Traffic Modeling for Deep Space Network in the Human Mars Exploration Era

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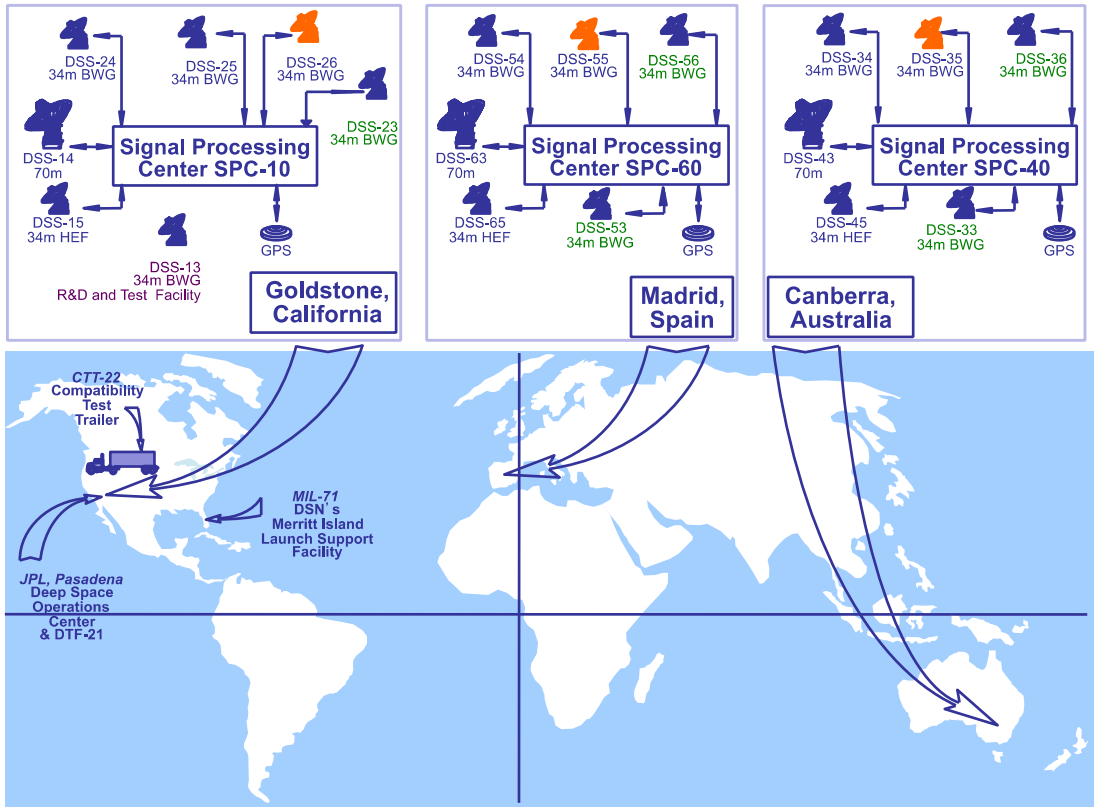
Outline of Talk

- Introduction
- Modeling of the Mission Traffic
- Network Modeling Tools and Mission Data Definition
- Terrestrial Network Bandwidth Statistics
- Concluding Remarks and Future Work

Introduction – DSN architecture and evolution path (Oct 26, 2015)



LEGEND
- Future 34m BWG Antenna
- New 80 kW Transmitter
- R&D and Test Antenna

New BWG Antenna – Expected Operation Dates

DSS-36 – October 2016 (Canberra)

DSS-56 – October 2019 (Madrid)

DSS-53 – October 2020 (Madrid)

DSS-23 – October 2023 (Goldstone)

DSS-33 – October 2025 (Canberra)

