Constant Bit Rate. Timestamp: second

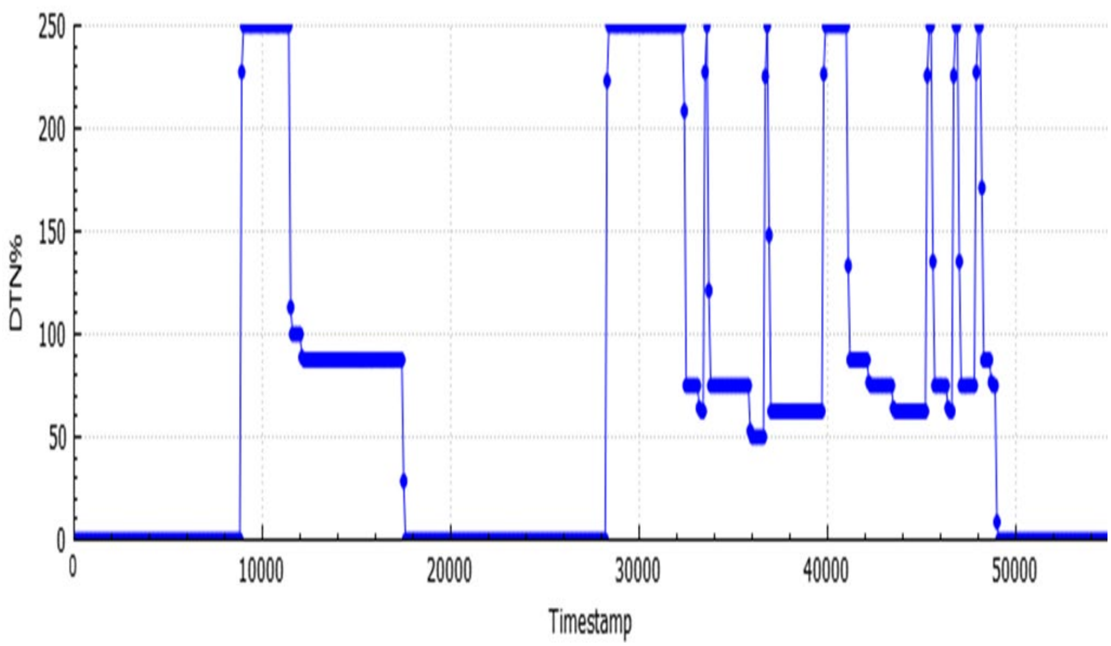

Figure 6. Observing Node to Relay to Goldstone station End-to-End Traffic Simulation: Static Routing, with DTN. Timestamp: second

The Behavior of Data at Relay with DTN

When satellites are not in view of the Relay, they store their collected data, and then when the Relay comes in view, the satellites forward their stored data and send collected data as its collected**.**

Data stored increases while the Ground Station is not in view and decreases when the Ground Station comes in view.

Figure 7 shows the behavior of data at the relay with DTN.

Observing Node to Relay to JPL Madrid Station End-to-End Traffic Simulation: Static Routing

Simulation results of observing node to relay to Earth End-to-End Traffic at JPL Madrid station, with DTN is shown in Figure 8. The behavior of data at Madrid is shown also. Total packets received at Madrid station is 452306 out of 648000 sent from satellites in 81000 seconds. Data is stored at Relay when the station is not in view.

Note that that similar or better results expected if the Optical Ground Station is in Australia.

Data traffic (no DTN) received at Relay from 8 satellites, Ad-hoc On Demand Distance Vector (AODV) Routing

The Ad-hoc On Demand Distance Vector (AODV) routing protocol was performed to simulate the data traffic between the Nodes and the Relay, as a comparison to boarding static routing protocol. AODV uses a sequence number at the destination, i.e., the Relay, to determine freshness of routing. Each node initiates a hello message to the Relay for acknowledgement before sending data, i.e., check for in view. If no response after 5 seconds, the next node on the sequence will repeat the process. Results of the AODV simulation is shown in Figure 7. Total received at relay is 654211 out of 691192 total Sends. The data throughout is 94.6%. With the AODV protocol, the connectivity is improved with alternative routes when the observing nodes are blocked from Enceladus.

