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GENERAL ATOMICS

DOTCOM

Deep-Space Orbital Telecommunications

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Project Definition

Project Definition → Baseline Design → Feasibility Analysis → Next Steps

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Mission Statement

Project DOTCOM aims to provide a scalable model of a representative network providing **high-speed, reliable communications** between **Earth-Moon and Mars-Moon systems.** A **Model-Based Systems Engineering simulation** and a **hardware network representation** will be used to demonstrate the network concept and provide an illustration of its processes. The software and hardware deliverables with provide insight that will inform the construction of a network architecture for current and future deep-space missions.

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Functional Requirements

FR 1 Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth-Moon and Mars-Moon systems.

FR 2 Satellite constellations around the Moon and Mars must be able to provide **communication** and **vehicle control capabilities** on their **surfaces** and in their **orbits**.

FR 3 Communication network must ensure safety of and be collaborative with **existing** and **future communications infrastructure.**

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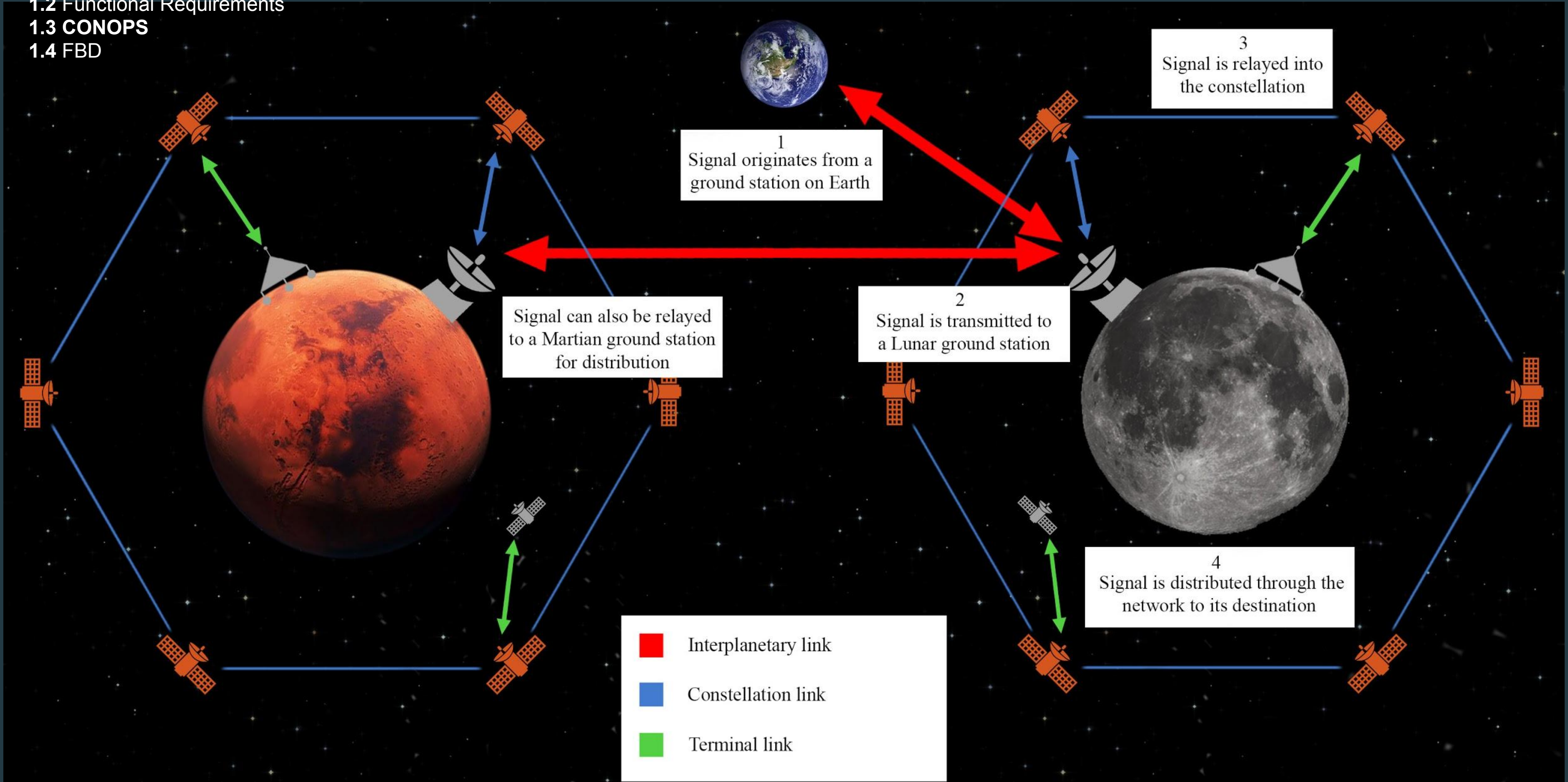
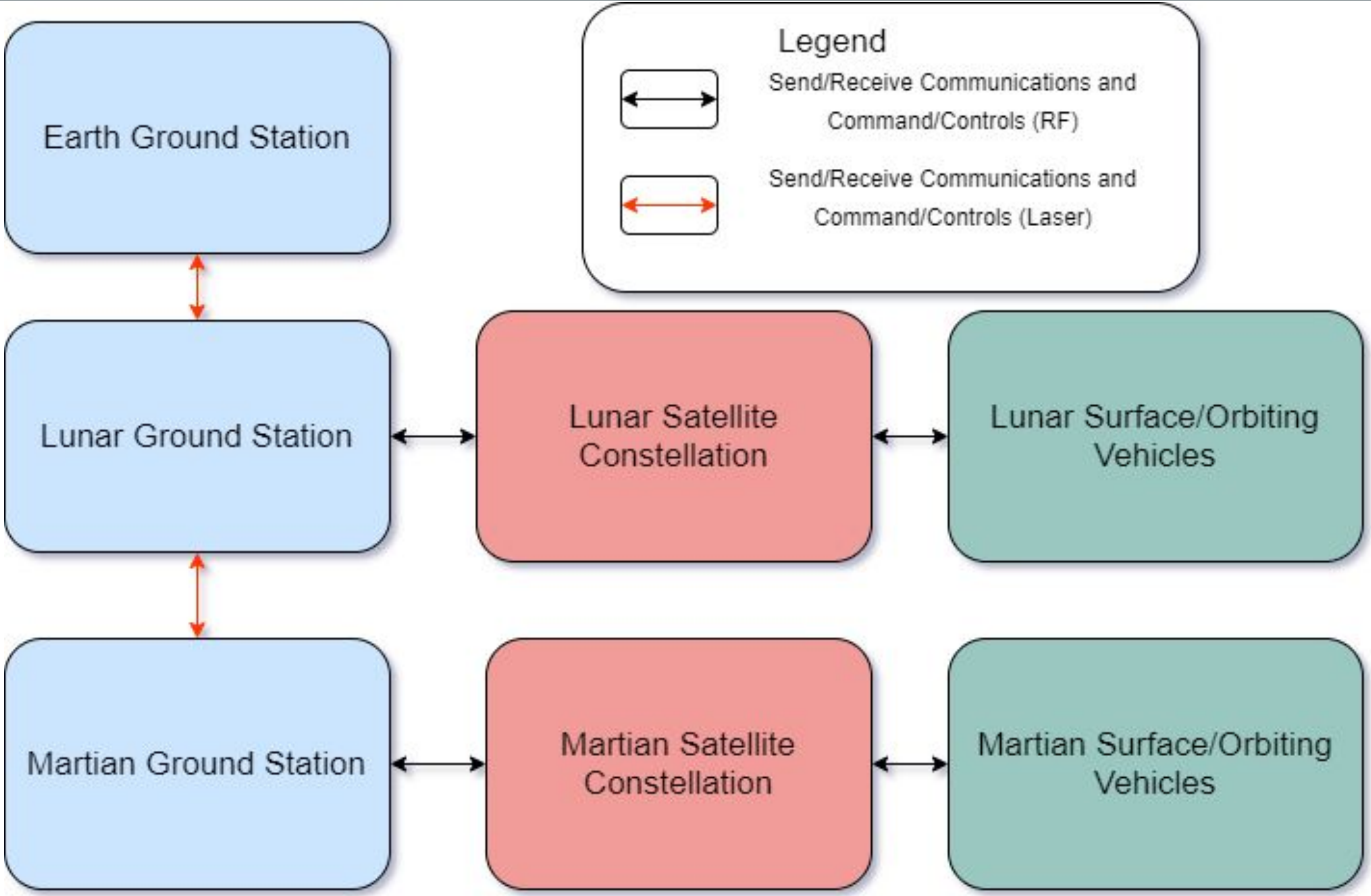
CONOPS


1
Signal originates from a ground station on Earth
2
Signal is transmitted to a Lunar ground station
3
Signal is relayed into the constellation
4
Signal is distributed through the network to its destination
Signal can also be relayed to a Martian ground station for distribution
Interplanetary link
Constellation link
Terminal link



Earth Ground Station
Legend
Send/Receive Communications and Command/Controls (RF)
Send/Receive Communications and Command/Controls (Laser)
Lunar Ground Station
Lunar Satellite Constellation
Lunar Surface/Orbiting Vehicles
Martian Ground Station
Martian Satellite Constellation
Martian Surface/Orbiting Vehicles

Baseline Design

Project Definition → Baseline Design → Feasibility Analysis → Next Steps

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Critical Project Elements

1) **Satellite Constellation Architecture:** Construction of ideal constellation architecture around each planetary body to satisfy coverage requirements.
2) **Extraterrestrial Relay Station:** The extraterrestrial support system allowing for direct access to communications between satellite constellations of each planetary communication system.
3) **Spectrum Allocation:** The project will meet certain data-relay rates for communication between the following: constellation satellites and ground stations, Earth and the Moon, and Mars and the Moon.
4) **Network Protocol:** Structured data transmission methodology that allows for high speed reliable communications from node to node.
5) **Network Representations:** Hardware + software models that demonstrate the network’s features.

