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GENERAL ATOMICS

DOT COM

Deep-Space Orbital Telecommunications

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DOTCOM

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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 system.** 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 will provide insight that will inform the construction of a network architecture for current and future deep-space missions.

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Hardware CONOPS

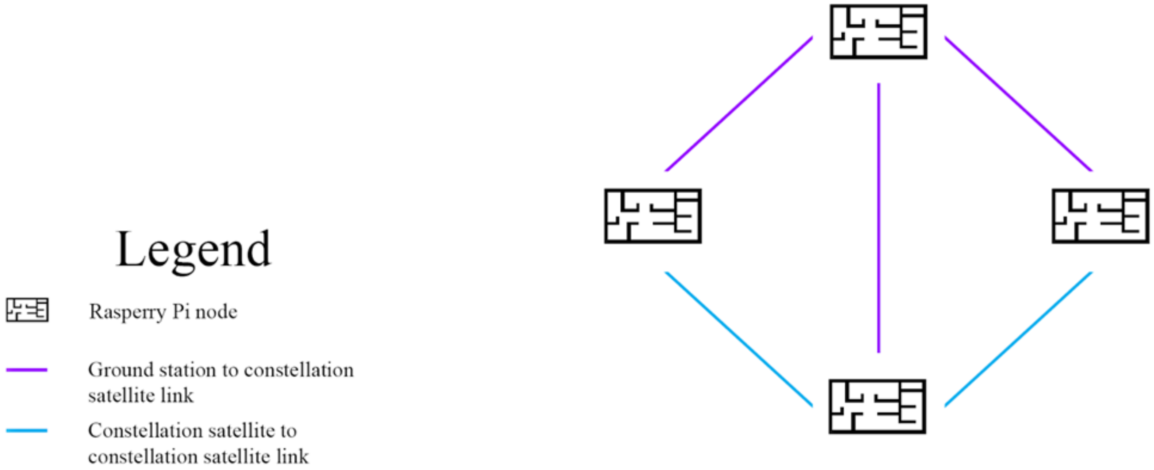
Level 1 Success

Legend

Rasperry Pi node

Ground station to ground station link

Level 2 Success



1 Project Purpose and Objectives

1.1 Mission Statement

1.2 CONOPS

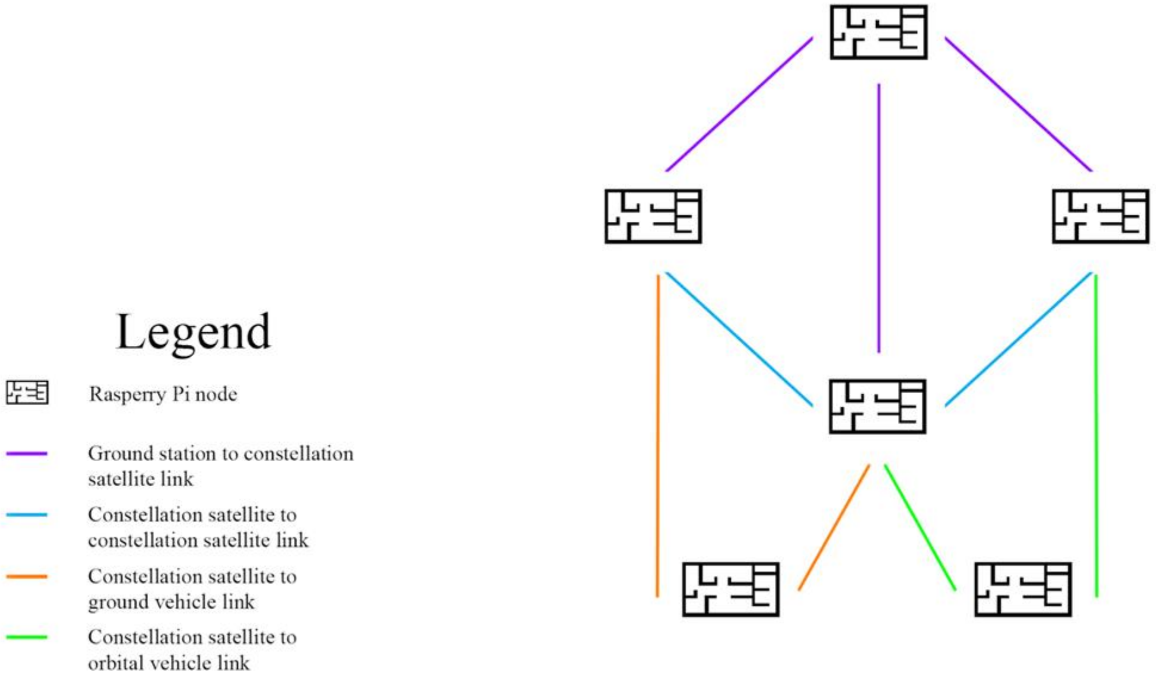
1.2.1 Hardware CONOPS

1.2.2 System CONOPS

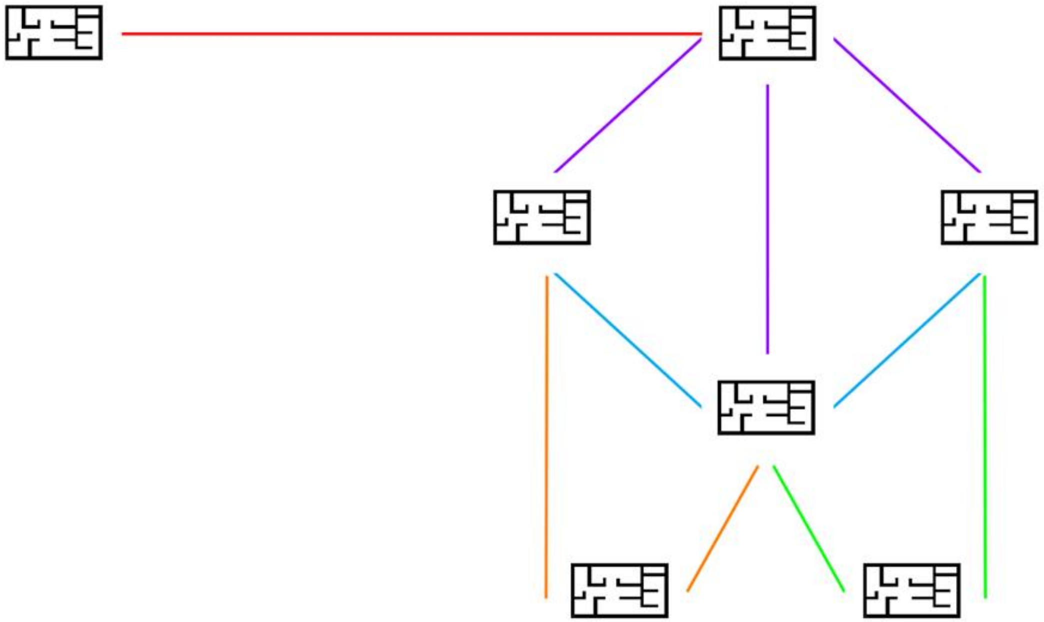
1.3 Functional Requirements

1.4 Project Goals

Level 3 Success



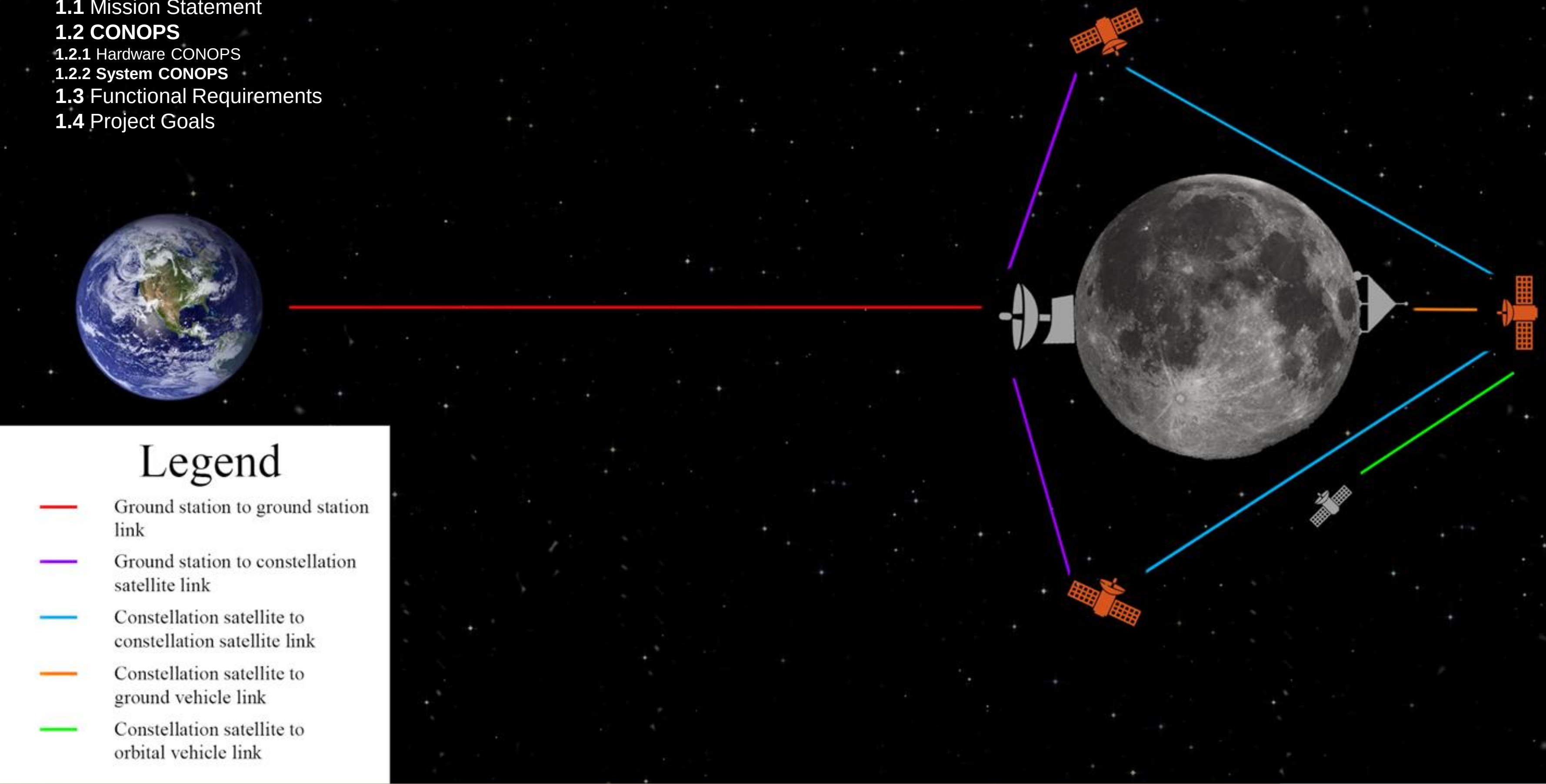
Level 4 Success



Legend

- Rasperry Pi node
- Ground station to ground station link
- Ground station to constellation satellite link
- Constellation satellite to constellation satellite link
- Constellation satellite to ground vehicle link
- Constellation satellite to orbital vehicle link

System CONOPS



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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 **Earth and the Moon.**

FR 2 - Satellite constellations around The Moon 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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FR 1 Transmit and Receive Data

- **Continuous data connections** between planetary bodies
- **Store and forward connections** not to exceed 6 hrs
- 99% telecommunications coverage in **Lunar Orbit**
- 99% telecommunications coverage on **Lunar Surface**

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FR 2 Vehicle Support

- Provide simultaneous communication for **5 or more lunar surface locations**
- Provide store and forward communication for **10 or more lunar surface locations**
- Provide simultaneous communication for **10 or more lunar orbit locations**
- Provide store and forward communication for **20 or more lunar orbit locations**

Network should have the capacity to support **15 surface vehicles and 30 orbital vehicles**

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FR 3 Compatibility

- Network utilize existing NASA communications architecture whenever possible
- Network should be compatible with the Lunar Gateway Project

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DOTCOM Project Goals

1. Design an **interplanetary communications network** that satisfies project design requirements
2. Model to **test and validate** design decisions
3. Use **hardware** to validate software model capabilities and design decisions

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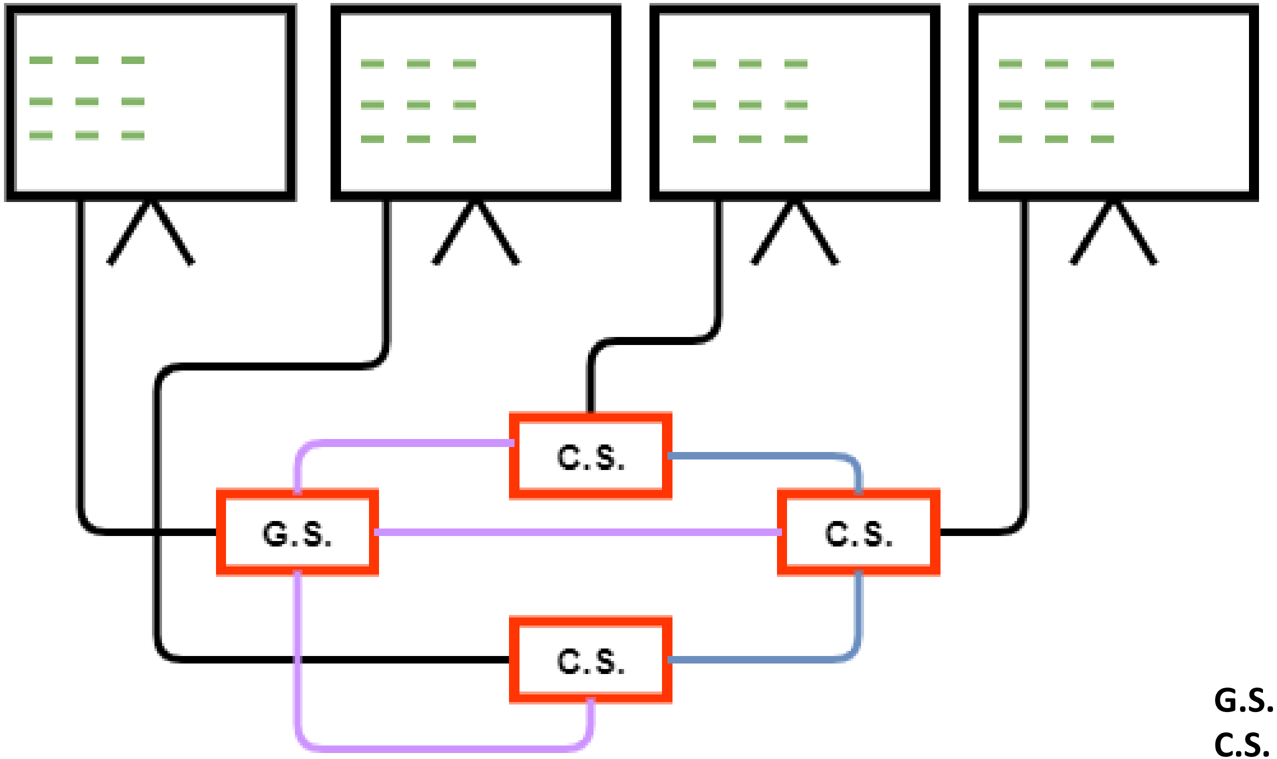
Design Solution