DTN is not modelled in QualNet tool. The DTN application utilizes the routing info in the IP routing table. AODV maintains their own routing table without updating IP routing table that is not suitable for simulation with DTN.

DRM Constellation to Relay to Earth End-to End Performance Efficiency/Throughout

Summary of the efficient/throughout (24 hours) is shown in Table 4. As indicated, AODV routing is more efficient than broadcast static routing. AODV determines/refresh of routing path if the view is blocked and improve the throughout. DTN network-based store and forward capabilities enable greater utilization of network assets.

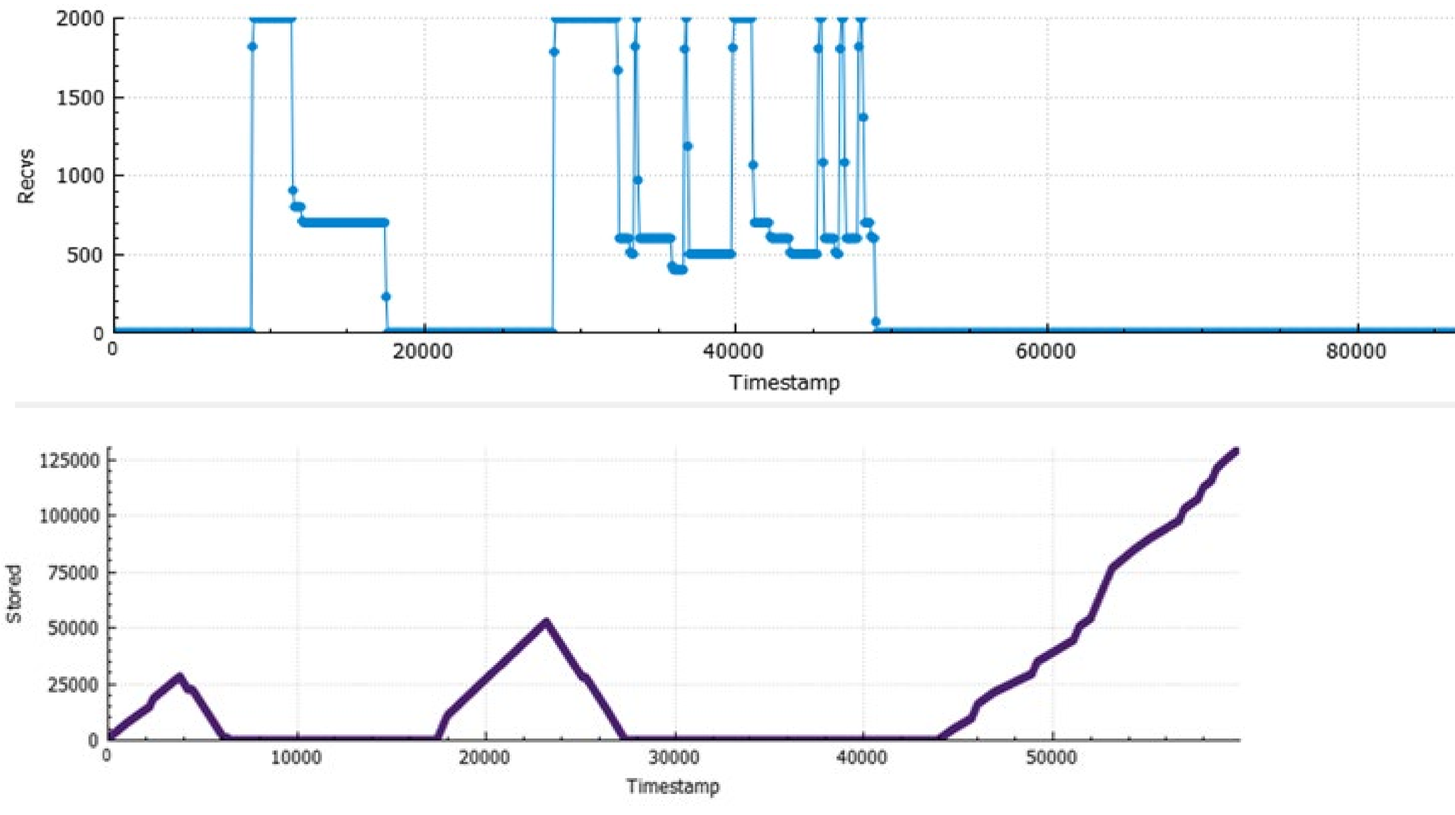

Figure 7. Data Behavior at Relay with DTN. Recevs: receive data (packet). Timestamp: second. Stored: data stored (packet)