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Satellite Constellation Architecture

Purpose: Distributes communication hardware in orbit so as to allocate connectivity throughout a planet's surface and orbit. Seeks to make efficient use of resources while also being effective, reliable, and compatible with all hardware, software, and electrical components of the project.

Functional Requirements:

- **FR 1** Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth-Moon and Mars-Moon systems.
- **FR 2** Satellite constellations around Moon and Mars must be able to provide communication and vehicle control capabilities on their surfaces and in their orbits.

Baseline Design Overview:

1) Satellite constellation architecture

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Extraterrestrial Relay

Purpose: Key design decision in overall network architecture. Seeks to seamlessly integrate network protocols into network architecture while attempting to minimize cost and maximize efficiency of the system over its lifespan.

Functional Requirements:

- **FR 1** Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth, Moon, and Mars.
- **FR 3** Communication network must ensure safety of and be collaborative with **existing** and **future communications infrastructure.**

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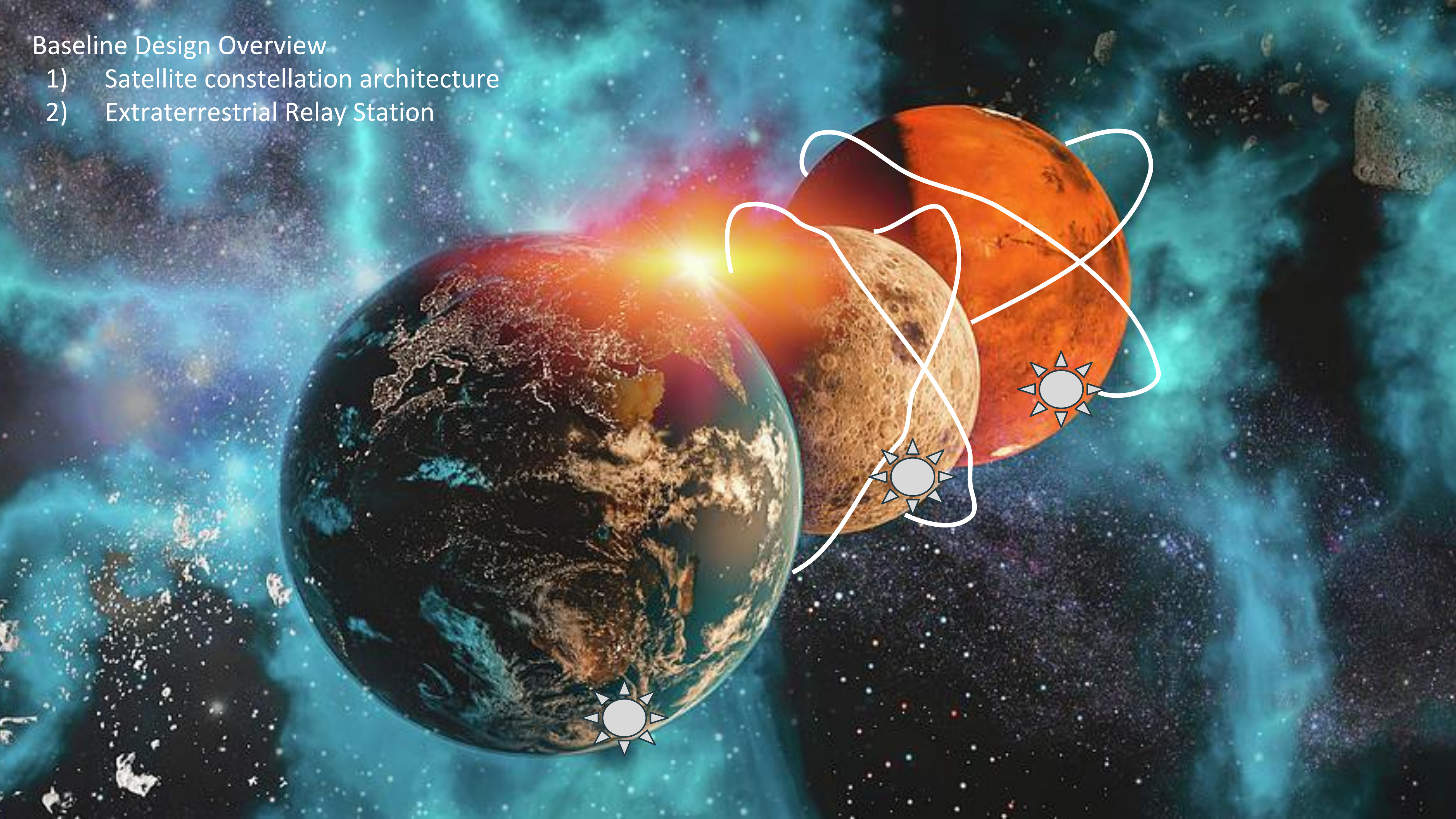
Baseline Design Overview

1) Satellite constellation architecture
2) Extraterrestrial Relay Station



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Spectrum Allocation

Purpose: Use RF communications for constellation data relay and laser communication for interplanetary data relay to provide total planetary coverage and to reach the objective data-transfer rates.

Functional Requirements:

- **FR 1:** Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth, Moon, and Mars.

- **FR 2:** Satellite constellations around the Moon and Mars must be able to provide **communication** and **vehicle control capabilities** on their **surfaces** and in their **orbits**.

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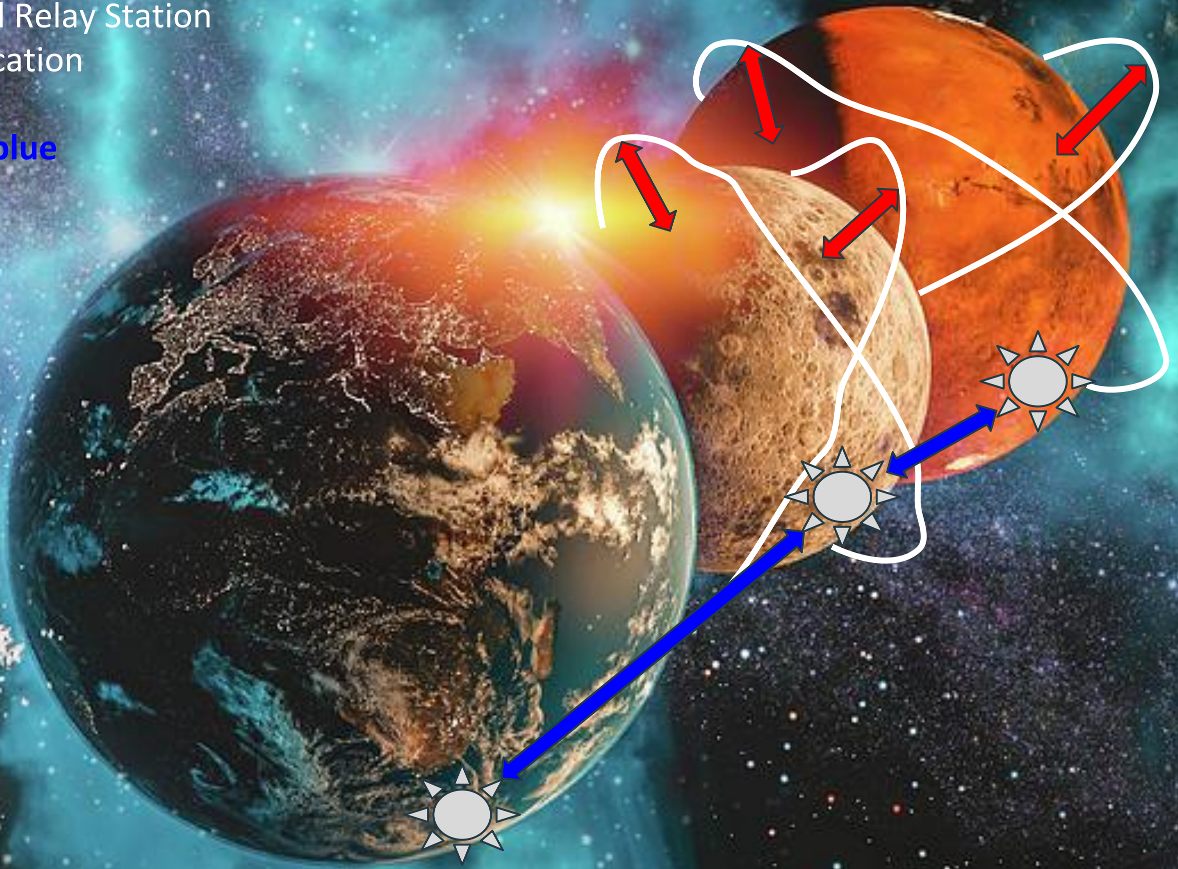
Baseline Design Overview:

1) Satellite constellation architecture
2) Extraterrestrial Relay Station
3) Spectrum Allocation
   a) RF = red
   b) Laser = blue



Network Protocol

Purpose: An approach to network architecture designed to handle intermittent connectivity in the network. Works to optimize transmission windows under high variability, be compatible with protocols existing within the network, and provide high speed telecommunications and data transmission throughout the network.

Functional Requirements:

- <u>**FR 1**</u> Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth, Moon, and Mars.