Project Purpose & Objectives | Design Solution | Critical Project Elements | Requirement Satisfaction | Project Risks | Verification & Validation | Project Planning

Hardware FBD



Major Elements

1. Raspberry Pi (Ground Station or Constellation Sat)
2. Monitors Connected to Output of Raspberry Pi
3. Ethernet Cables (GS-CS & CS-CS)
4. Flight-Ready DTN-ION

G.S. - Ground Station
C.S. - Constellation Satellite

System FBD

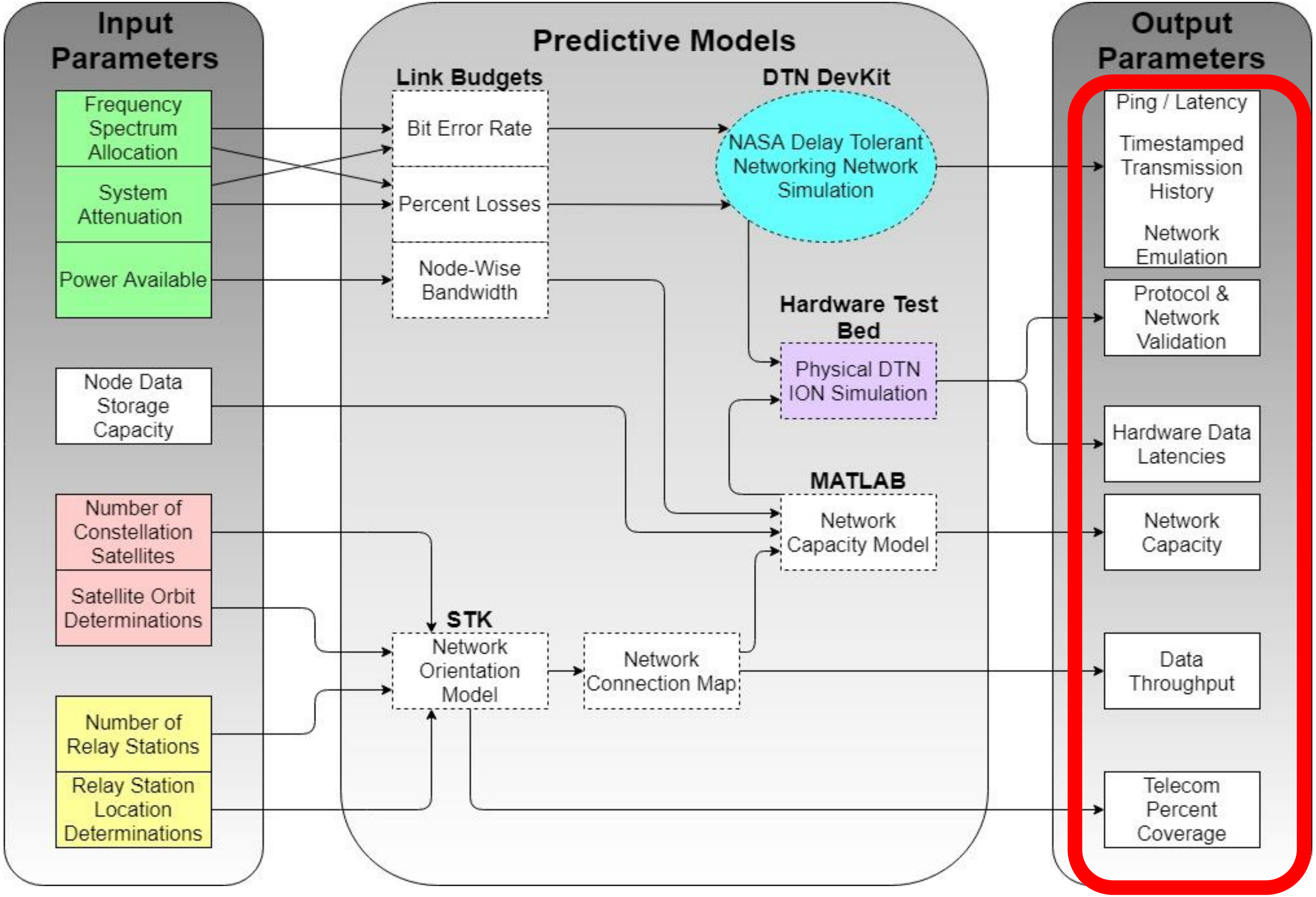
CPE 1 Satellite Constellation Architecture

CPE 2 Network Protocol

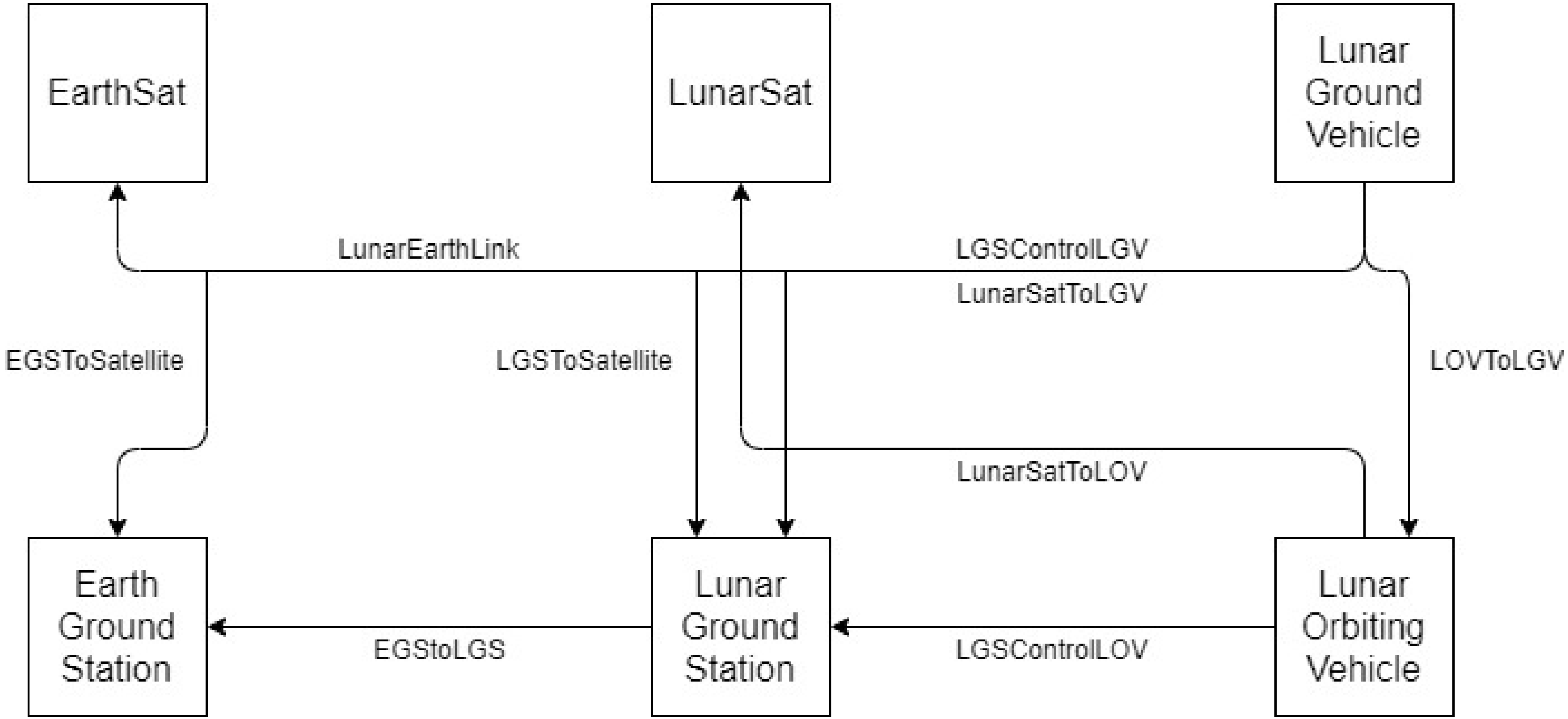
CPE 3 Extraterrestrial Relay Station

CPE 4 Spectrum Allocation

CPE 5 Hardware Simulation



MBSE Block Definition Diagram (BDD)



Critical Project Elements

Project Purpose & Objectives → Design Solution → Critical Project Elements → Requirement Satisfaction → Project Risks → Verification & Validation → Project Planning

Critical Project Elements

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1. **Hardware Test Bed:** Demonstrate various network characteristics.
2. **Network Protocol:** Structured data transmission methodology that allows for high speed reliable communications from node to node.
3. **Link Budget:** The project will meet certain data-relay rates for communication between all communication nodes.
4. **Relay Station:** Allows for direct access to communications between Earth and The Moon.
5. **Satellite Constellation Architecture:** Construction of ideal constellation architecture around each planetary body to satisfy coverage requirements.
6. **System Prototype Validation:** Ensure all system elements are valid.

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Requirement Satisfaction

- Project Purpose & Objectives
- Design Solution
- Critical Project Elements
- Requirement Satisfaction
- Project Risks
- Verification & Validation
- Project Planning

Hardware Satisfactions

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Design Requirement	Satisfaction
DR 1.1 Relay <1 sec (excluding propagation delay)	Test
DR 1.5 Rely data between mission segments	Test
DR 1.7 Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective	MBSE Integration
DR 2.1-2.2 Provide command and control capabilities to surface and orbit vehicles	Test

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Test: *Testing the various configurations to generate latency values and verify the congestion model*

MBSE Integration: *Taking latency values from the test and implementing them into the MBSE model verifies data rate*

System Satisfactions

Functional Requirement	Design Requirement	Satisfaction
FR 1	99% telecommunications coverage in Lunar orbit	
	99% telecommunications coverage on Lunar Surface	
FR 2	5+ nodes for simultaneous ‘real time’ communications on Lunar surface	
	10+ nodes for non simultaneous (within 6 hrs) communication on Lunar surface	
	10+ nodes for simultaneous ‘real time’ communication in Lunar orbit	
	20+ nodes for non-simultaneous (within 6 hours) communication in Lunar orbit	
	Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective	
FR 3	Network is compatible with and ensures the safety of existing and future infrastructure	

Network Capacity Model

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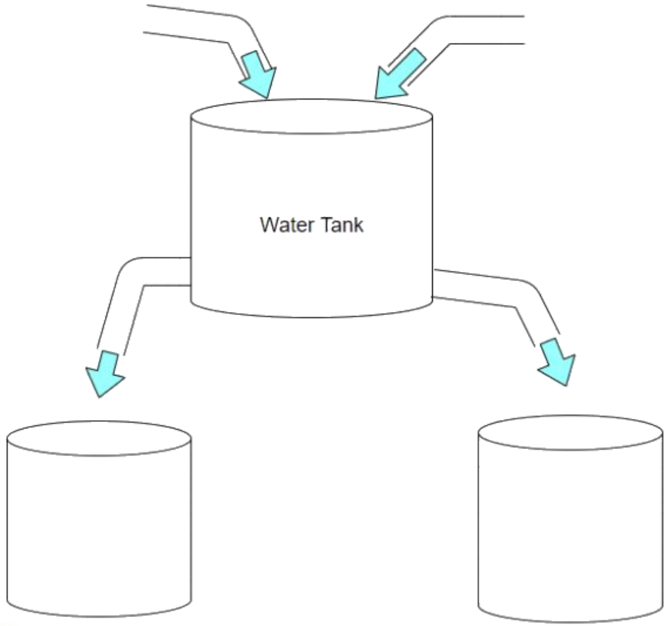

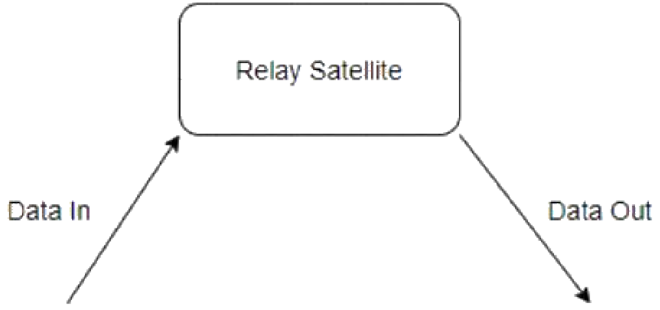

Overflowing water tank is analogous to a saturated / max capacity network

Rate in - rate out = rate of storage change

Network endpoints analogous to faucets adding water to the system

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System Satisfactions

Functional Requirement	Design Requirement	Satisfaction
FR 1	99% telecommunications coverage in Lunar orbit	
	99% telecommunications coverage on Lunar Surface	
FR 2	5+ nodes for simultaneous ‘real time’ communications on Lunar surface	**Congestion Model**
	10+ nodes for non simultaneous (within 6 hrs) communication on Lunar surface	**Congestion Model**
	10+ nodes for simultaneous ‘real time’ communication in Lunar orbit	**Congestion Model**
	20+ nodes for non-simultaneous (within 6 hours) communication in Lunar orbit	**Congestion Model**
	Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective	
FR 3	Network is compatible with and ensures the safety of existing and future infrastructure	

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RF Link Budget

- **Key Inputs** that will vary or will be influenced by architecture
  - Distance Between Nodes
  - Aperture Diameter
  - Transmit power
- **Outputs:**
  - Link Margin

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RF Considerations

- Compatibility with Lunar Gateway
- ITU recommendations for communications between lunar orbit and lunar surface: Ka-band
- RF Frequencies and modulation schemes chosen to enable this:
    - Orbiting satellite downlink to Lunar surface: 22.55-23.15 GHz (OQPSK Modulation)
    - Lunar surface to orbiting satellite uplink: 25.5-27.0 GHz (OQPSK Modulation)