80 kW Transmitter – Operation Dates

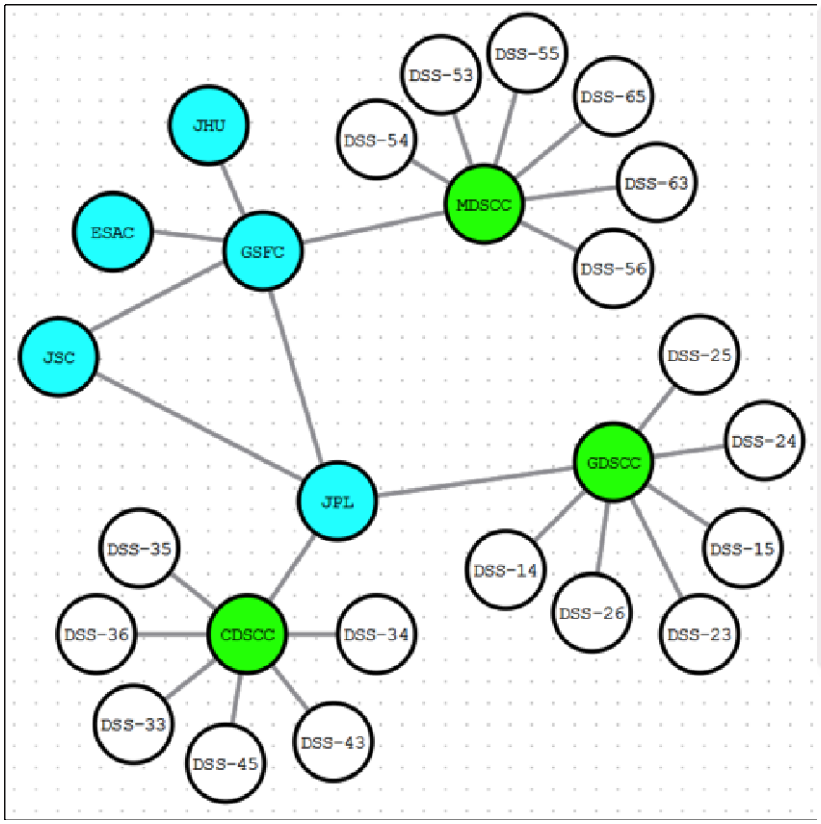
DSS-26 – June 2015 (Goldstone)

DSS-35 – circa 2020-2021 (Canberra)

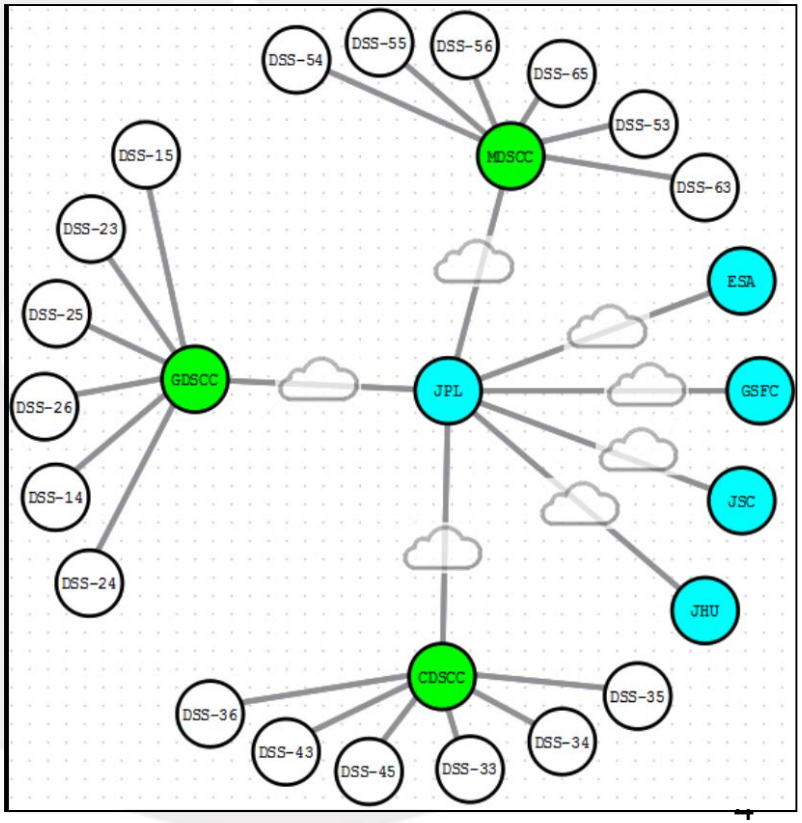
DSS-55 – circa 2020-2021 (Madrid)

Introduction – DSN Terrestrial Network Topology

- NASA/CSO is transitioning the DSN terrestrial network from dedicated landlines to commercial cloud-based internet services
- Consider functional flow instead of physical flow in this paper