- <u>**FR 3**</u> Communication network must ensure safety of and be collaborative with **existing** and **future communications infrastructure.**

Network Protocol

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DTN Operating Assumptions

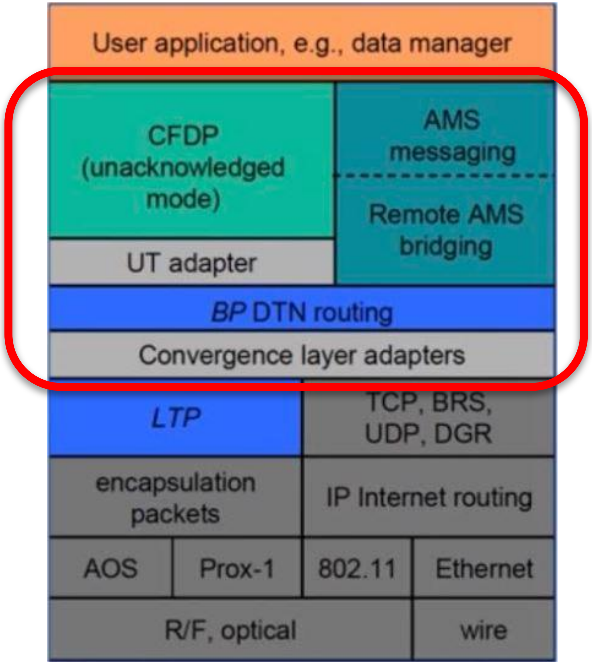
1. Long round trip data times
2. Intermittent connectivity
3. High bit error rates

Store and forward operating strategy

DTN Protocol Stack

- Universal compatibility with other protocols (TCP, LTC, etc.)

DTN Protocol Stack



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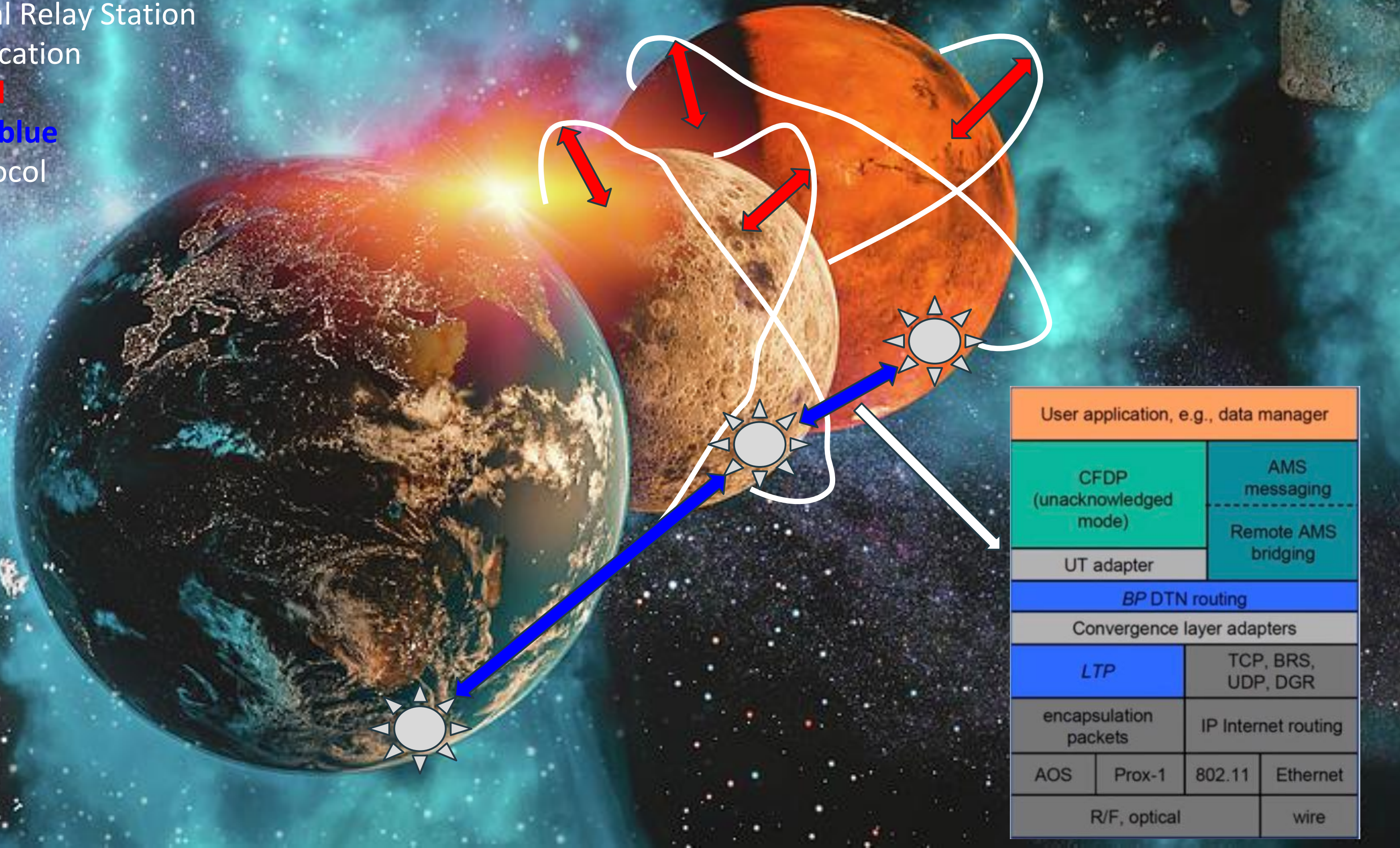
Baseline Design Overview:

1) Satellite constellation architecture
2) Extraterrestrial Relay Station
3) Spectrum Allocation
    a) RF = red
    b) Laser = blue
4) Network Protocol



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Network Representations

Purpose: Demonstrate the key features of the DOTCOM network and how its components will operate in order to meet our functional requirements.

1) A Model-Based Systems Engineering (MBSE) approach will be taken to create a software model of the detailed processes involved with data transmission between nodes of the network.
2) A hardware representation will be used to illustrate the functional capabilities that underlie the DOTCOM network concept. (protocol & comm systems).

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Model-Based Systems Engineering (MBSE)

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Purpose: MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases using System Markup Language (SysML). These system models are useful for showing relationships among system functions, requirements, developers, and users. MBSE will be used to do simulations based modifying our network design architecture, allowing us to optimize the communications network for the specific targets required by General Atomics, as well as verify all functional requirements.

Functional Requirements:

- <u>FR 1:</u> Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth, Moon, and Mars.
- <u>FR 2:</u> Satellite constellations around the Moon and Mars must be able to provide **communication** and **vehicle control capabilities** on their **surfaces** and in their **orbits**.
- <u>FR 3:</u> Communication network must ensure safety of and be collaborative with **existing** and **future communications infrastructure.**

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Credit to Lockheed Martin Corporation

Baseline Design

1. **Network Protocol**
- Will implement Delay Tolerant Networking protocol.
- Provide environmental transmission optimization and compatibility with existing and future networks.
2. **Spectrum Allocation**
- RF for short distance and laser communication for long distance data-transfer.
3. **Extraterrestrial Relay Station**
- Ground based relay station for increased accessibility, decreased cost, and easier communications.
4. **Satellite Constellation Architecture**
- Establish a medium-altitude constellation that provides complete coverage while minimizing the number of satellites required to do so.
5. **System Prototype Design/Testing**
- Demonstrate DTN capability through use of a scaled, physical system, as well as conceptual network architecture using MBSE simulation.

Project Deliverables

1) Complete MBSE simulation of the entire system architecture encompassing all aspects of the design and implementations.
2) Physical hardware simulation to test a scaled model of the network protocol using differentiated nodes representing key parts of the network architecture (laser communications, RF communications, and varied transmission windows).

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Evidence of Baseline Feasibility

Project Definition

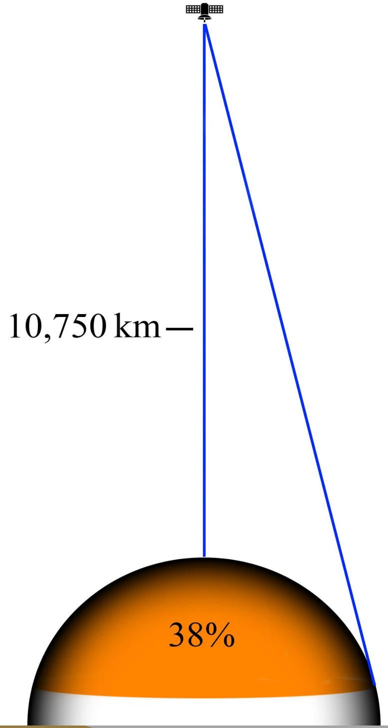
Baseline Design

Feasibility Analysis

Next Steps

Medium-Altitude Constellation Feasibility

- Cost effective, requiring minimal vehicles
- Accommodating of communications hardware, with modest power and pointing accuracy requirements
- More resilient to vehicle failure than a high-altitude constellation