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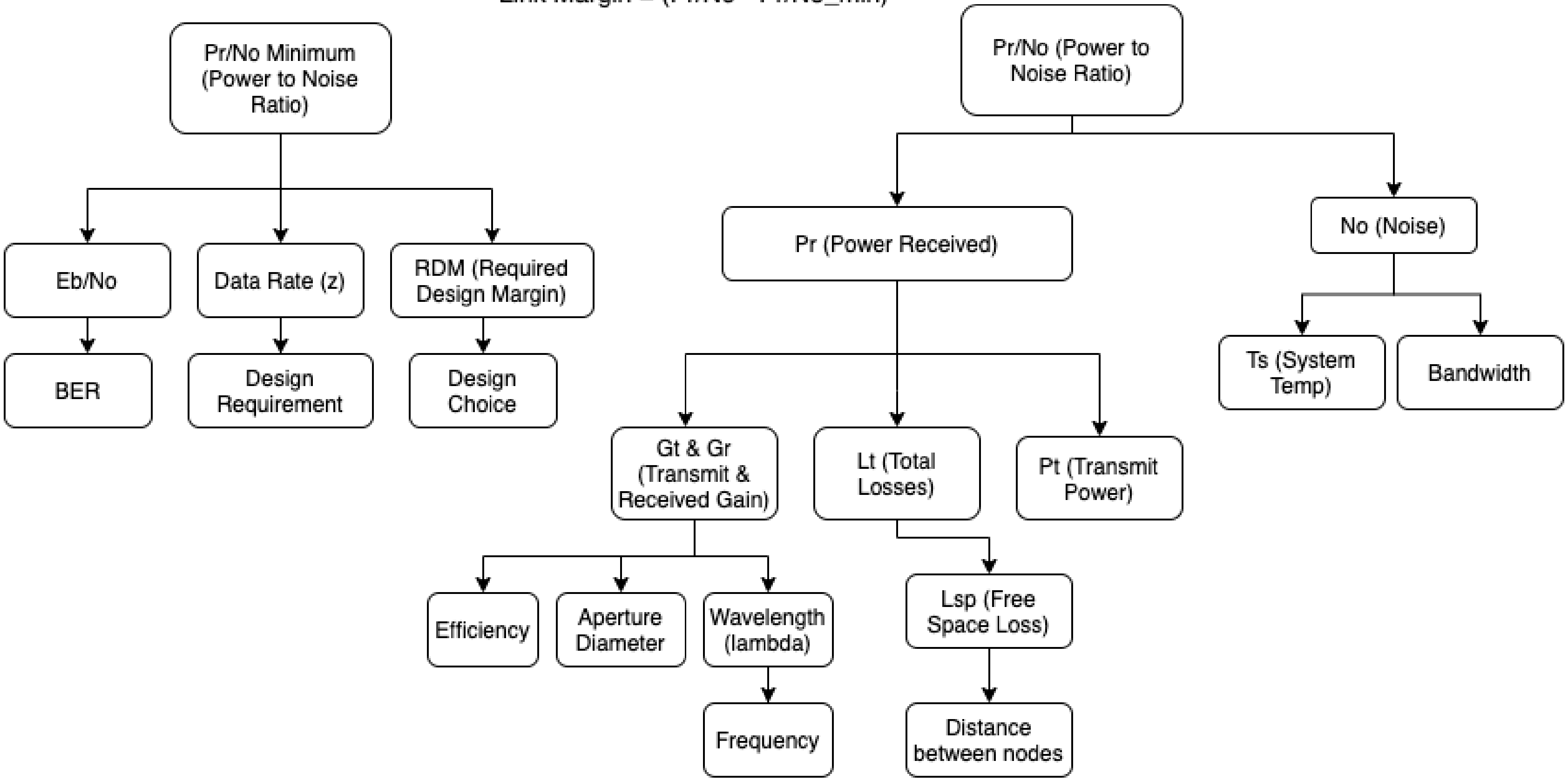
High-Level Overview of RF inter-satellite and satellite-to-Lunar Ground Link Budget flow chart

Link Margin = (Pr/No - Pr/No_min)



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Additional Laser Link Considerations

Additional total losses in Received Power Term

- Atmospheric Losses
- Transmitter Pointing Loss
- System Losses
  - Transmitter Optical Efficiency
  - Receiver Optical Efficiency
  - Receiver Pointing Loss

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System Satisfactions

Functional Requirement	Design Requirement	Satisfaction
FR 1	99% telecommunications coverage in Lunar orbit	
	99% telecommunications coverage on Lunar Surface	
FR 2	5+ nodes for simultaneous 'real time' communications on Lunar surface	Congestion Model
	10+ nodes for non simultaneous (within 6 hrs) communication on Lunar surface	Congestion Model
	10+ nodes for simultaneous 'real time' communication in Lunar orbit	Congestion Model
	20+ nodes for non-simultaneous (within 6 hours) communication in Lunar orbit	Congestion Model
	Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective	**Link Budget**
FR 3	Network is compatible with and ensures the safety of existing and future infrastructure	**Link Budget**

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Relay Station

- Likely using ground stations:
  - Better accessibility to **build, maintain, and upgrade.**
  - Leads to **significantly lower establishment costs** and **more use** throughout the lifecycle (due to lower costs and easier accessibility).
- Seek to seamlessly integrate network protocols into network architecture while attempting to minimize cost and maximize efficiency of the system over its lifespan.
- On Earth, existing ground station infrastructure owned by the US and allies will be explored in order to decrease initial costs.

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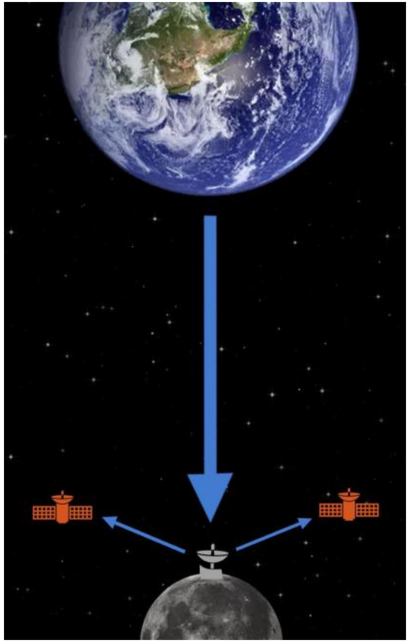
Ground Station Considerations

The geometric placement of ground relay stations will vary between Earth and The Moon due to the differing atmospheric conditions and established infrastructure.

- **Inputs:**
  - Atmospheric Bend
  - Atmospheric Absorption
  - Locations of established ground stations on Earth
- **Outputs:**
  - Required spacing and number of ground stations on each body
  - Location of each ground station



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System Satisfactions

Functional Requirement	Design Requirement	Satisfaction
FR 1	99% telecommunications coverage in Lunar orbit	**Relay Station**
	99% telecommunications coverage on Lunar Surface	**Relay Station**
FR 2	5+ nodes for simultaneous 'real time' communications on Lunar surface	Congestion Model
	10+ nodes for non simultaneous (within 6 hrs) communication on Lunar surface	Congestion Model
	10+ nodes for simultaneous 'real time' communication in Lunar orbit	Congestion Model
	20+ nodes for non-simultaneous (within 6 hours) communication in Lunar orbit	Network Protocol
	Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective	Link Budget
FR 3	Network is compatible with and ensures the safety of existing and future infrastructure	Link Budget, **Relay Station**

Constellation Satellite Architecture

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- A **medium altitude (5,509 km)** constellation around the moon, utilizing **six satellites**, will be used as a baseline design to fulfill the requirements of >99% coverage of the surface and orbital space of the moon.
- Beyond the baseline, additional designs, varying the altitude, number of satellites, and orbital geometries, will also be tested to investigate their effect on the **performance** and **cost of the system.**
- **Redundancy** will be included as a factor, with tests being performed on doubly, triply, and quadruply redundant systems.

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Satellite Constellation Considerations

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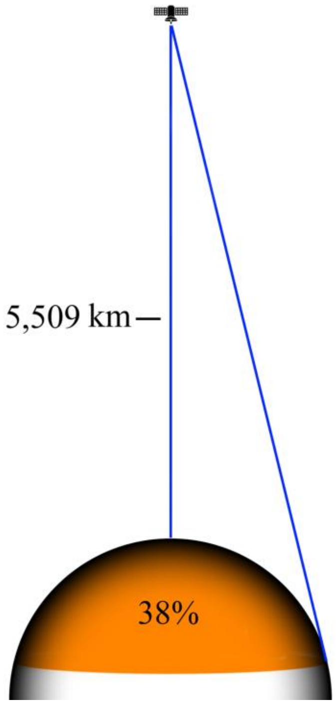
The geometry of the satellite constellation directly affects the **distance between nodes** and the **time windows** through which nodes can communicate.

- **Inputs:**
  - Number of satellites
  - Orbital parameters
- **Outputs:**
  - Network connection windows
  - Coverage map



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System Satisfactions

Functional Requirement	Design Requirement	Satisfaction
FR 1	99% telecommunications coverage in Lunar orbit	Relay Station, **Satellite Constellation**
	99% telecommunications coverage on Lunar Surface	Relay Station, **Satellite Constellation**
FR 2	5+ nodes for simultaneous ‘real time’ communications on Lunar surface	Network Protocol
	10+ nodes for non simultaneous (within 6 hrs) communication on Lunar surface	Network Protocol
	10+ nodes for simultaneous ‘real time’ communication in Lunar orbit	Network Protocol
	20+ nodes for non-simultaneous (within 6 hours) communication in Lunar orbit	Network Protocol
	Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective	Link Budget
FR 3	Network is compatible with and ensures the safety of existing and future infrastructure	Link Budget, Relay Station, **Satellite Constellation**

Project Risks

Project Purpose & Objectives → Design Solution → Critical Project Elements → Requirement Satisfaction → Project Risks → Verification & Validation → Project Planning

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Modeling Risks

Risk	Description	Effect
NCP: Network Capacity Model	Inaccurate Network Capacity Model	Network capacity model will not provide sufficient evidence to support network architecture design
IA: Inaccurate Assumptions	Inaccurate Assumptions utilized	Models will contain systematic errors that will reduce accuracy
CTI: Cross Team Integration	Cross-team MBSE integration	One comprehensive model of the system will be unavailable

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Risk Matrix

		Severity				
Likelihood		Negligible	Minor	Moderate	Major	Catastrophic
	Almost Certain					
	Likely					
	Possible		**IA**		**NCP**	
	Unlikely					
	Rare					**CTI**

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Inaccessibility Risks

Risk	Description	Effect
OA: Outside Architecture	Outside architecture information unavailable (eg. Lunar Gateway)	System architecture will not utilize existing infrastructure
FI: Facility Inaccessibility	COVID imposes inaccessibility to facilities required for hardware construction and testing	Large increase in difficulty to construct and test hardware component

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Risk Matrix

		Severity				
		Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost Certain					
	Likely					
	Possible			**FI**		
	Unlikely			**OA**		
	Rare					

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Additional Risks

Risk	Description	Effect
RPI: Raspberry Pi ION integration	Not being able to integrate ION into Raspberry Pi's	Raspberry Pi hardware simulation will not resemble overall network implementation
PC: Project Complexity	DOTCOM requires complex hardware, software, and architecture design and integration for final deliverable	Limited to a year of research and design for a highly complex task could lead to reduced deliverable depth

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Risk Matrix

		Severity				
Likelihood		Negligible	Minor	Moderate	Major	Catastrophic
	Almost Certain			**PC**		
	Likely			**RPI**		
	Possible					
	Unlikely					
	Rare					

Complete Risk Matrix

Likelihood	Severity					
		Negligible	Minor	Moderate	Major	Catastrophic
	Almost Certain			**PC**		
	Likely			**RPI**		
	Possible		**IA**	**FI**	**NCP**	
	Unlikely			**OA**		
	Rare					**CTI**

Verification & Validation

Hardware System Interface: PYION

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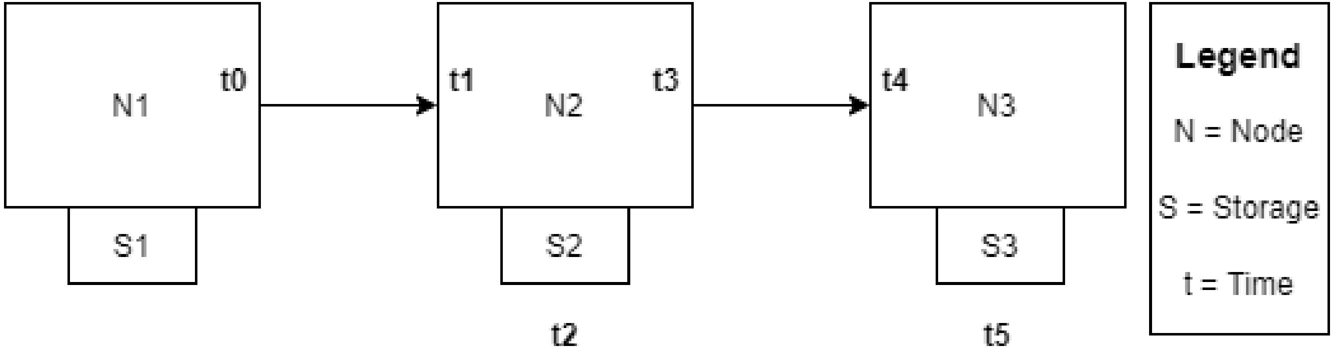
- Transmit
  - Endpoint Creations
  - Input Destination
  - Data File Input
- Reception
  - TTL Properties
  - Timeout Selection
  - Data Exchange Measurements

```
import pyion

# Create a proxy to node 1 and attach to ION
proxy = pyion.get_bp_proxy(1)
proxy.bp_attach()

# Open endpoint 'ipn:1.1' and send data to 'ipn:2.1'
with proxy.bp_open('ipn:1.1') as eid:
    eid.bp_send('ipn:2.1', b'hello')
```

```
with proxy.bp_open(EID) as eid:
    while eid.is_open:
        try:
            # We set a timeout of 60 seconds
            data = eid.bp_receive(timeout=60)

            # We check if the timeout has gone off
            if isinstance(data, Exception):
                print('Timeout when off.')
                break
```

Hardware Key Measurements (Asynchronous)



t1 - t0 = Light Time Latency
t2 - t1 = N2 Storage Latency
t3 - t2 = N2 Forward Latency
t3 - t1 = N2 Hardware Latency
t5 - t0 = Total Signal Latency
(t5-t0)-t4-t1 = Total Hardware Latency