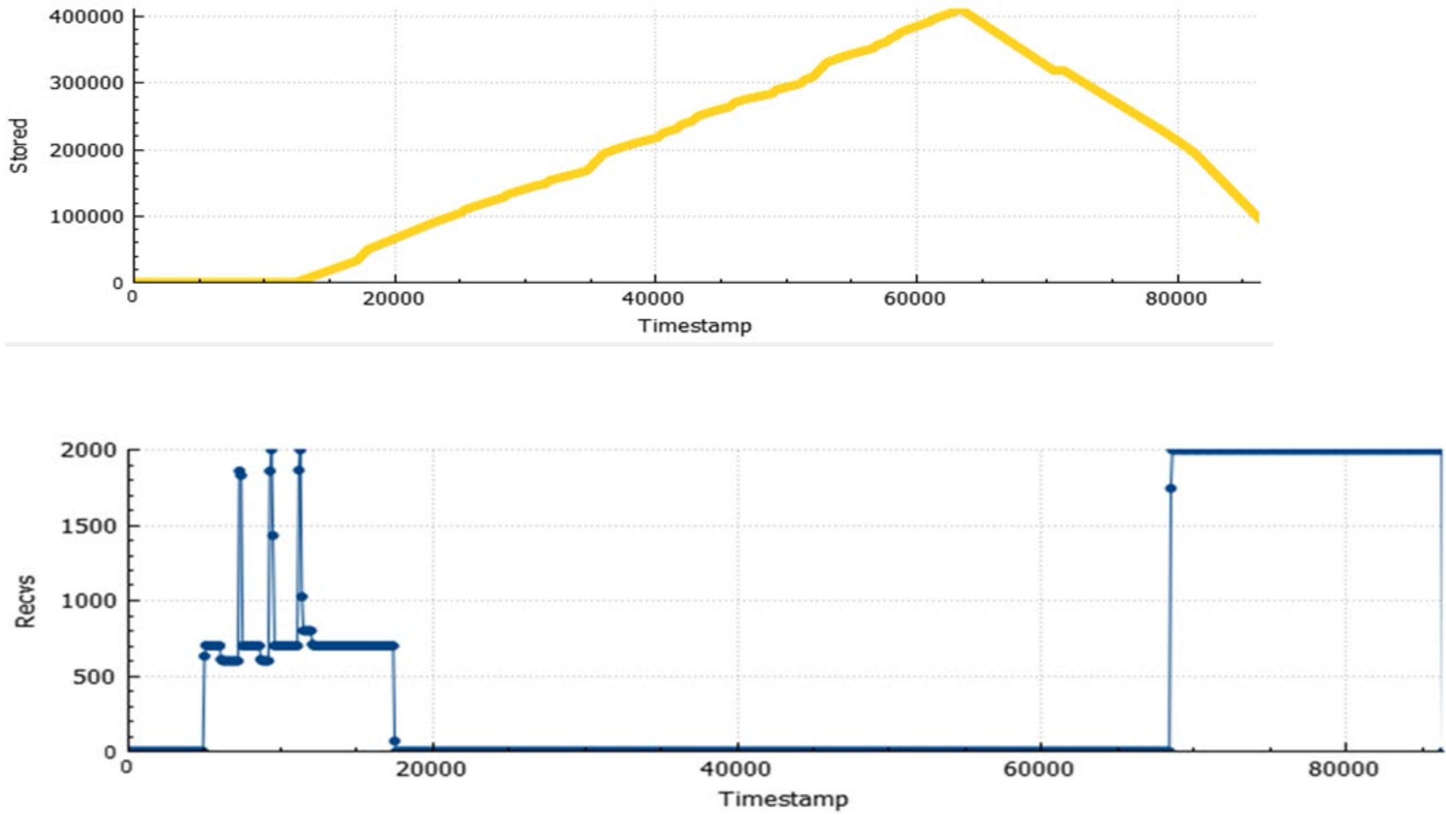

Figure 8. Observing Node to Relay to Madrid station End-to-End Traffic Simulation: Static Routing, With DTN. Stored: data Stored (packet). Recvs: receive data (packet). Timestamp: second

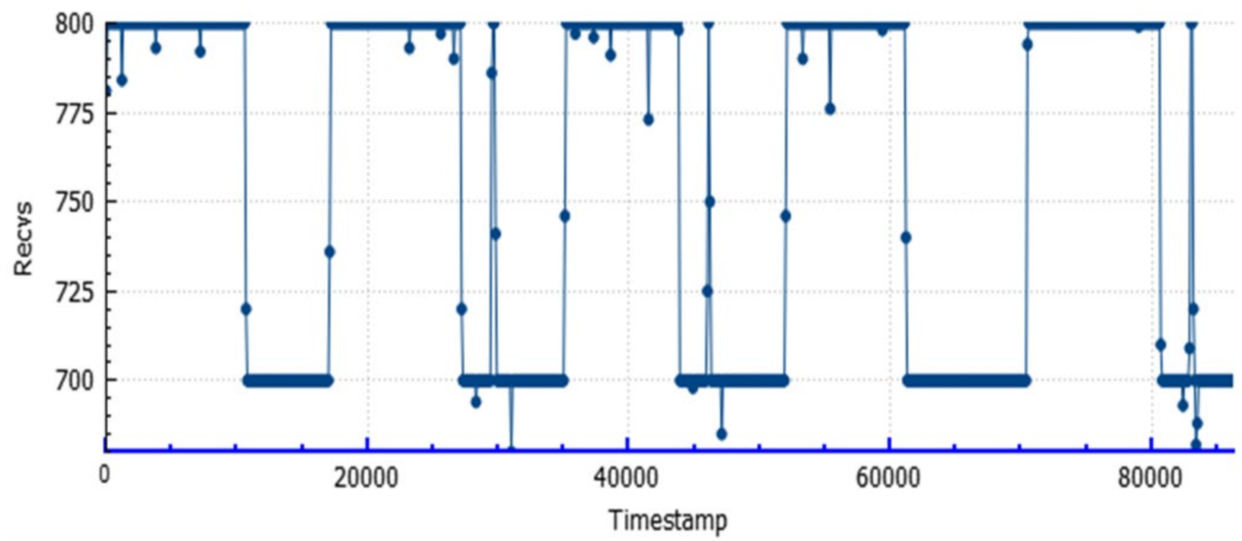

Figure 9. Data traffic (no DTN) received at Relay from 8 satellites, AODV

Recvs: receive data (packet). Timestamp: second

Table 4. Performance Efficiency/Throughout Summary

Link	Routing	Data Rate	Total Messages Sent	Total Message Received	Efficiency
Observing Node to Relay	Broadcast/ AODV	100 Mbps	648000 691192	452306/(no DTN) 613008/DTN) 654211 (no DTN)	69.8% 94.6% 94.6%
Relay to Earth Station	Broadcast	50 Mbps	351993 (until 49000s)	185182 (no DTN) 310297 (DTN)	52.6% 88.15%