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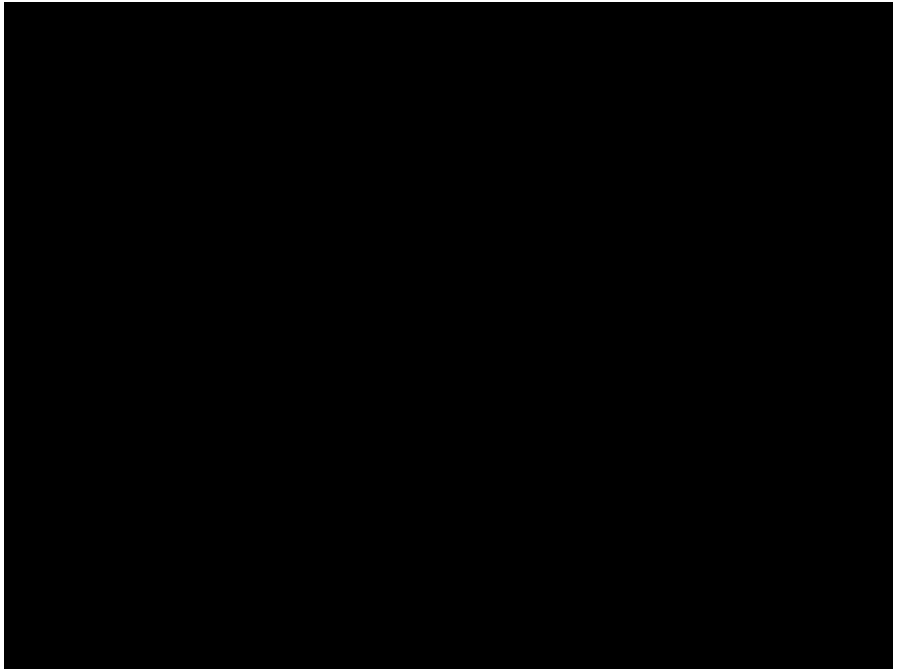
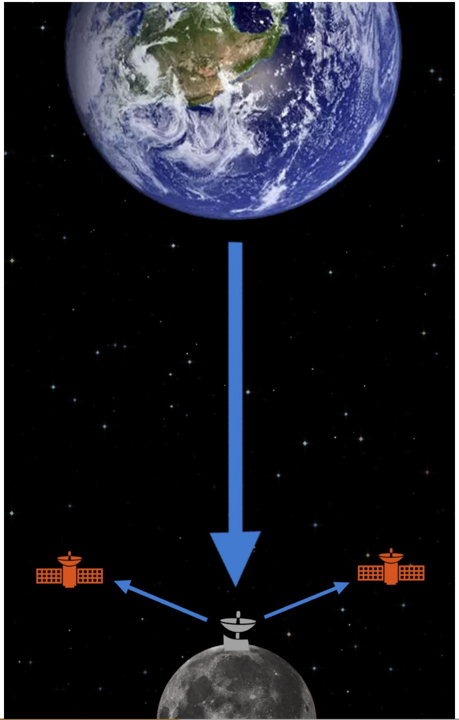
Medium-Altitude Constellation Feasibility

- 6 satellites
- Walker-Delta constellation
- Medium altitude
  - 10,750 km over Mars
  - 5,510 km over Moon



Ground-Based Relay Station Feasibility

- Advantages:
  - Low Costs
    - Development
    - Maintenance
  - Good Accessibility
    - Maintenance
    - Upgrades
    - Scaling
- Disadvantages:
  - Location Restrictions
  - More Infrastructure



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RF Communications for Surface to Constellation Data Relay Feasibility

- Fewer satellites in constellation and less ground stations
- Easier to achieve total planetary coverage (pointing accuracy for RF is less strict than laser)
  - Larger footprint with RF = better coverage
- Less atmospheric interference and more reliable, can use X band (<12GHz), not affected by atmosphere (could be an issue on Mars)

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Laser Communication for Interplanetary Data Relay Feasibility

- High data rates = large data packages to be sent in shorter amount of time (especially important for long distance relay)
- Can achieve the required data rates between planetary bodies DR 1.6 & 1.7)
- Wavelengths are 10,000 times shorter, allowing for a narrower beam and significantly more bandwidth
- Optical band unlicensed and highly unregulated compared to electromagnetic spectrum (RF)

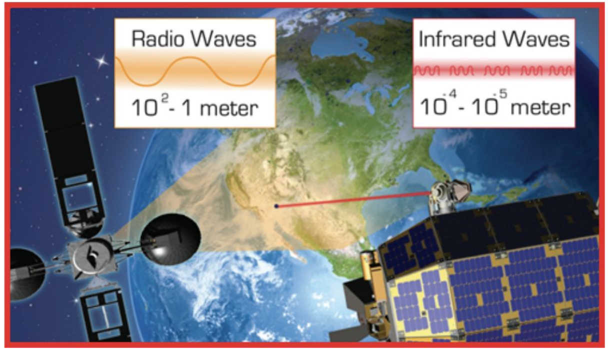

Image Reference: NASA LLCDFactSheet (https://www.nasa.gov/sites/default/files/llcdfactsheet.final_.web_.pdf, 2020)

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RF vs Laser Comparison Analysis

- Laser: Low mass s/c disturbance isolation assembly, flight qualified photon counting detector array, high efficiency flight laser amplifier, high efficiency photon counting detector array for ground-based receiver
- RF: needs more power, has larger antenna diameter, and weighs more than a laser system. Coverage of celestial bodies is much easier with RF

Link	Optical	RF
GEO-LEO		
Antenna Diameter	10.2 cm (1.0)	2.2 m (21.6)
Mass	65.3 kg (1.0)	152.8 kg (2.3)
Power	93.8 W (1.0)	213.9 W (2.3)
GEO-GEO		
Antenna Diameter	13.5 cm (1.0)	2.1 m (15.6)
Mass	86.4 kg (1.0)	145.8 kg (1.7)
Power	124.2 W (1.0)	204.2 W (1.6)
LEO-LEO		
Antenna Diameter	3.6 cm (1.0)	0.8 m (22.2)
Mass	23.0 kg (1.0)	55.6 kg (2.4)
Power	33.1 W (1.0)	77.8 W (2.3)

Table Reference: Optical Communication in Space: Challenges and Mitigation Techniques (https://arxiv.org/pdf/1705.10630.pdf, 2020)

RF vs Laser Comparison Analysis

- Beam spread by optical carrier is narrower and allows for increased intensity of signal at receiver for given transmitted power
- Smaller wavelengths = smaller antenna with same gain compared to RF b/c antenna gain scales inversely proportional to the square of operating wavelength

λ = carrier wavelengths, D_R = aperture diameter

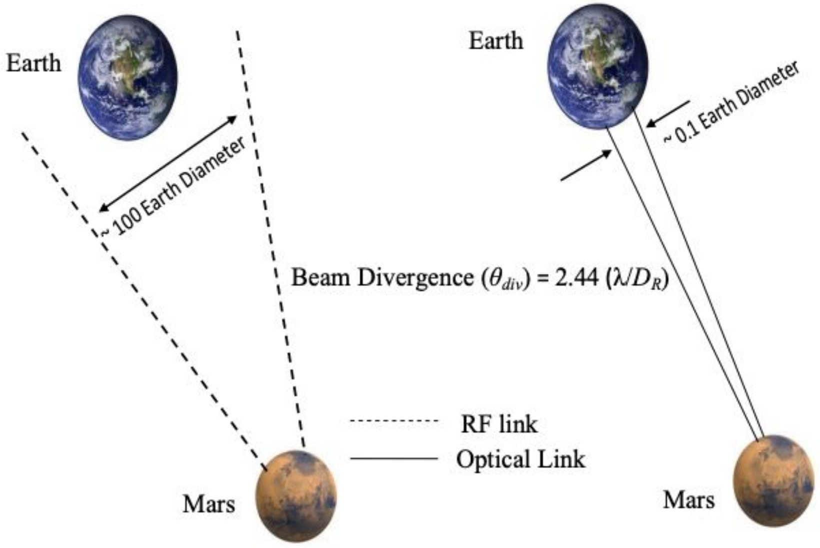

Image Reference: Optical Communication in Space: Challenges and Mitigation Techniques (https://arxiv.org/pdf/1705.10630.pdf, 2020)

DTN Feasibility

1) Flight ready tech with open source software and NASA development tool
2) DTN provides:
   a) Decreased latency over networks with variable connections
   b) More data throughput
   c) Faster corrections for missing or corrupted bundles
   d) Compatible with TCP, UDP, LTP, SCPS
   e) User set congestion control options
   f) Built in security and encryption options