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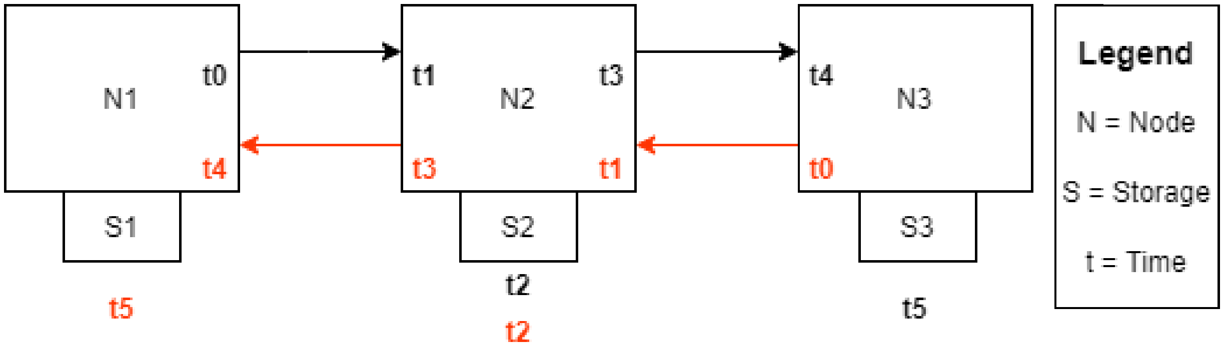
Hardware Key Measurements (Synchronous)



t1 - t0 = Light Time Latency
t2 - t1 = N2 Storage Latency
t3 - t2 = N2 Forward Latency
t3 - t1 = N2 Hardware Latency
t5 - t0 = Total Signal Latency
(t5-t0)-t4-t1 = Total Hardware Latency

t1 - t0 = Light Time Latency
t2 - t1 = N2 Storage Latency
t3 - t2 = N2 Forward Latency
t3 - t1 = N2 Hardware Latency
t5 - t0 = Total Signal Latency
(t5-t0)-t4-t1 = Total Hardware Latency

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MBSE Verification

Unlike most senior design projects, main customer deliverables are the models themselves. Base-level MBSE modeling of network devices has been completed, including:

- Requirement tracing and verification steps
- Block Definition and Internal Block Diagrams
- Defined data types for network node input/output
- SysML state machines for modeling network node behavioral aspects

Further steps include expanding this modeling to **further network aspects** and **increasing model fidelity.**

		A	B
		name : String [0..1]	/satisfiedBy : NamedElement [*]
0	/ownedElement		
1	FR-1: Comms must have transmit/receive capability simultaneously & non-simultaneously between Earth, Moon, Mars.	FR-1: Comms must have transmit/receive capability simultaneously & non-simultaneously between Earth, Moon, Mars.	x
2	/ownedElement		
3	R-001: Real time data relay between environments	R-001: Real time data relay between environments	AntennalO, AntennalO, AntennalO
4	R-005: Data relay between mission segments.	R-005: Data relay between mission segments.	LunarSat, EarthSat, EarthGroundStation, LunarGroundStation
5	R-008: Simultaneous comms to 5 locations on Lunar surface.	R-008: Simultaneous comms to 5 locations on Lunar surface.	inboundSignalProcessing, outboundSignalProcessing
6	R-009: Non-simultaneous comms to 10+ locations on Lunar surface.	R-009: Non-simultaneous comms to 10+ locations on Lunar surface.	inboundSignalProcessing, outboundSignalProcessing, centralStorage

Requirements Tracing

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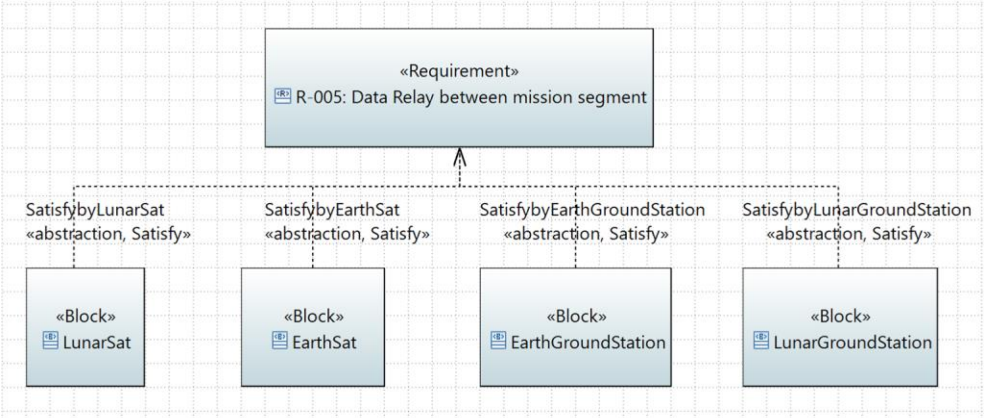
Blocks and their internal parts/processes can be used to *satisfy* design requirements.

In this example, EarthSat has data flow connections to EarthGroundStation, LunarSat and LunarGroundStation which fulfill requirement R-005.



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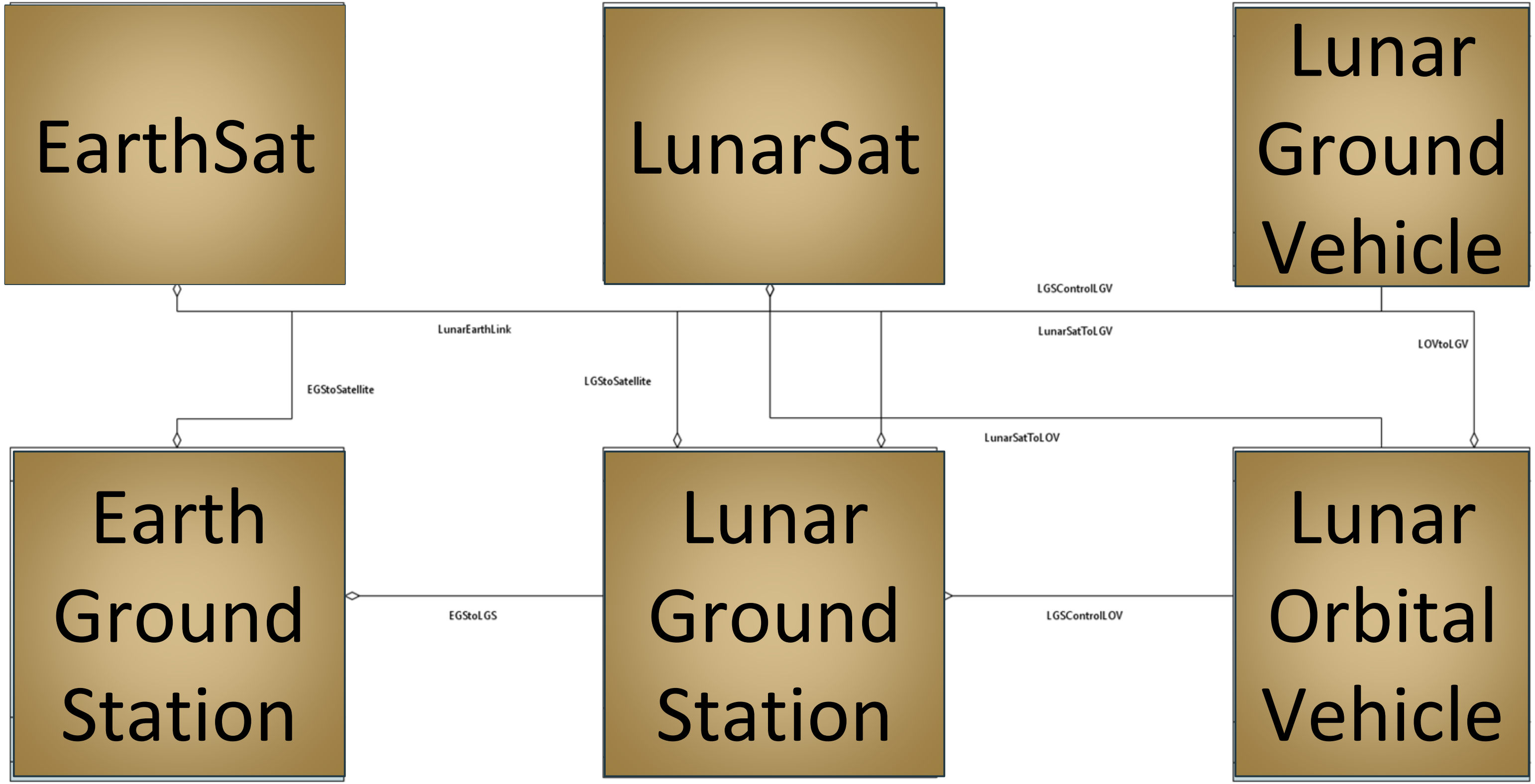
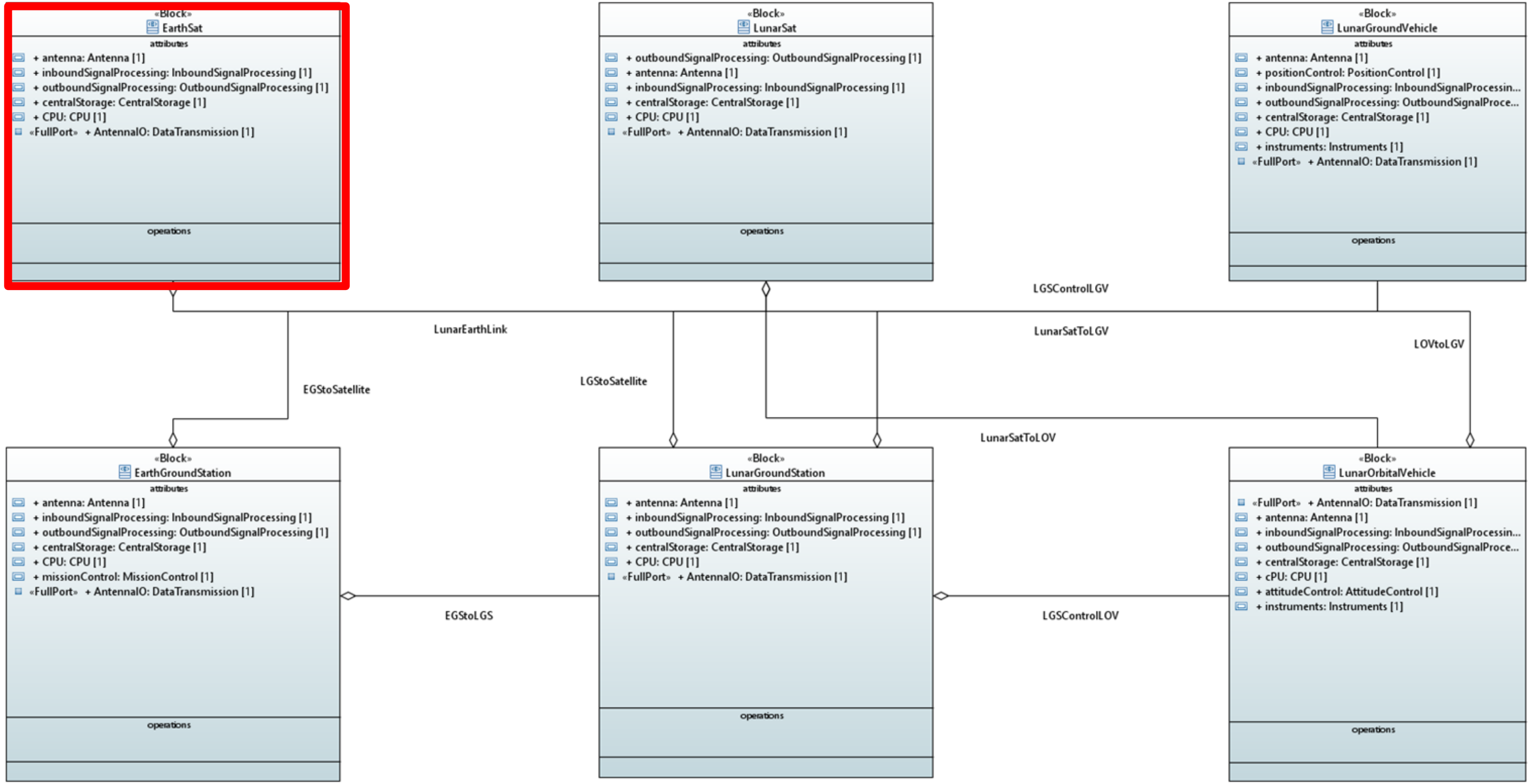
Papyrus Contact Graph Mapping



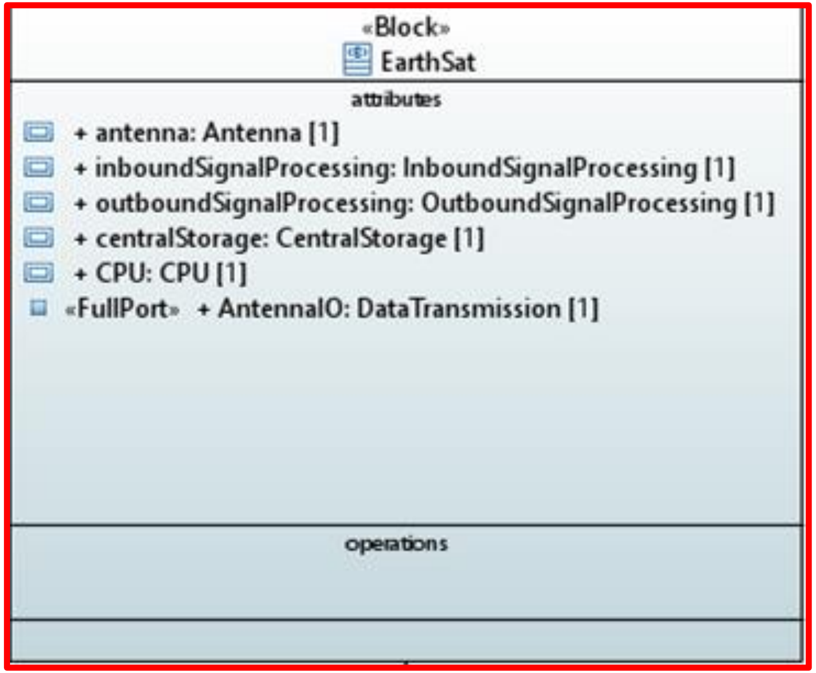
Block Definition Diagram (MBSE)