6.0 USE OF OPTICAL MULTIPLE ACCESS (OMA) FOR THE PLUME DRM

Optical MA (OMA) is an all-optical communications capability that provides optical communications MA capabilities like those of the well-known RF MA capabilities, but with much less mass and space burden on user. OMA is a new concept that has never been flown. However, its development will be based on a SBIR technology: "the Inter-spacecraft Omnidirectional Optical Communicator (ISOC)", which will enable the Plume DRM inter-satellite link application.

ISOC will provide fast connectivity and navigation information to small spacecraft forming a swarm or a constellation. It operates at 1550 nm and employs a dodecahedron body holding 6 optical telescopes and 20 external arrays of detectors for angle-of-arrival determination. It will provide full sky (4π steradian) coverage, simultaneous multi-links operations and gigabit (in cislunar space) connectivity among smallsats forming a swarm or constellation. It can also provide positioning information among the spacecraft, i.e., the bearing, elevation, and range information among the smallsats that are interconnected via this terminal. [5] Figure 10 is the image of the ISOC.

OMA will use optical beam beaconless angle of arrival (AOA) methods in fast acquisition to establish a link between user and provider, as well as for pointing/tracking and re-acquisition with user initiated-connection protocol. Once service request is granted, high-rate optical communication will be followed.

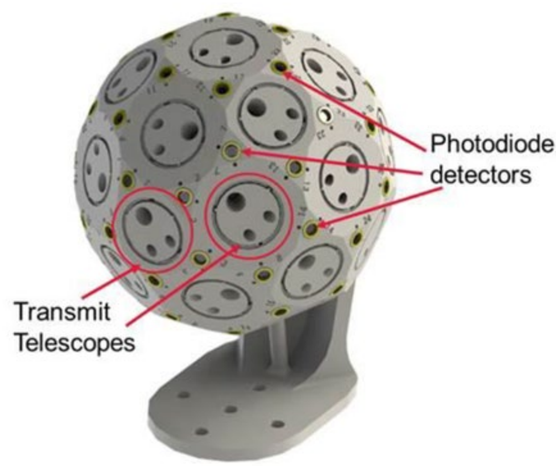

Figure 10. Image of the ISOC

The ISOC is capable of enabling swarms of spacecraft as Relay nodes. It can achieve synthetically large optical apertures and large amount of transmitted power using clusters of spacecraft.[6]

Figure 11 is the notional DRM communication architecture with swarms of spacecraft as a relay node enabled by ISOCs arraying for relaying the data from the constellation observing nodes to Earth. An initial study was performed for DRM link design with swarms arraying technique. The synthetical optical aperture with transmit power was determined using the method in the paper.[7] Table 5 is summary of preliminary DRM OMA link design with swarm arraying technique.[8]