- Downside: requires 'smart' intermediary nodes with data storage capability

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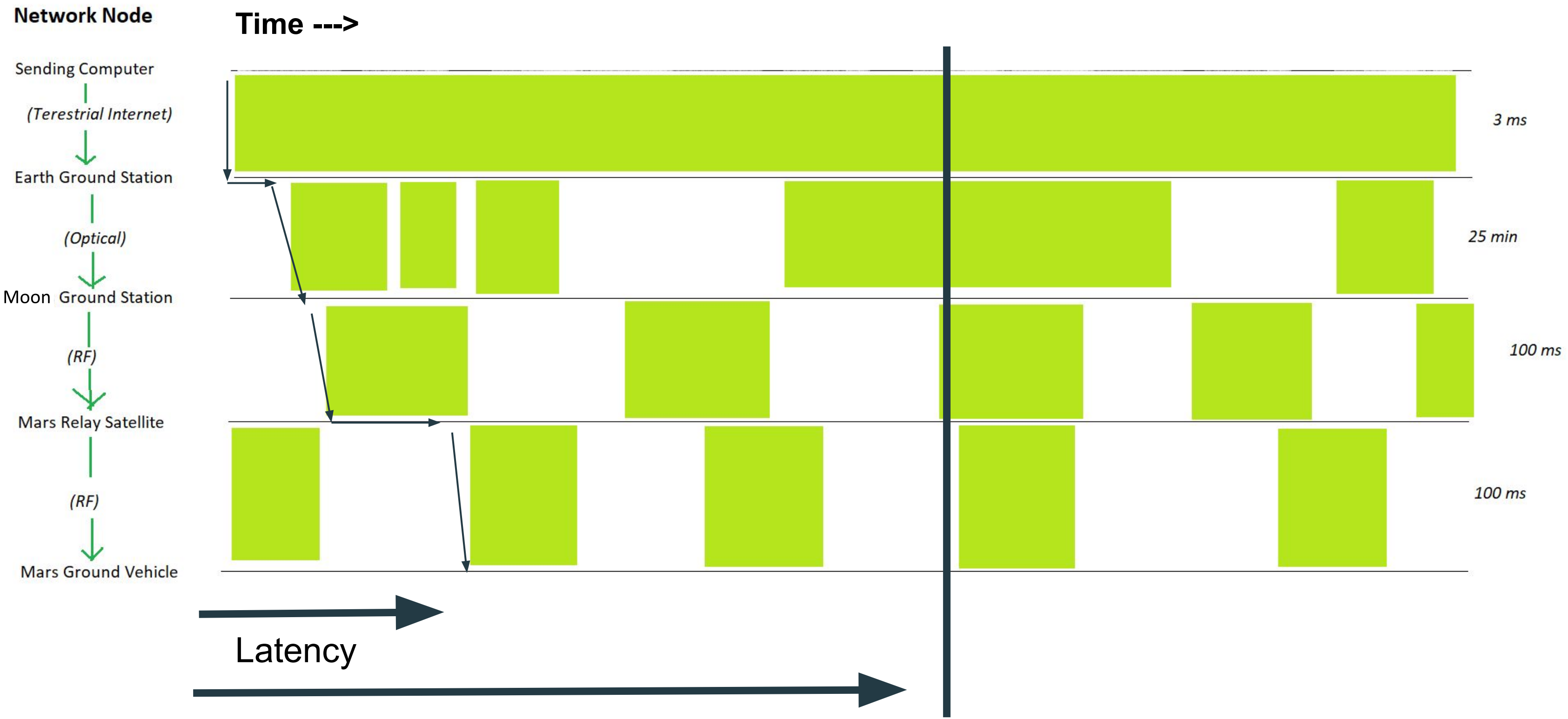
DTN vs TCP/IP Latency



DTN Feasibility

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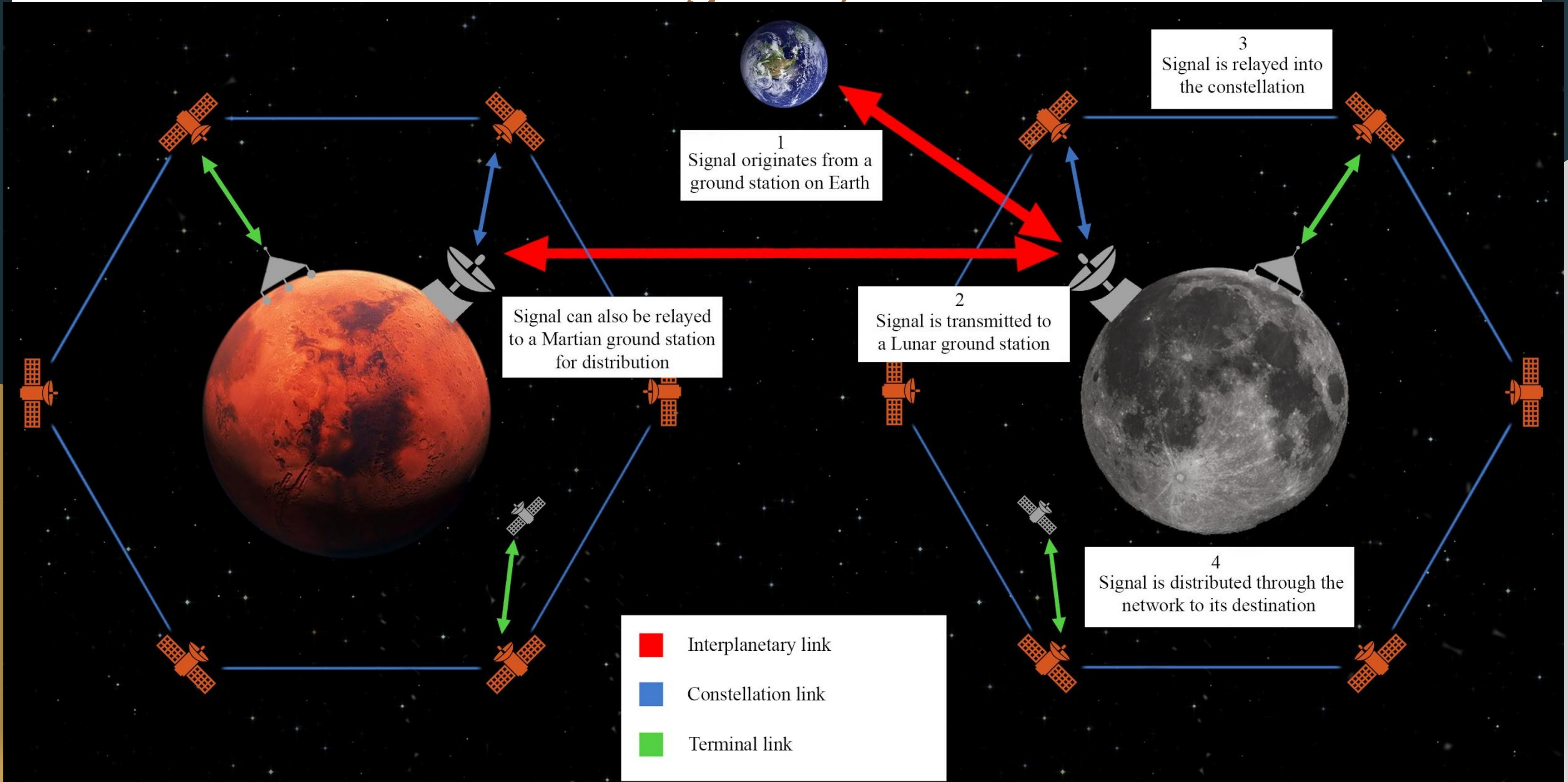
Network Diagram, i.e. CONOPS



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DTN Feasibility

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- Downside: requires ‘smart’ intermediary nodes with data storage capability

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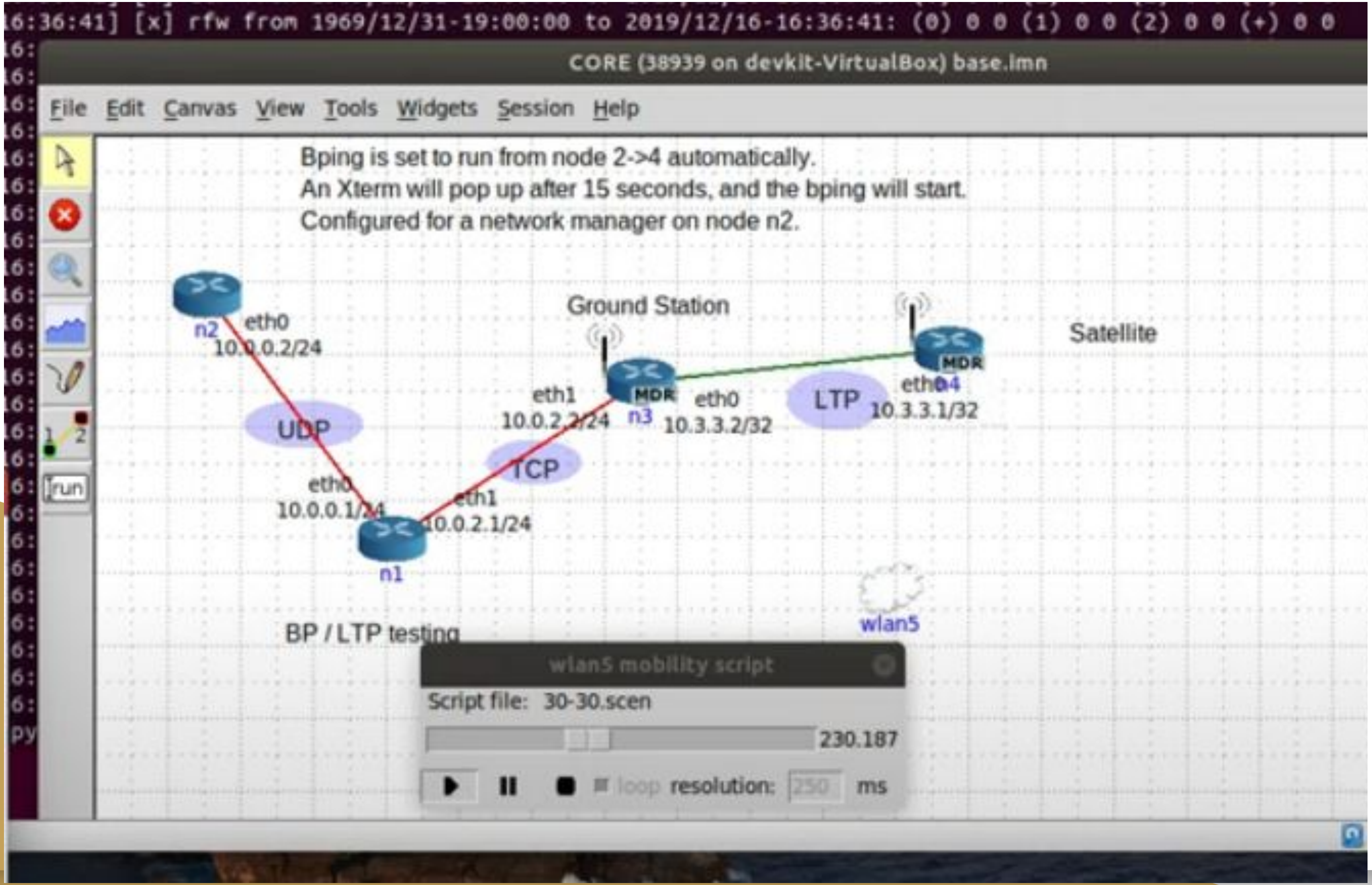
NASA DevKit DTN Simulation