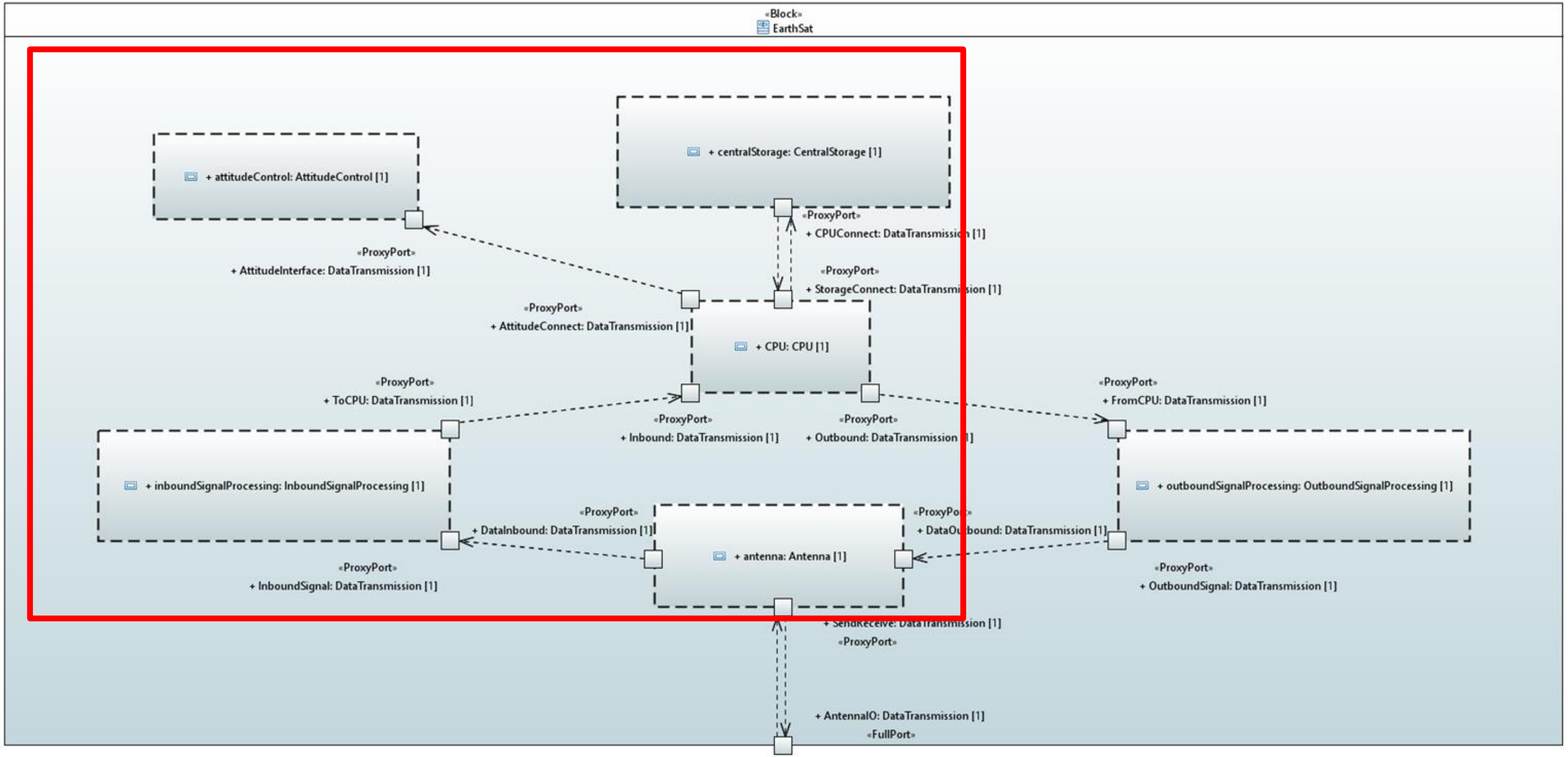
Block Definition Close-up

Connections to other blocks are modeled via *associations*, and each block within the BDD exists with internal parts & subsystems.

- Relations between subsystems are shown via *Internal Block Diagrams (IBDs)*
- Each subsystem's behavior is modeled through *state machines*



Internal Block Diagram (IBD) - EarthSat

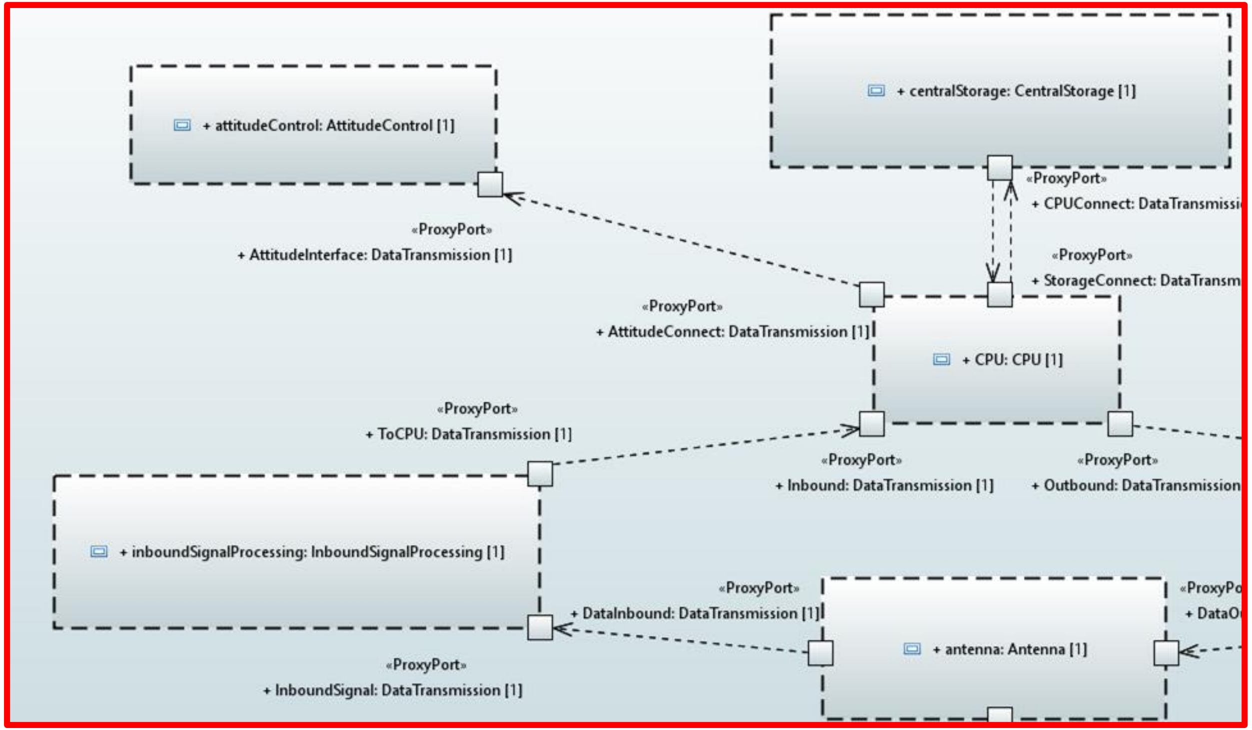


SysML Internal Block Diagram for a communications satellite in Earth orbit, with store and forward technology.

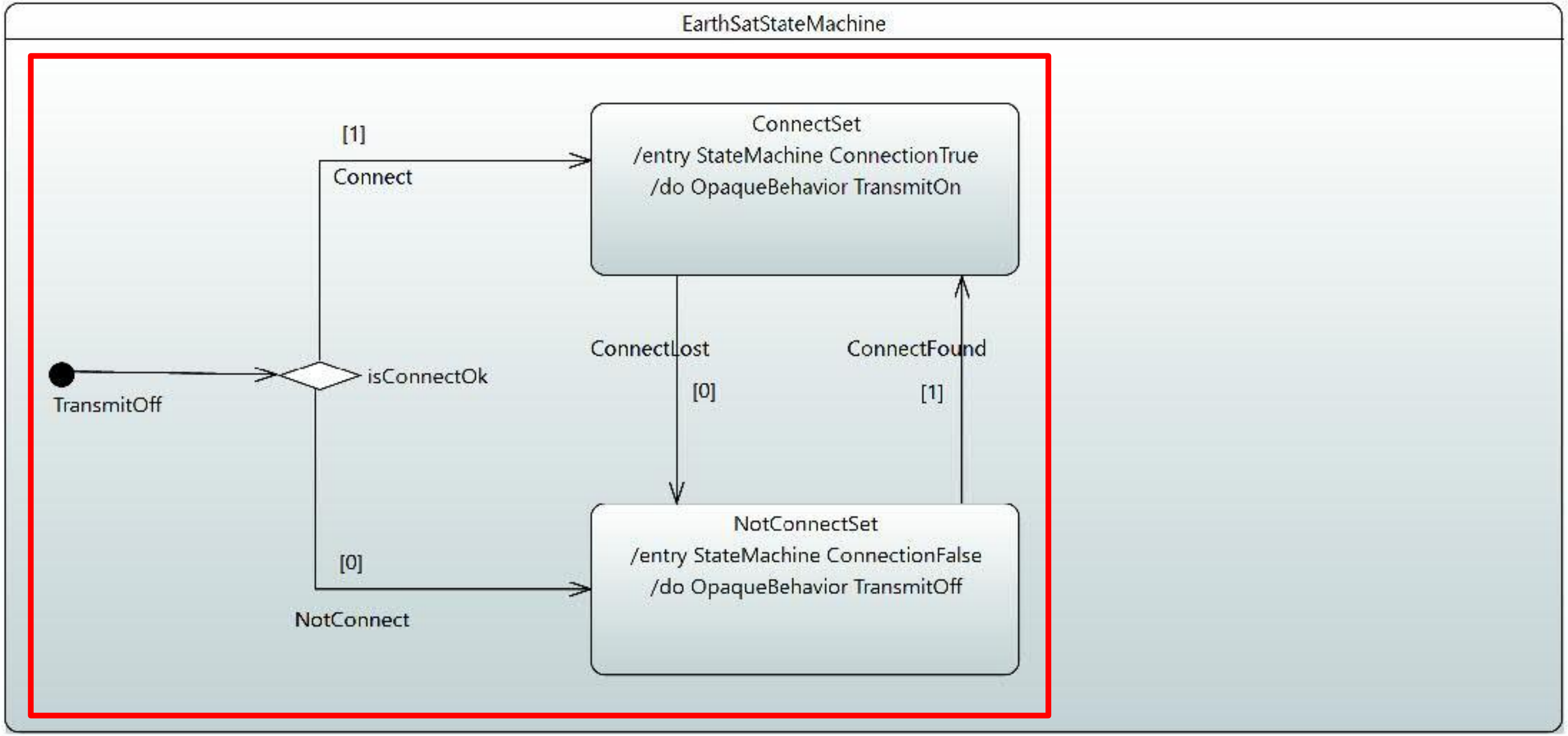
Internal Block Diagram Close-Up

IBD shows item (data) flows and interfaces between parts. Each part can be modeled outside of MBSE and then integrated

Fidelity of model increases over time as the system is drilled down to lower level structure.



State Machine Diagram - EarthSat



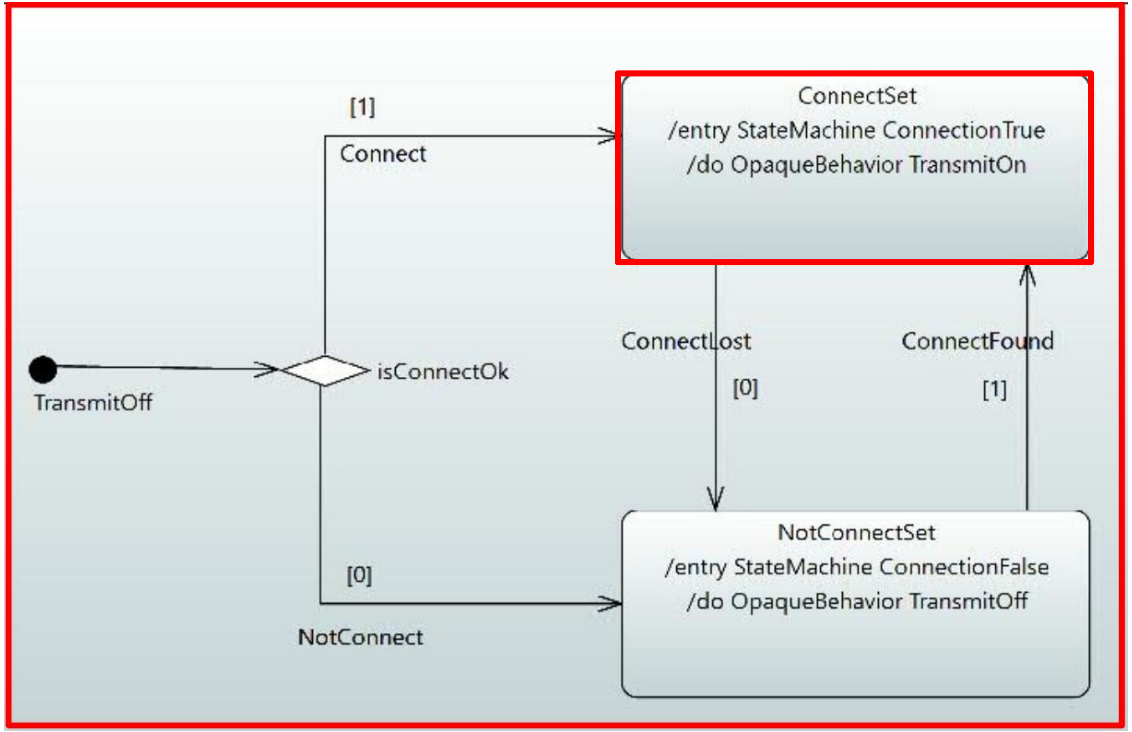
SysML state machine diagram for a communications satellite in Earth orbit.