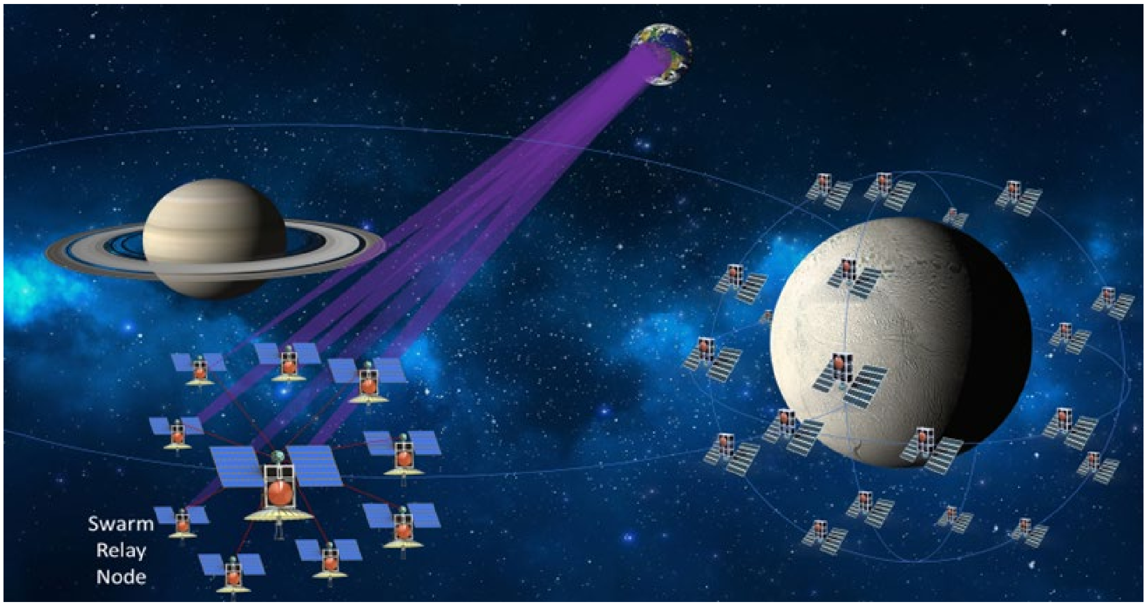

Figure 11. Notional Communication Architecture of Constellation to Relay to Earth ISL with Swarms of Spacecraft

Table 5. Preliminary DRM OMA link Design with swarms arraying

Parameters	Constellation ISOC to ISOC	Constellation Node to Relay Optical Link	Relay Swarm to Earth Direct to Ground Link
Wavelength	1550 nm	1550 nm	1550 nm
Distance	2000 km	50,000 km	1.4 billion km
Data Rate	100 Mbps	100 Mbps	50 Mbps
Modulation	OOK	OOK	OOK
Node or Relay transmit Power	1 W	1 W	100 W by combining the output of 10 swarm smallsat each with 10 W
Node Tx/Rx telescope Aperture size	5 cm	5 cm	54.77 cm aperture by combining the output of 10 swarm smallsat each with 20 cm
Relay Receive telescope aperture size	N/A	45.8 cm aperture by combining the output of 7 swarm smallsat each with 20 cm	8 m (Earth)
Implementation Loss	2 dB	2 dB	3 dB
Link Margin	9.37 dB	0.65 dB	5.9 dB

Note: Wavelength division multiplexing is used for the Constellation to Relay optical link for interference mitigation.

CONCLUSIONS

The NASA GSFC IRAD program establishes Enceladus as the Plume DRM for the Distributed Systems Mission (DSM) in 2022. The DRM Enceladus contains 24 small satellites constellation as observing nodes for science measurement. The mission science data will be sent back to the Earth through the Relay orbiting the Saturn and the constellation inter-satellite link (ISL). A QualNet/STK tool was developed to model the relay and constellation ISL optical and RF links for the design and optimization of the link parameters, orbital parameters and inter-networking protocols, as well as end-to-end traffic multi-layer simulation for the data throughout/latency. The design of constellation observing nodes to Relay to Earth optical ISL and RF housekeeping coordination link are presented. End-to-End observing nodes to Relay to Earth data traffic performance throughout and latency are provided. The use of optical multiple access (OMA) for the Plume DRM was investigated. This study will enable the system planner to validate performance and effectiveness of the notional communication architecture, link design and mission operation concepts under consideration for the DSM Design Reference Mission(s). It is essential for Technology Readiness Level (TRL) advancement to develop DSM ISL solutions. The modeling and simulation methodology developed in this paper is applicable to other DSMs in near earth and deep space such as L1/L2 and Lunar region.

Acknowledgments

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