Reverting to full screen capture at every frame.
To disable this check run with --no-wm-check
(though that is not advised, since it will probably produce faulty results).
Initializing...
Buffer size adjusted to 4096 from 4096 frames.
Opened PCM device default
Recording on device default is set to:
1 channels at 22050Hz
Capturing!
X Error: BadAccess (attempt to access private resource denied)
ccess private resource denied)
ccess private resource denied)
bpsend ipn:4.3 curiosity.png

MBSE Feasibility

As team DOTCOM's project is heavily future-tense technology with full implementation not expected until 2040, a lack of hard document-based engineering exists for this area of study, allowing MBSE to shine

- Moves record authority from documents to continuously updating digital SysML modeling, a perfect fit for today's highly-asynchronous online work environment where all involved parties must have up-to-date information
- MBSE allows design changes to be more readily explained and disseminated through the project workforce before a project is actually built
- Allows for any mistakes or defects in design to be caught earlier in development, a must-have for a project on a timeline and theoretical budget such as ours

The combined strengths of MBSE make for a more cohesive project environment for all shareholders while reflecting the interconnected nature of engineering a space-based communications network

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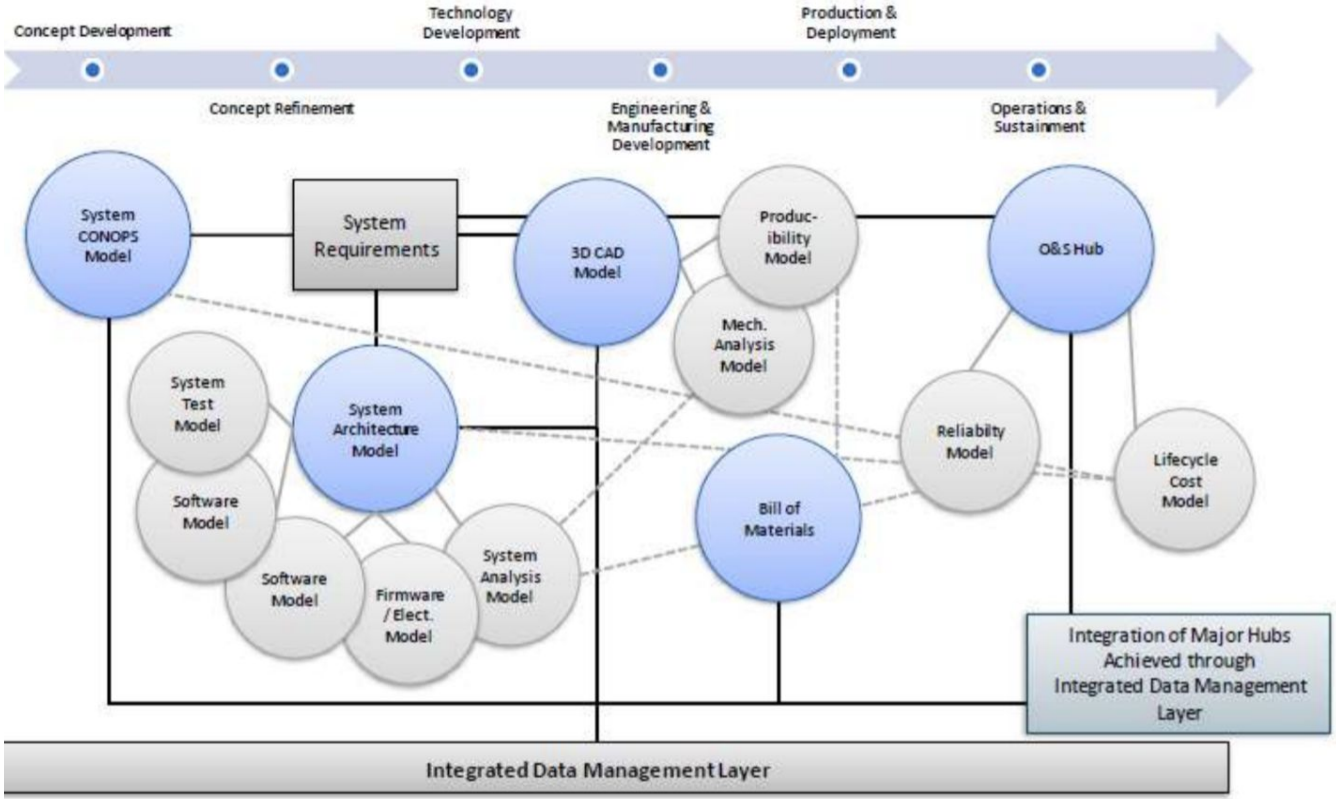
Focus on System Models



Within MBSE, project focus is on **System Models** generated from the **Overall Network Architecture** through representative diagrams

Subsystems of the System Architecture Model include the **Domain Models**

Development of Domain Models

Domain Models are the Critical Project Elements

Subteams will develop their domain models to be implemented into MBSE

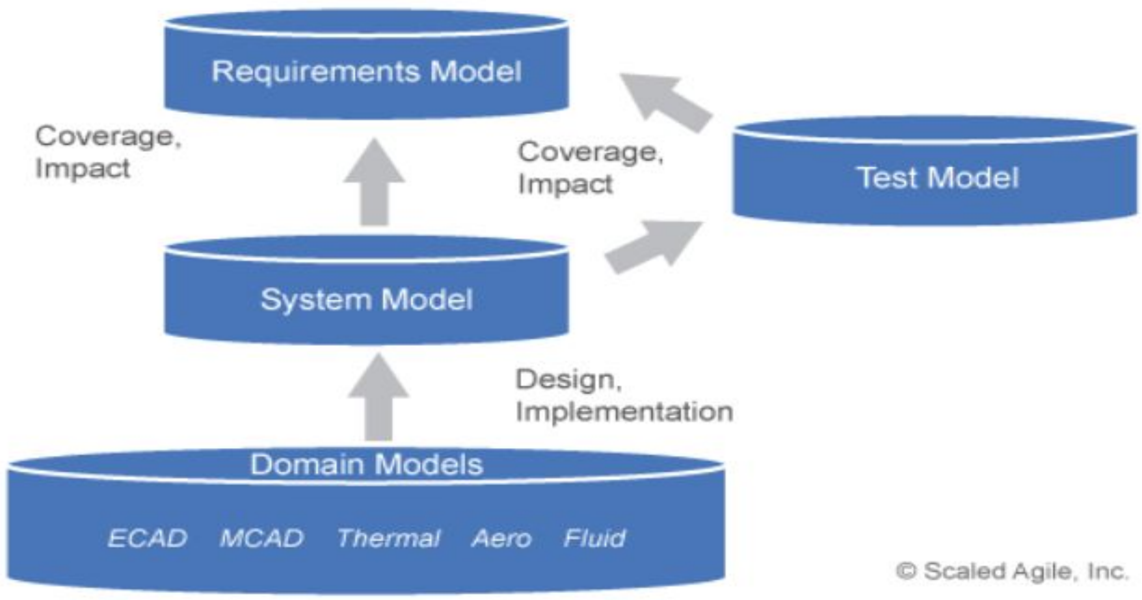


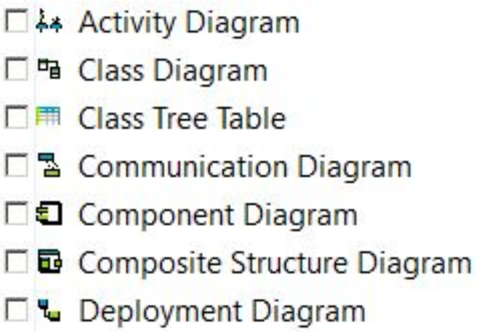
Figure 3. Linking cross-domain models

MBSE Software

Best Option: **Eclipse - Papyrus:** free to use, flexible UI, demonstrable system architecture

Others: need license

- IBM Rhapsody
- CAMEO
- Capella
- Enterprise Architect



Hardware Design Feasibility

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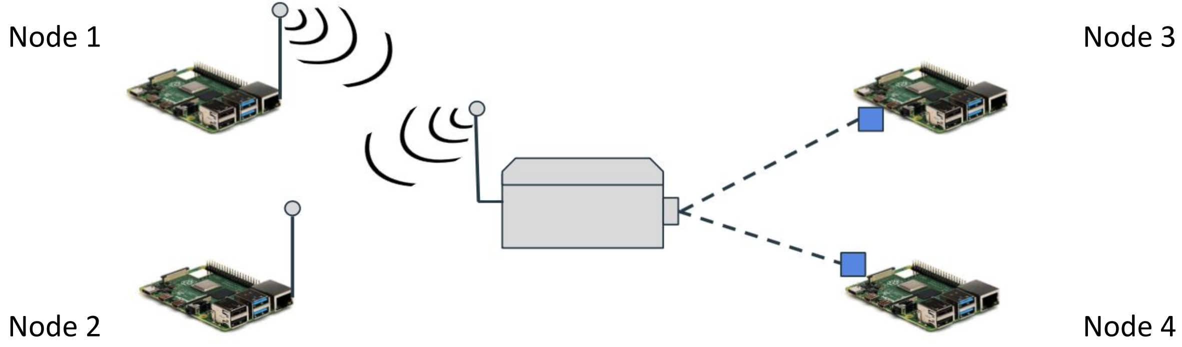
- The design gives a hands-on demonstration of the DTN through the RF/laser communication
- Demonstrate the performance of DTN with RF and laser communication as pertaining to the overall network concept
- Raspberry Pi computers exchanging communications via both signal transmission methods and operating using DTN procedures