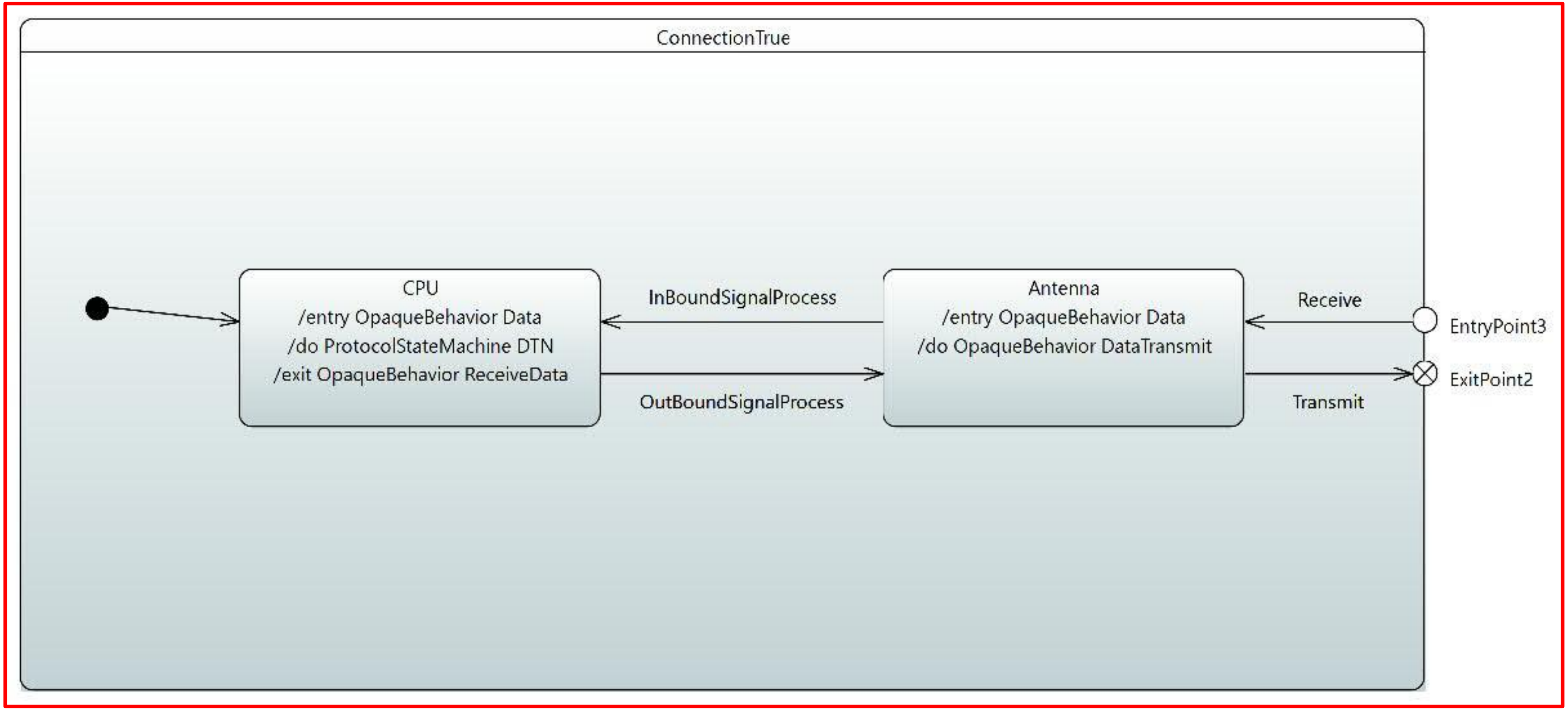
State Machine Diagram Close-up

State machine diagrams describe the behavior happening within a block.

- Begin at initial state
- Behavior follows pathing depending on status of internal variables

Inside the state machine, *entry* is the action that happens when progressing into the state. *Do* represents the action performed while inside the state.

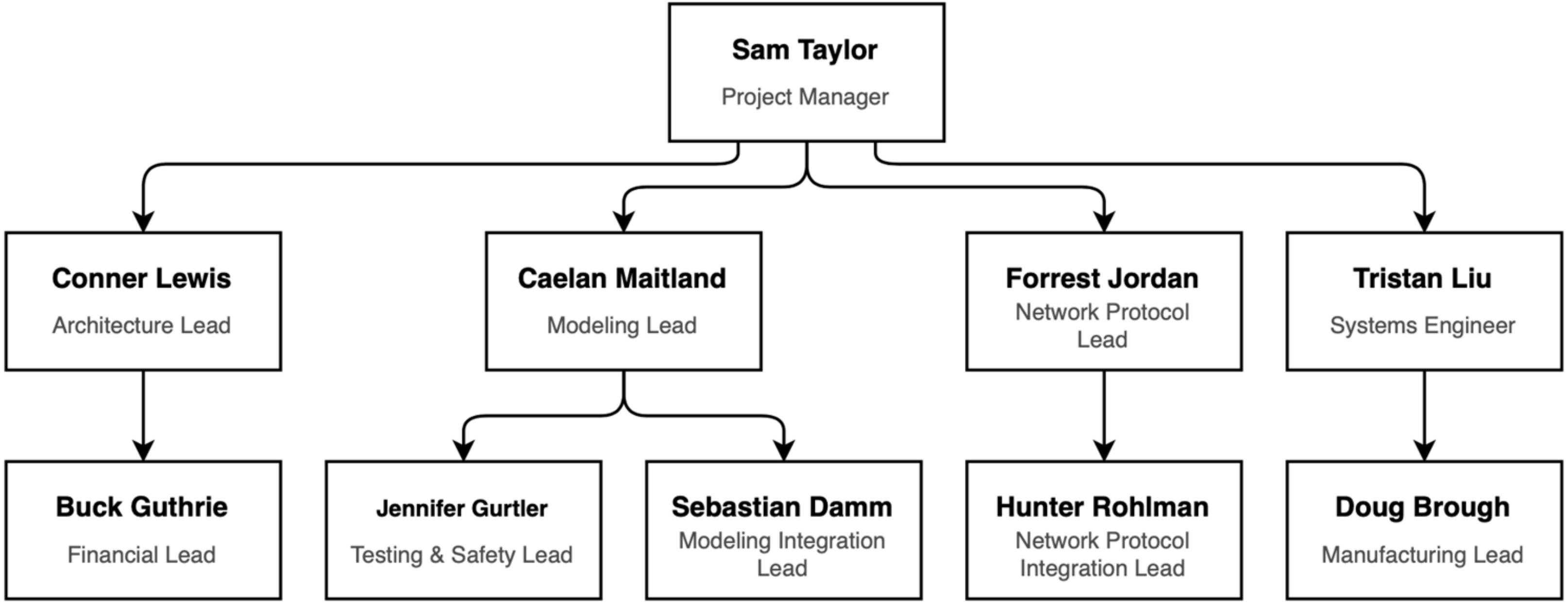




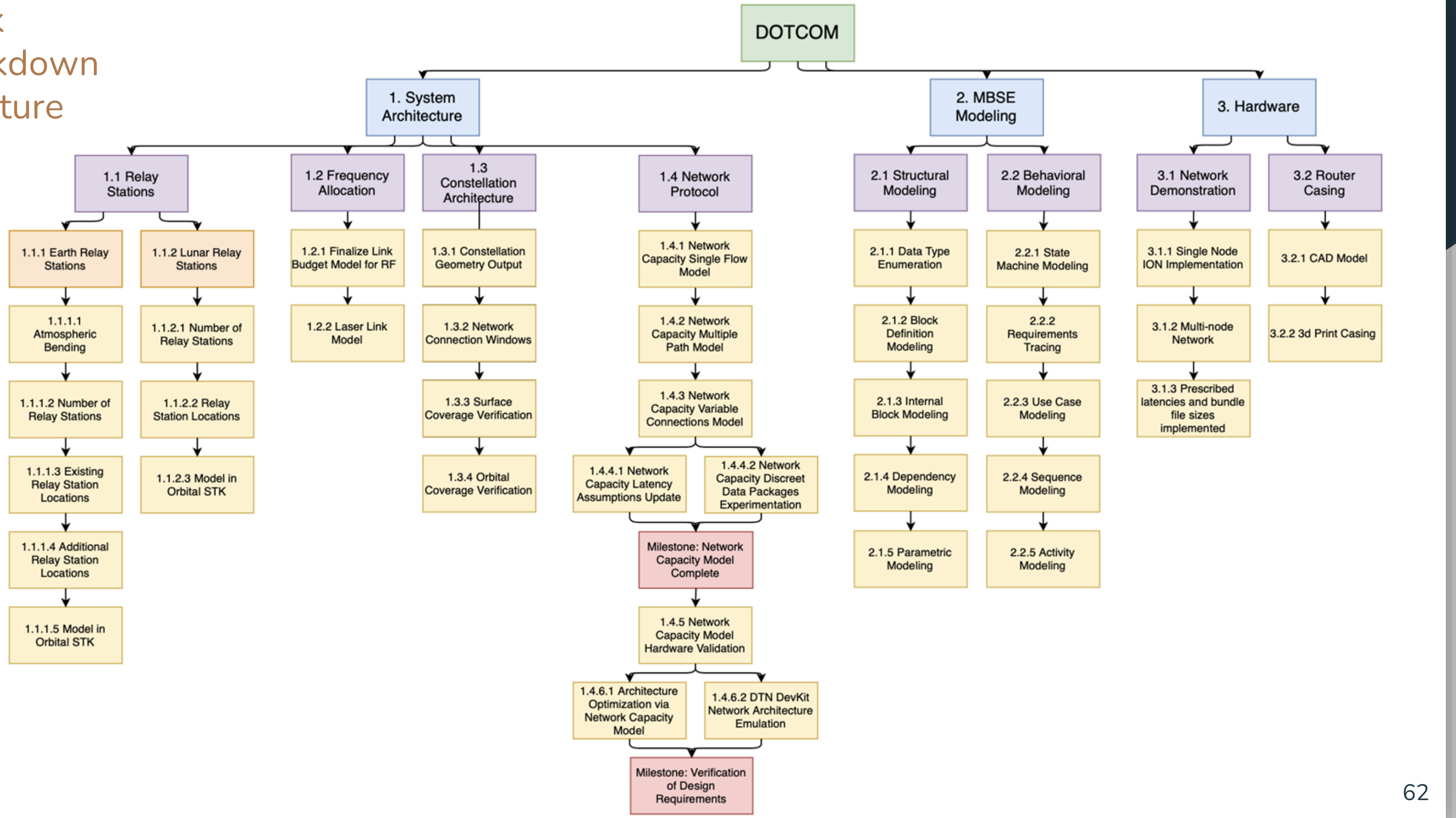
State machine for the "ConnectionTrue" behavior within the higher-level EarthSatStateMachine.