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Next Steps

Project Definition

Baseline Design

Feasibility Analysis

Next Steps

Studies Left

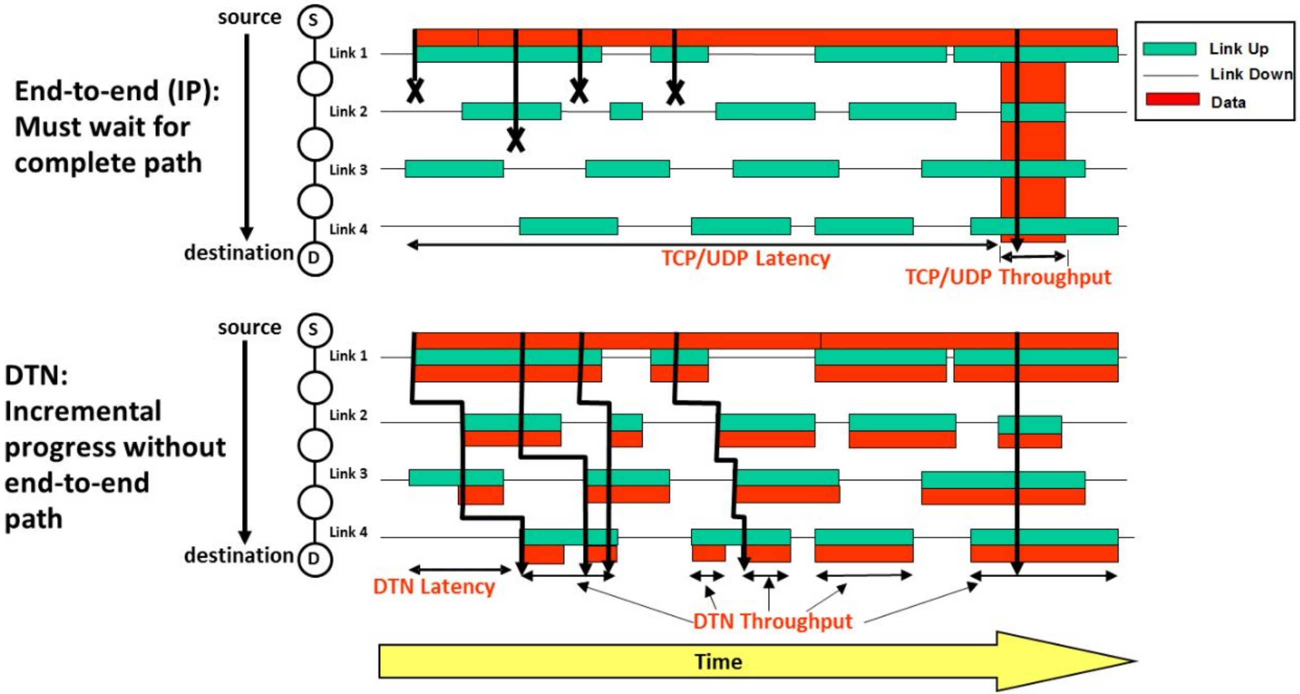
- What other DTN features can we illustrate in our hardware representation?
  - Network congestion, bandwidth, transmit/receive timestamps.
- Detailed cost analysis on all system elements.
- **Analyze and compare various network designs to optimize the system:**
  - **# of nodes & locations, constellation orbits, connection windows, data routing, implementation (timeline).**

APPENDIX

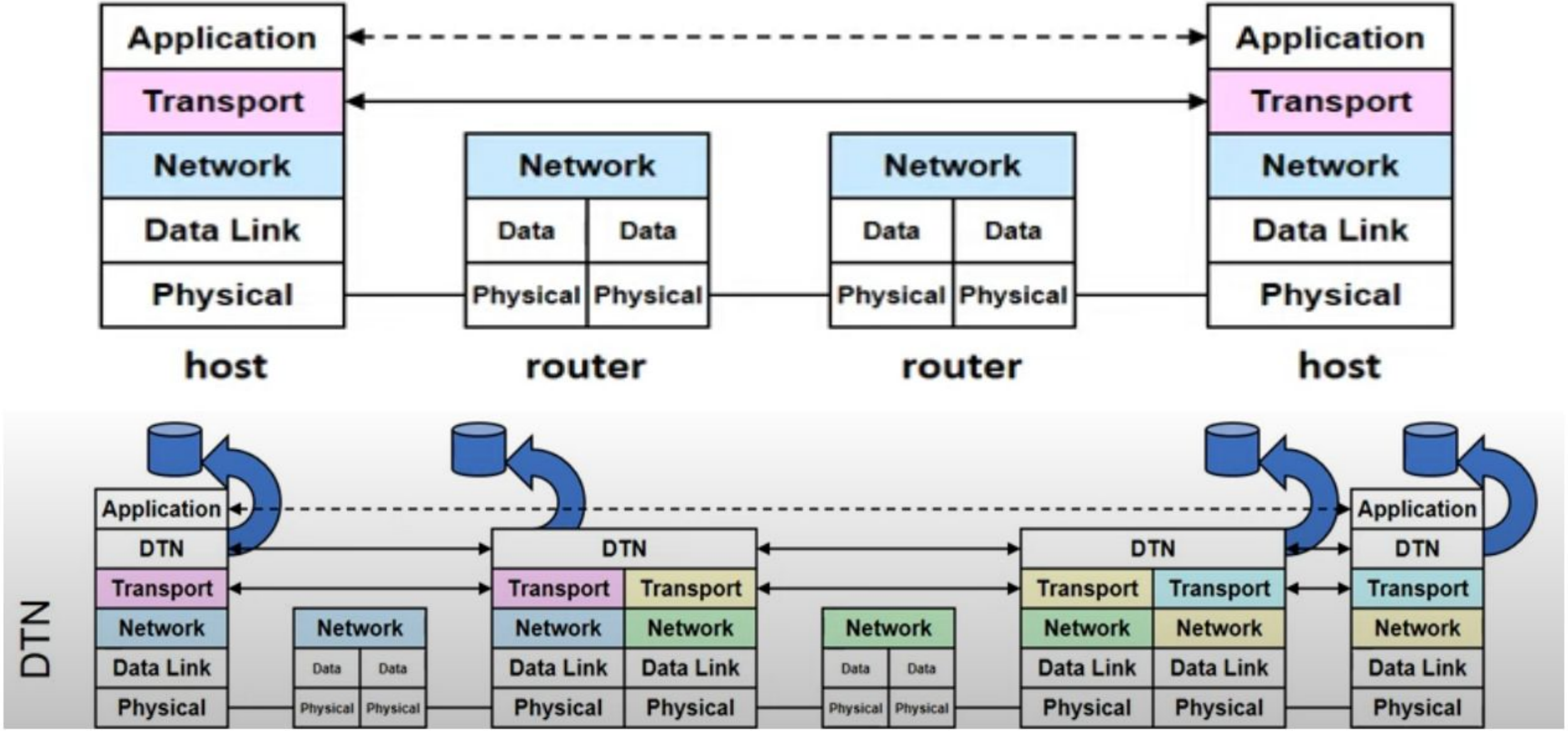
DTN Trade Study

Criteria	Weight	Evaluation		Score	
		IP	DTN	IP	DTN
Robustness	2.5	4	8	10	20
Latency	2.5	4	6	10	15
Network Congestion	2	4	7	8	14
Complexity	.5	7	3	3.5	1.5
Scalability	1	4	7	4	7
Compatibility	1.5	4	9	6	13.5
		Total Score		41.5	71

DTN Latency and Throughput - NASA



DTN VS IP intermediary nodes



FR 1 Communication architecture must be capable of transmitting and receiving data **simultaneously** and **non-simultaneously (store-and-forward)** between the Earth, Moon, and Mars

DR 1.1 The mission shall provide real time (light-time delay with additional delay less than 1 second) relay of data from the Lunar and Martian environments to Earth-based communications networks.

DR 1.2 The mission shall provide global surface telecommunications coverage (>99%) of the Lunar and Martian surface.

DR 1.3 The mission shall provide simultaneous telecommunications availability (>99%) of the Lunar and Martian surface.

DR 1.4 The mission shall provide simultaneous telecommunications availability (>99%) of the Lunar and Martian orbit.

DR 1.5 The mission shall provide the ability to relay data between mission segments (Earth/Lunar/Martian communication networks).

DR 1.6 The mission shall allow for high speed data transmission between the Moon and Mars, with threshold and objective rates to be 50 Mbps and 500 Mbps, respectively.

DR 1.7 The mission shall allow for high speed data transmission between the Moon and Earth, with threshold and objective rates being 500 Mbps and 5 Gbps, respectively

FR 2 Satellite constellations around the Moon and Mars must be able to provide **communication** and **vehicle control capabilities** on their **surfaces** and in their **orbits**.

DR 2.1 The mission shall provide the ability to command Lunar and Martian surface vehicles.

DR 2.2 The mission shall provide the ability to command Lunar and Martian orbiting vehicles.

DR 2.3 The mission shall provide simultaneous communication support to 5 or more locations on the Lunar Surface and 10 or more locations on the Martian Surface.

DR 2.4 The mission shall provide non-simultaneous store and forward (within six hours of transmission) communication support of 10 or more locations on the Lunar Surface and 20 or more locations on the Martian Surface.