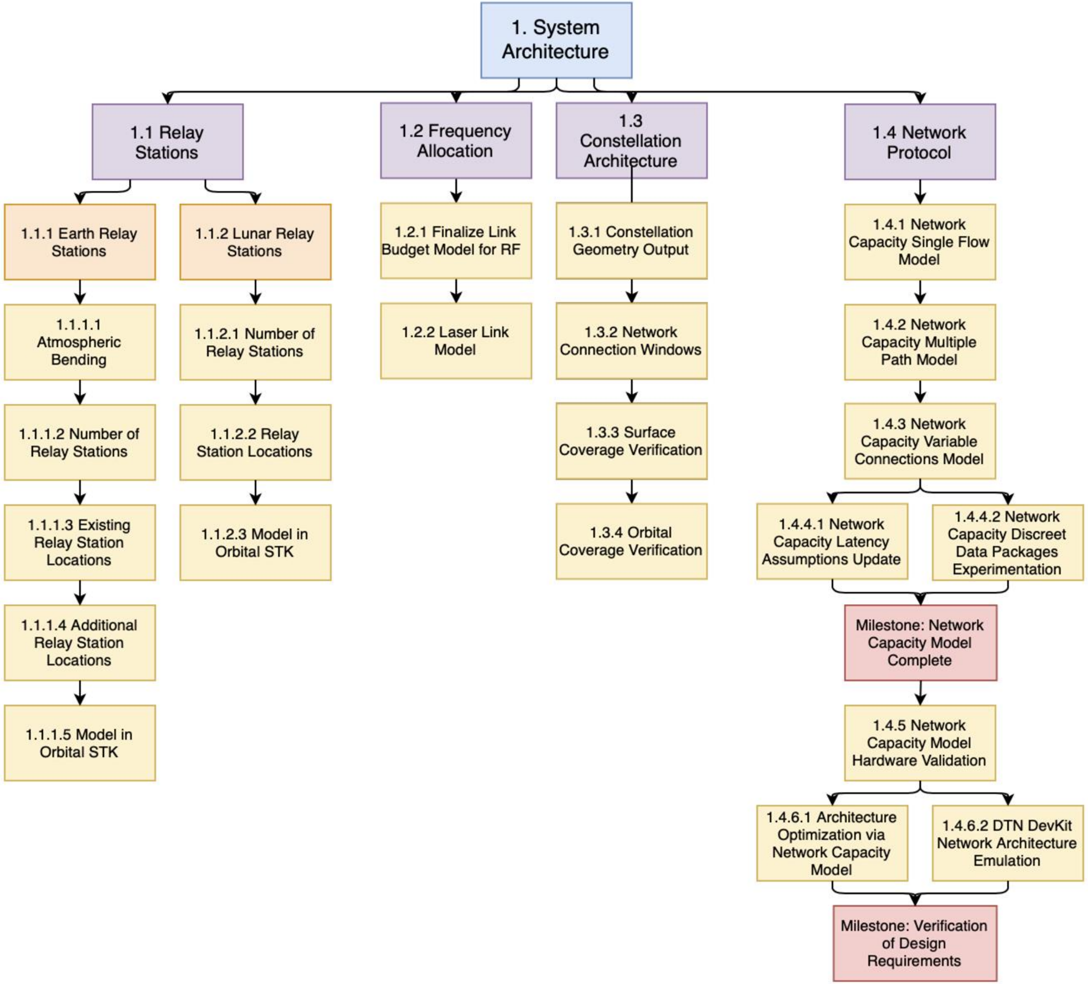
Project Planning

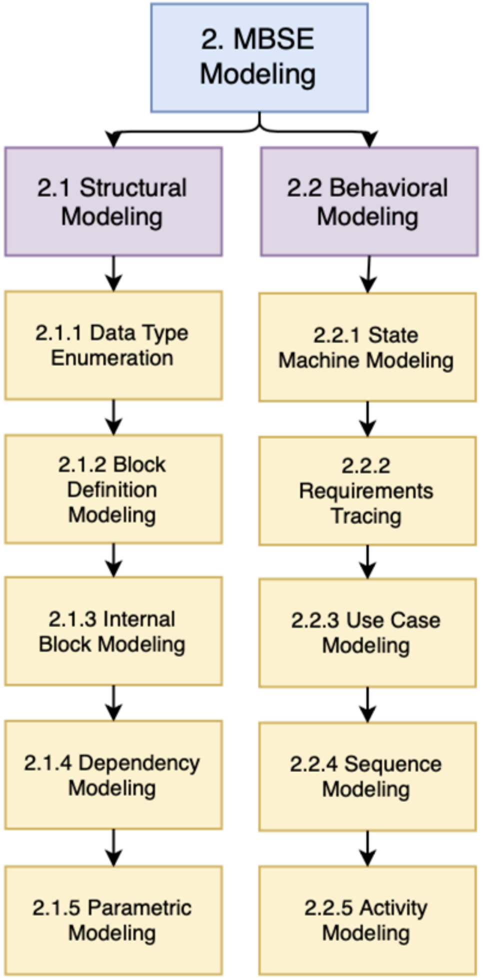
Organizational Chart

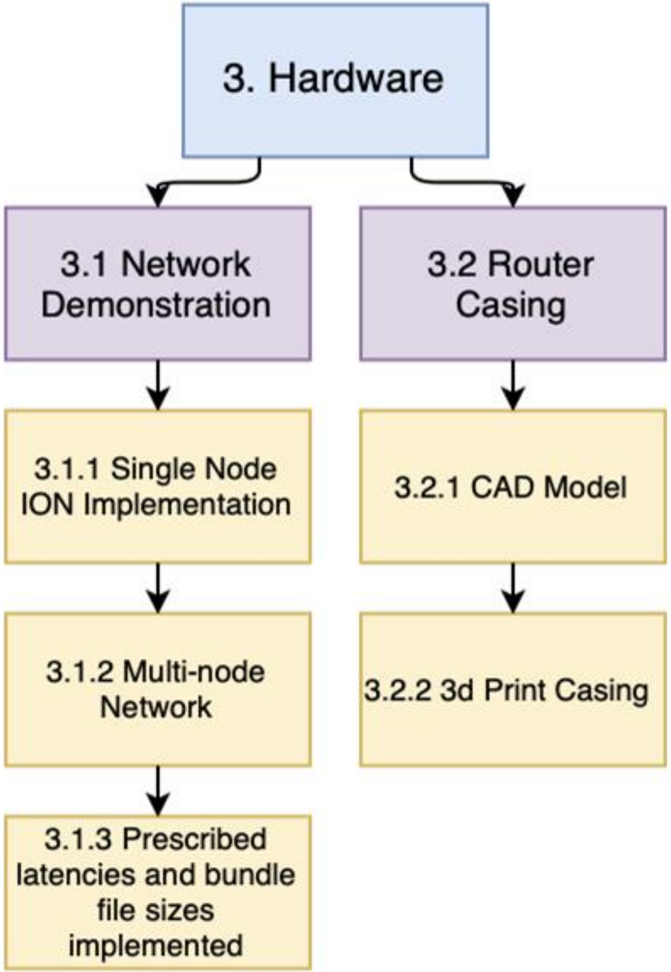


Work Breakdown Structure



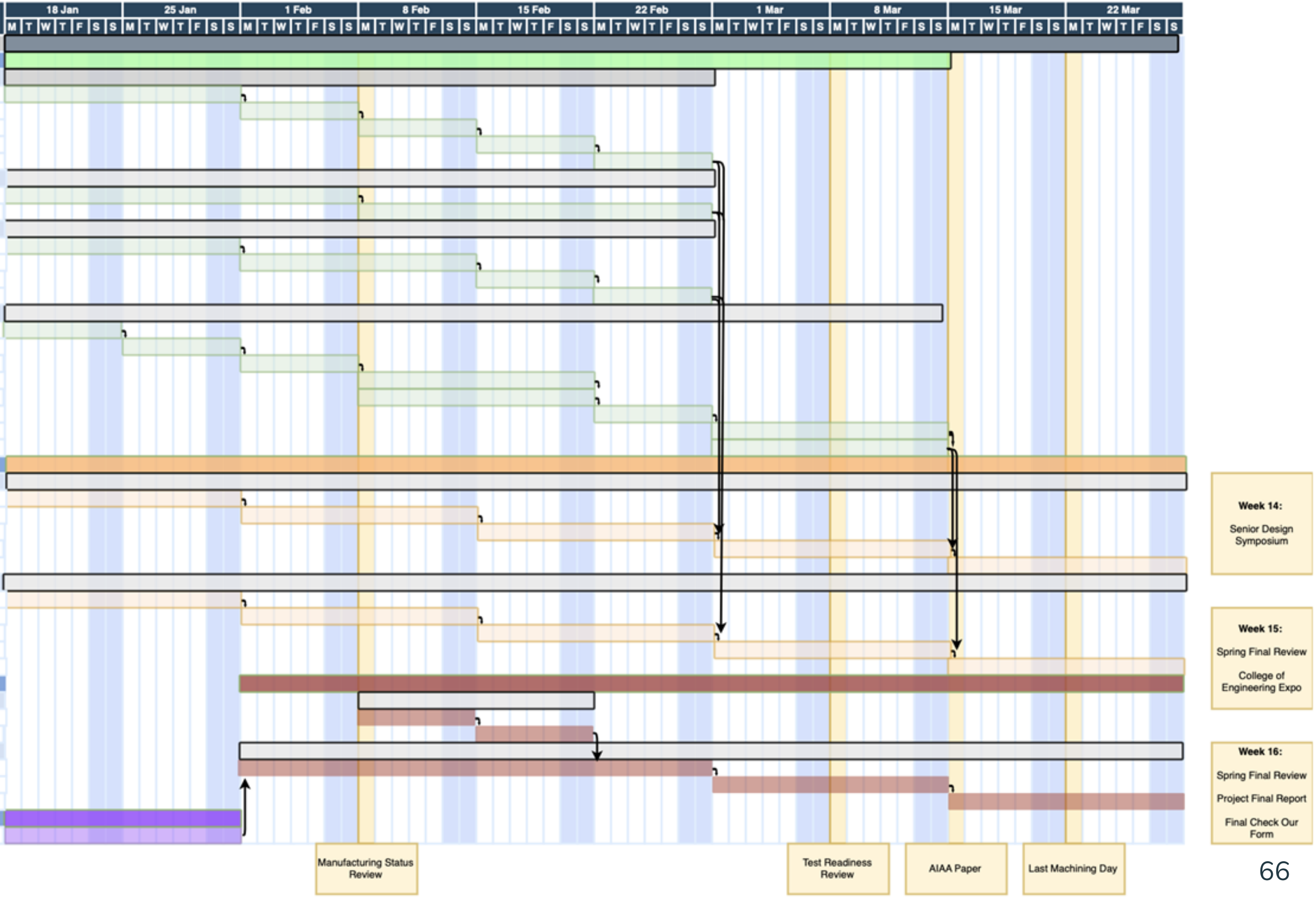

1. System Architecture
1.1 Relay Stations
1.2 Frequency Allocation
1.3 Constellation Architecture
1.4 Network Protocol
1.1.1 Earth Relay Stations
1.1.2 Lunar Relay Stations
1.2.1 Finalize Link Budget Model for RF
1.3.1 Constellation Geometry Output
1.4.1 Network Capacity Single Flow Model
1.1.1.1 Atmospheric Bending
1.1.2.1 Number of Relay Stations
1.2.2 Laser Link Model
1.3.2 Network Connection Windows
1.4.2 Network Capacity Multiple Path Model
1.1.1.2 Number of Relay Stations
1.1.2.2 Relay Station Locations
1.3.3 Surface Coverage Verification
1.4.3 Network Capacity Variable Connections Model
1.1.1.3 Existing Relay Station Locations
1.1.2.3 Model in Orbital STK
1.3.4 Orbital Coverage Verification
1.4.4.1 Network Capacity Latency Assumptions Update
1.4.4.2 Network Capacity Discreet Data Packages Experimentation
1.1.1.4 Additional Relay Station Locations
Milestone: Network Capacity Model Complete
1.1.1.5 Model in Orbital STK
1.4.5 Network Capacity Model Hardware Validation
1.4.6.1 Architecture Optimization via Network Capacity Model
1.4.6.2 DTN DevKit Network Architecture Emulation
Milestone: Verification of Design Requirements


2. MBSE Modeling
2.1 Structural Modeling
2.2 Behavioral Modeling
2.1.1 Data Type Enumeration
2.1.2 Block Definition Modeling
2.1.3 Internal Block Modeling
2.1.4 Dependency Modeling
2.1.5 Parametric Modeling
2.2.1 State Machine Modeling
2.2.2 Requirements Tracing
2.2.3 Use Case Modeling
2.2.4 Sequence Modeling
2.2.5 Activity Modeling


3. Hardware
3.1 Network Demonstration
3.2 Router Casing
3.1.1 Single Node ION Implementation
3.2.1 CAD Model
3.1.2 Multi-node Network
3.2.2 3d Print Casing
3.1.3 Prescribed latencies and bundle file sizes implemented

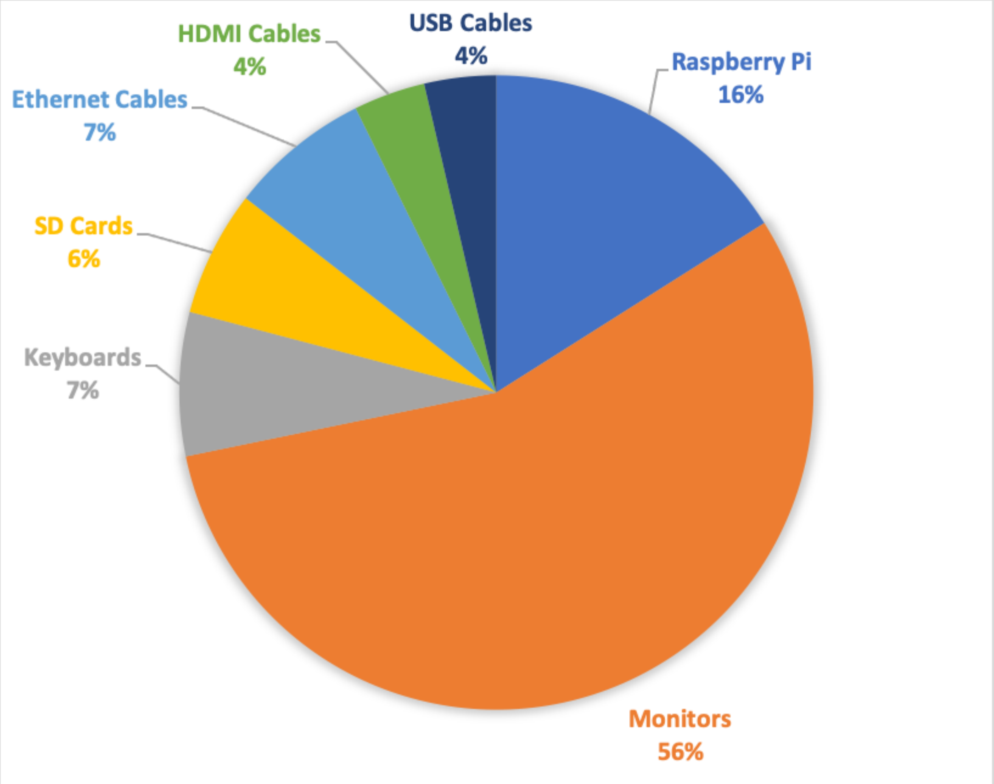
Work Plan

	Task Name	Duration	Start	ETA
1	Complete Project Execution	70 days	01.18.21	03.28.21
2	System Architecture	56 days	01.18.21	03.14.21
3	Relay Stations	42 days	01.18.21	02.28.21
4	Earth's Atmospheric Conditions	14 days	01.18.21	01.31.21
5	Relay Station Determination	7 days	01.31.21	02.07.21
6	Existing Relay Station Locations	7 days	02.07.21	02.14.21
7	Relay Station Placement	7 days	02.14.21	02.21.21
8	Model Verification	7 days	02.21.21	02.28.21
9	Link Budget	42 days	01.18.21	02.28.21
10	RF Link Budget	21 days	01.18.21	02.07.21
11	Laser Link Budget	21 days	02.07.21	02.28.21
12	Constellation Architecture	42 days	01.18.21	02.28.21
13	Constellation Geometry Output	14 days	01.18.21	01.31.21
14	Network Connection Windows	14 days	01.31.21	02.14.21
15	Surface Coverage Verification	7 days	02.14.21	02.21.21
16	Orbital Coverage Verification	7 days	02.21.21	02.28.21
17	Network Protocol	56 days	01.18.21	03.14.21
18	Network Capacity Single Flow Model	7 days	01.18.21	01.24.21
19	Network Capacity Multiple Path Model	7 days	01.24.21	01.31.21
20	Network Capacity Variable Connections Model	7 days	01.31.21	02.07.21
21	Network Capacity Latency Assumptions Update	14 days	02.07.21	02.21.21
22	Network Capacity Discreet Data Packages Experimentatio	14 days	02.07.21	02.21.21
23	Network Capacity Model Hardware Verification	7 days	02.21.21	02.28.21
24	Architecture Optimization via Network Capacity Model	14 days	02.28.21	03.14.21
25	DTN DevKit Network Architecture Emulation	14 days	02.28.21	03.14.21
26	MBSE Modeling	70 days	01.18.21	03.28.21
27	Structural Modeling	70 days	01.18.21	03.28.21
28	Data Type Enumeration	14 days	01.18.21	01.31.21
29	Block Definition Modeling	14 days	01.31.21	02.14.21
30	Internal Block Modeling	14 days	02.14.21	02.28.21
31	Dependency Modeling	14 days	02.28.21	03.14.21
32	Parametric Modeling	14 days	03.14.21	03.28.21
33	Behavioral Modeling	70 days	01.18.21	03.28.21
34	State Machine Modeling	14 days	01.18.21	01.31.21
35	Requirements Tracing	14 days	01.31.21	02.14.21
36	Use Case Modeling	14 days	02.14.21	02.28.21
37	Sequence Modeling	14 days	02.28.21	03.14.21
38	Activity Modeling	14 days	03.14.21	03.28.21
39	Hardware	56 days	01.31.21	03.28.21
40	Behavioral Modeling	14 days	02.17.21	02.21.21
41	CAD Model	7 days	02.07.21	02.14.21
42	3D Print Casting	7 days	02.14.21	02.21.21
43	Network Demonstration	56 days	01.31.21	03.28.21
44	Single Node ION Implementation	21 days	01.31.21	02.28.21
45	Multi-Node Network	14 days	02.28.21	03.14.21
46	Prescribed Latencies and Bundle File Sizes Implemented	14 days	03.14.21	03.28.21
47	Purchase	14 days	01.18.21	01.31.21
48	Hardware	14 days	01.18.21	01.31.21



Cost Plan

Key Project Components:
Raspberry Pi (7)
Monitors (7)
Keyboards (7)
SD cards (7)
Ethernet Cables (14)
HDMI Cables (7)
Power Cables (7)
Total: $1,528.45



Note: Estimated shipping costs $25 - $50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APPENDIX

Wavelengths and Frequencies

Add these to CONOPS instead of having this slide?