DR 2.5 The mission shall provide simultaneous communication support of 10 or more space vehicles in Lunar Orbit and 15 or more space vehicles in Martian Orbit.

DR 2.6 The mission shall provide non-simultaneous store and forward (within six hours of transmission) communication support of 20 or more space vehicles in Lunar Orbit and 30 or greater space vehicles in Martian Orbit.

FR 3 Communication network must ensure safety of and be collaborative with **existing** and **future communications infrastructure.**

DR 3.1 The mission shall utilize existing NASA communications infrastructure wherever possible.

DR 3.2 The mission shall not interfere with the operational capabilities of the Lunar Gateway.

DR 3.3 The mission shall be capable of supporting Lunar Gateway communications signals.

DR 3.4 The mission shall be capable of interfacing with government and/or commercial communications infrastructure.

DR 3.5 The mission shall comply with FTC/ITU regulations.

Laser vs RF Trade Study

5.2.2 Trade Study Evaluation

Criteria	Weight	Evaluation		Score	
		RF Coms	Laser Coms	RF Coms	Laser Coms
Power Requirements	1	4	9	4	9
Range and Coverage	4	10	4	40	16
Bandwidth and Frequency	5	10	10	50	50
			Total Score	94	75

Table 20: Communications Method Trade Study Surface To Constellation

Criteria	Weight	Evaluation		Score	
		RF Coms	Laser Coms	RF Coms	Laser Coms
Power Requirements	1	3	8	3	8
Range and Coverage	4	10	6	40	24
Bandwidth and Frequency	5	2	10	20	50
			Total Score	63	82

Table 21: Communications Method Trade Study Interplanetary

Link Difficulty Summary NASA Deep Space Optical Communications

Link difficulty summary of recent and planned NASA optical communications

		Data rate (Mb/s)	Distance (AU)	Link difficulty (Mb/s-AU²)	Link difficulty (dB-Mb/s-AU²)
LLCD	Downlink	622.0	2.70E–03	4.53E–03	–23.4
	Uplink	20.0	2.70E–03	1.46E–04	–38.4
LCRD	Downlink	1200.0	2.68E–04	8.65E–05	–40.6
	Uplink	1200.0	2.68E–04	8.65E–05	–40.6
DSOC	Downlink	267.0	2.00E–01	1.07E+01	10.3
	Downlink	267.0	5.50E–01	8.08E+01	19.1
	Uplink	0.2	2.00E+00	8.00E–01	–1.0

Source: NASA Fact Sheet: Deep Space Optical Communications (DSOC) https://www.nasa.gov/sites/default/files/atoms/files/fs_dsoc_factsheet_150910.pdf

Laser Wavelengths

Mission	Laser	Wavelength	Other parameters	Application
Semiconductor Inter-satellite Link Experiment (SILEX) [52]	AlGaAs laser diode	830 nm	60 mW, 25 cm telescope size, 50 Mbps, 6 μrad divergence, direct detection	Inter-satellite communication
Ground/Orbiter Lasercomm Demonstration (GOLD) [27]	Argon-ion laser/GaAs laser	Uplink: 514.5 nm Downlink: 830 nm	13 W, 0.6 m and 1.2m transmitter and receiver telescopes size, respectively, 1.024 Mbps, 20 μrad divergence	Ground-to-satellite link
RF Optical System for Aurora (ROSA) [53]	Diode pumped Nd:YVO4 laser	1064 nm	6 W, 0.135 m and 10 m transmitter and receiver telescopes size, respectively, 320 kbps	Deep space missions
Deep Space Optical Link Communications Experiment (DOLCE) [54]	Master oscillator power amplifier (MOPA)	1058 nm	1 W, 10-20 Mbps	Inter-satellite/deep space missions
Mars Orbiter Laser Altimeter (MOLA) [55]	Diode pumped Q switched Cr:Nd:YAG	1064 nm	32.4 W, 420 μrad divergence, 10 Hz pulse rate, 618 bps, 850 μrad receiver field-of-view (FOV)	Altimetry
General Atomics Aeronautical Systems, Inc. (GA-ASI) & TESAT [56]	Nd:YAG	1064 nm	2.6 Gbps	Remotely piloted aircraft (RPA) to LEO
Altair UAV-to-ground Lasercomm Demonstration [57]	Laser diode	1550 nm	200 mW, 2.5 Gbps, 19.5 μrad jitter error, 10 cm and 1 m uplink and downlink telescopes size, respectively	UAV-to-ground link
Mars Polar Lander [58]	AlGaAs laser diode	880 nm	400 nJ energy in 100 nsec pulses, 2.5 kHz rate, 128 kbps	Spectroscopy
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) [59]	Nd:YAG	532 nm/1064 nm	115 mJ energy, 20 Hz rate, 24 ns pulse	Altimetry
KIrari's Optical Downlink to Oberpfaffenhofen (KIODO) [60]	AlGaAs laser diode	847 nm/810 nm	50 Mbps, 40 cm and 4 m transmitter and receiver telescopes size, respectively, 5μrad divergence	Satellite-to-ground downlink
Airborne Laser Optical Link (LOLA) [36]	Lumics fiber laser diode	800 nm	300 mW, 50 Mbps	Aircraft and GEO satellite link
Tropospheric Emission Spectrometer (TES) [61]	Nd:YAG	1064 nm	360 W, 5 cm telescope size, 6.2 Mbps	Interferometry
Galileo Optical Experiment (GOPEX) [25]	Nd:YAG	532 nm	250 mJ, 12 ns pulse width, 110 μrad divergence, 0.6 m primary and 0.2 m secondary transmitter telescope size, 12.19 x 12.19 mm charge coupled device (CCD) array receiver	Deep space missions
Engineering Test Satellite VI (ETS-VI) [62]	AlGaAs laser diode (downlink) Argon laser (uplink)	Uplink: 510 nm Downlink: 830 nm	13.8 mW, 1.024 Mbps bidirectional link, direct detection, 7.5 cm spacecraft telescope size, 1.5 m Earth station telescope	Bi-directional ground-to-satellite link
Optical Inter-orbit Communications Engineering Test Satellite (OICETS) [63]	Laser Diode	819 nm	200 mW, 2.048 Mbps, direct detection, 25 cm telescope size	Bi-directional Inter-orbit link
Solid State Laser Communications in Space (SOLACOS) [64]	Diode pumped Nd:YAG	1064 nm	1 W, 650 Mbps return channel and 10 Mbps forward channel, 15 cm telescope size, coherent reception	GEO-GEO link
Short Range Optical Inter-satellite Link (SROIL) [65]	Diode pumped Nd:YAG	1064 nm	40 W, 1.2 Gbps, 4 cm telescope size, BPSK homodyne detection	Inter-satellite link
Mars Laser Communications Demonstration (MLCD) [66]	Fiber laser	1064 nm and 1076 nm	5 W, 1- 30 Mbps, 30 cm transmitter telescope size and 5 m and 1.6 m receiver telescope size, 64 PPM	Deep space missions

Table II
WAVELENGTHS USED IN PRACTICAL FSO COMMUNICATION SYSTEMS

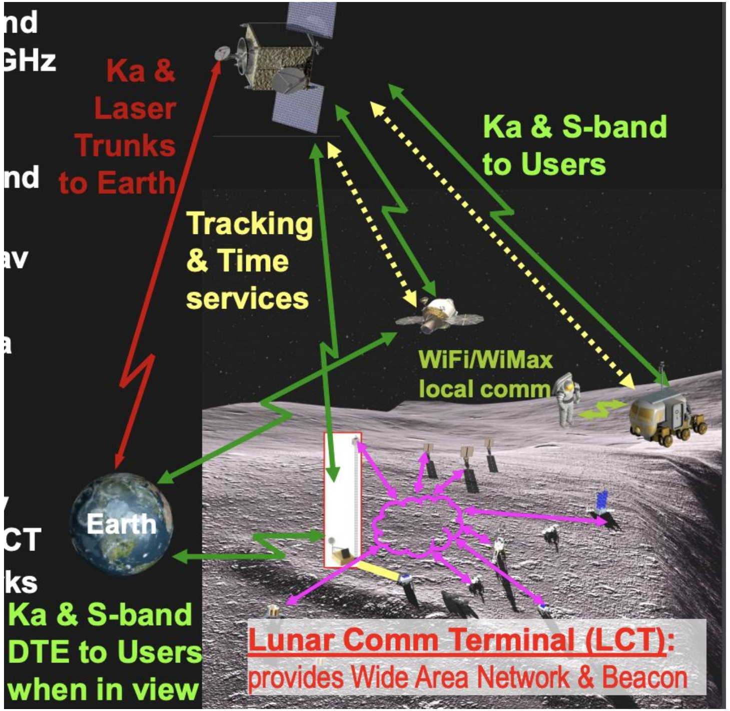
NASA Deep Space Network (DSN) Ground Station Locations

IEEE COMMUNICATIONS SURVEYS & TUTORIALS (DRAFT)

Fig. 15. Locations' of NASA Deep Space Network and ESA ESTRACK sites

NASA Lunar Communication 2020

- Optical comm with 1 Gbps return rate; 100 Mbps forward
- RF: Up to 250 Mbps return data and 100 Mbps forward data using 40 GHz Ka-band



Constellation Architecture Trade Study

Criteria	Weight	Evaluation			Score		
		High	Medium	Low	High	Medium	Low
Cost	5	10	9	2	50	45	10
Link Budget	3	3	5	7	9	15	21
Failure	2	2	3	10	4	6	20
				Total	63	66	51

Preliminary Constellation Design Groundtracks