- Earth Ground-Lunar Ground: Optical 1550 - 1064 nm
- Lunar Surface-Constellation: Ka-band
- Constellation-Constellation: Ka-band
- Constellation-Ground Vehicle: Ka-band
- Constellation-Orbiting Vehicle: Ka-band

Laser Communication Risks

- Ground lasers regulated by the US to avoid accidental irradiation with aircraft
  - S Air Force Laser Clearing House (LCH) regulates ground-based laser transmission by having Predictive Avoidance (PA) timing winderos during which transmitted lasers could possibly damage s/c
  - Use a spatial window defines by center of moon +/- a zone of about 0.5 degrees
- US Federal Aviation Agency (FAA) regulates potential lasers interactions with aircraft
  - If ground station not placed in no-fly zone, then airplane sensors can be used to control laser shuttering to avoid aircraft

Source: Khatri, F. I., Robinson, B. S., Semprucci, M. D., and Boroson, D. M., "Lunar Laser Communication Demonstration operations architecture," *Acta Astronautica* Available: https://www.sciencedirect.com/science/article/pii/S0094576515000387#bib11.

Link Budget Assumptions

- RF Communications
  - Main Loss is free space loss due to communications being inter-satellite and satellite-lunar ground
  - BPSK Modulation
  - Aperture efficiencies constant
- Laser
  - PPM/DPSK Modulation
  - Strehl ratio due to atmospheric turbulence: 0.27 dB

The Future of High Data Rate Coms

- China recently launched a 6G satellite
- NASA Space Communications and Navigation (SCaN) investing in 10 cm optical module for use in LLCD and LCRD
    - Upgrade is in the modem (DPSK at 1.244 Gbps for LCRD and PPM at 622 Mbps for LLCD)
- NASA Laser Optical Communications Near-Earth Satellite System (LOCNESS) Project (2025)
    - Optical terminals that will provide up to 10Gbps from Earth up to LEO, MEO, GEO and out to Earth-Sun Lagrange (1.25 Mkm), & 100Gbps cross links and space-to-ground links

Current Laser Ground Stations

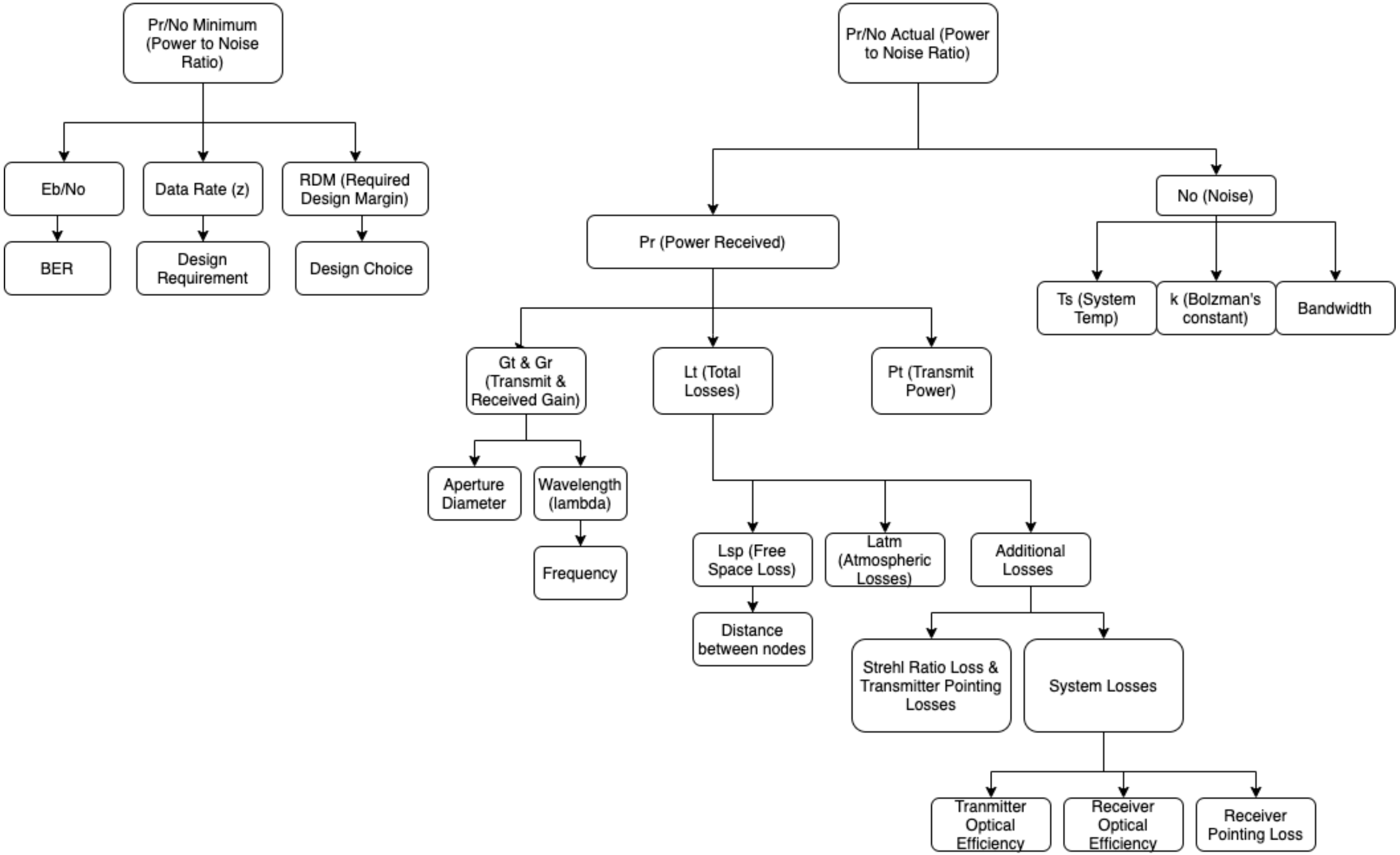
Lunar Laser Communications Demonstration (LLCD)

- LLGT (White Sands, NM)
  - 15 cm transmit aperture
  - 20 W transmitter
  - 40 cm receive aperture
- LLOT (Table Mountain Wrightwood, CA)
  - 1 m transmit and receive aperture
  - 20 W transmitter

Source: Khatri, F. I., Robinson, B. S., Semprucci, M. D., and Boroson, D. M., "Lunar Laser Communication Demonstration operations architecture," *Acta Astronautica* Available: https://www.sciencedirect.com/science/article/pii/S0094576515000387#bib11.

Laser Communications Link Budget Flow Chart

Link Margin = (Pr/No - Pr/No_min)_



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)

GENERAL ATOMICS

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)

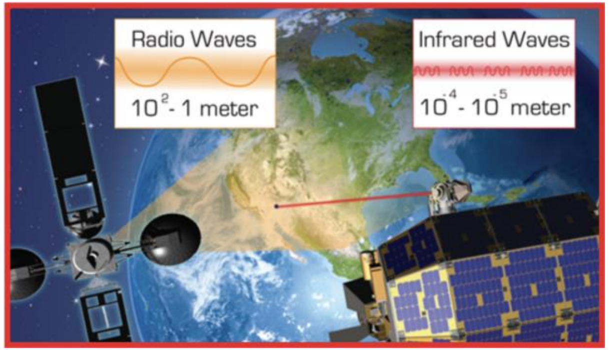


Image Reference: NASA LLCDFactSheet (https://www.nasa.gov/sites/default/files/llcdfactsheet.final_.web_.pdf, 2020)

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Risk Scale

Level	Likelihood	Severity
1	Rare	Negligible
2	Unlikely	Minor
3	Possible	Moderate
4	Likely	Major
5	Almost Certain	Catastrophic

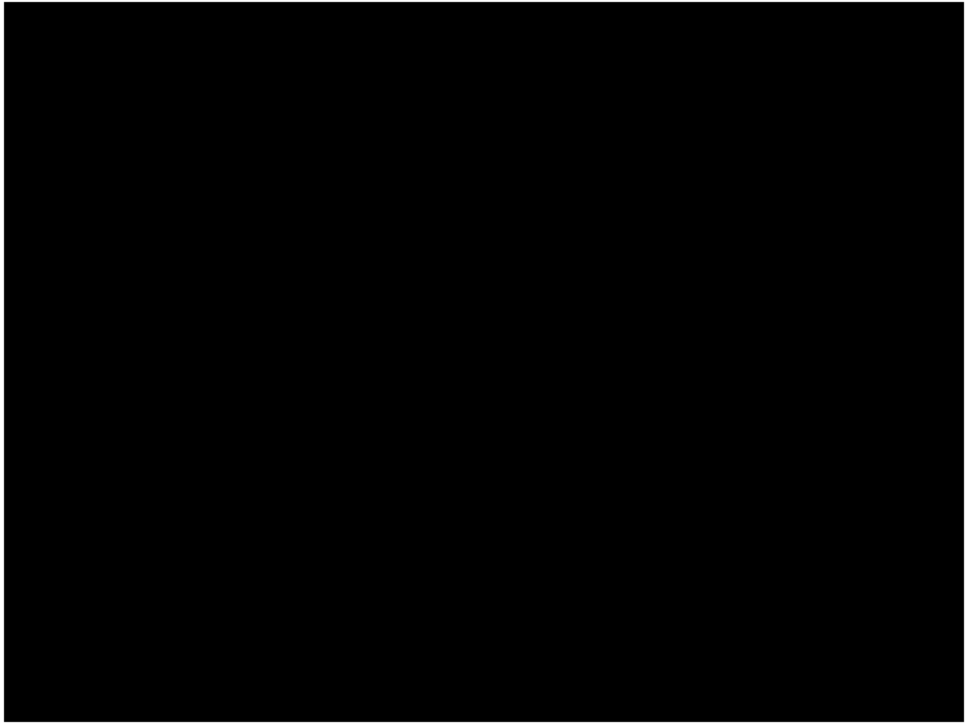
Combined Score (Likelihood x Severity)	Risk Level
1-4	Low
5-9	Low Moderate
10-14	High Moderate
15-25	High

Risk	Description	Effect
RPI: Raspberry Pi ION integration	Not being able to integrate ION into Raspberry Pi's	Raspberry Pi hardware simulation will not resemble overall network implementation
NCP: Network Capacity Model	Inaccurate Network Capacity Model	Network capacity model will not provide sufficient evidence to support network architecture design
OA: Outside Architecture	Outside architecture information unavailable (eg. Lunar Gateway)	System architecture will not utilize existing infrastructure
IA: Inaccurate Assumptions	Inaccurate Assumptions utilized	Models will contain systematic errors that will reduce accuracy
PC: Project Complexity	DOTCOM requires complex hardware, software, and architecture design and integration for final deliverable	Limited to a year of research and design for a highly complex task could yield reduced deliverable depth
FI: Facility Inaccessibility	COVID imposes inaccessibility to facilities required for hardware construction and testing	Large increase in difficulty to construct and test hardware component
CTI: Cross Team Integration	Cross-team MBSE integration	One comprehensive model of the system will be unavailable

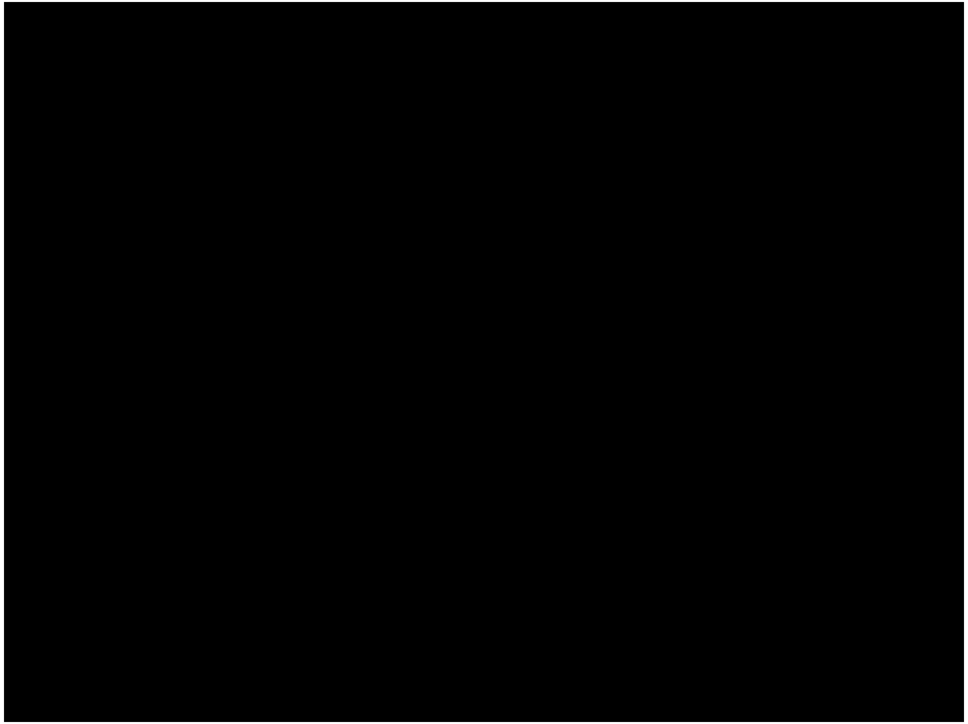
Critical Project Elements

1. **Hardware Test Bed:** Demonstrate various network characteristics.
- Create nodes from Raspberry Pi's to resemble system architecture and implement ION as the network protocol to validate future and existing simulations.
- Design and 3D print housing for the Raspberry Pi's to function properly.
1. **Network Protocol:** Structured data transmission methodology that allows for high speed reliable communications from node to node.
- Implement Delay Tolerant Networking protocol.
- Provide environmental transmission optimization and compatibility with existing and future networks.
1. **Link Budget:** The project will meet certain data-relay rates for communication between all communication nodes.
- Use RF for short distance and laser for long distance data-transfer.
1. **Relay Station:** Allows for direct access to communications between Earth and The Moon.
- Establish ground based relay station for increased accessibility, decreased cost, and easier communications.
1. **Satellite Constellation Architecture:** Construction of ideal constellation architecture around each planetary body to satisfy coverage requirements.
- Establish a medium-altitude constellation, providing complete coverage while minimizing the number of satellites required to do so.
1. **System Prototype Validation:** Ensure all system elements are valid.
- Demonstrate system capabilities through a conceptual network architecture using MBSE simulation.

Satellite Constellation Animation



Satellite Groundtrack Animation



Cost Breakdown

Key Project Components	Cost
Raspberry Pi (6)	$245.00
Monitors (6)	$851.97
Keyboards (6)	$111.93
SD cards (6)	$97.93
Ethernet Cables (12)	$109.76
HDMI Cords (6)	$55.86
Power Cables (6)	$56.00
Total:	**$1,528.45**

Note: already have material needed for 3D printed housing.

Hardware Test Plan

- Major Tests
  - Depicted in CONOPS (Levels 1-4)
  - Data Analytics
  - Network Congestion Model Verification
- No Need for Specialized Equipment or Facilities