Physical Flow



Functional Flow

Introduction – Modeling and Simulation Approach

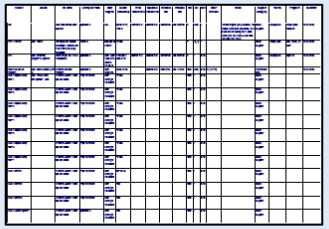
- Scope: mission downlink traffic, terrestrial network, RF communications only
- Considers the functional flow (instead of physical flow) of data from DSN sites to JPL Central, and from JPL Central to the destination mission operations centers (MOCs)
  - JPL Central performs data conditioning, and data merging from multiple sources, e.g. station hand-over
- Generate the deep space mission traffic for the 30-day period within July/August 2039
  - Specify pass types with different data type compositions
  - Specify latency requirement of each data type
- Exercise the SCMM-derived mission traffic model to simulate mission data that flow into the terrestrial network regulated via store-and-forward techniques
  - Estimate the required network bandwidths of the DSN sites and mission MOCs
  - Estimate the required buffer to perform store-and-forward flow control at the DSN sites

Mission Traffic Modeling – Tools that Generate Tracking Schedule

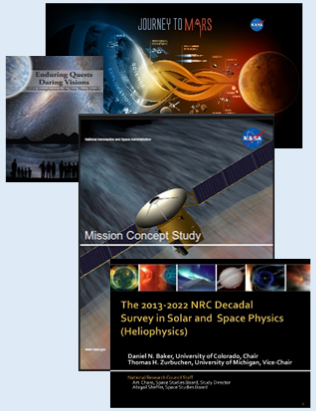
- Space Communication Mission Model (SCMM)
  - Is managed by NASA's Space Communications and Navigation (SCaN) Office.
  - Enumerates current and anticipated future missions potentially requiring communications support from any of SCaN's three communications networks. Used DSN portion.
- Mission Set Analysis Tool (MSAT)
  - Is populated with detailed mission design, spacecraft telecom, and ground tracking requirements for each applicable SCMM mission across all of its operational segments.
  - Applies SCaN-standard link budget tool to analyze all links across all mission ops segments.
  - Provides mission requirements as a function of time to the Architecture Loading Analysis Tool.
- Orbital Trajectory Inference Engine (OTIE)
  - Computes spacecraft-ground station visibilities as a function of time from mission trajectory files.
  - Generates new trajectories when they are missing or in need of updating.
  - Provides spacecraft range data as a function of time for MSAT link budget calculations.
- Architecture Loading Analysis Tool (ALAT)
  - Loads DSN antennas per MSAT inputs and OTIE visibilities; simulates antenna loading as a function of time; generates simulated tracking schedule (including data rates, link types, etc.).

Mission Traffic Modeling – 30-day within July/Aug 2039 (one mission prepared to leave Mars, and one in route to Mars)

Space Communications Mission Model (SCMM)



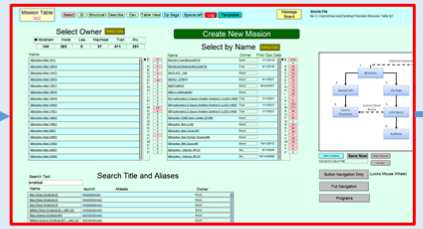
Missions & Mission-Line Placeholders



NASA Roadmaps & Mission Concept Studies

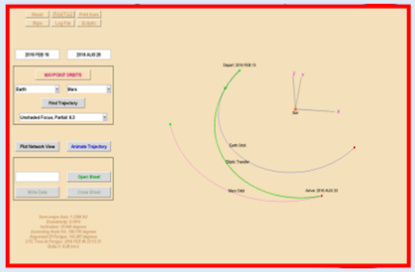
Candidate Mission and Spacecraft Design Data

Mission Set Analysis Tool (MSAT)



Key Mission Design Data

Orbital Trajectory Inference Engine (OTIE)

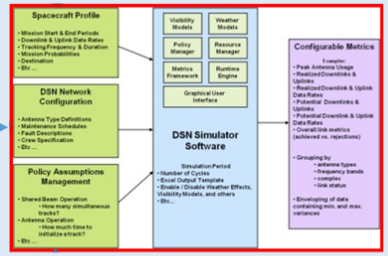


Spacecraft Range Distance as a Function of Time

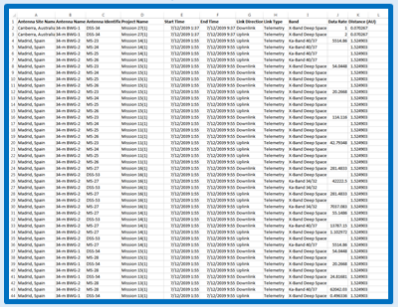
Visibility Relative to Ground Stations as a Function of Time

RF Link Requirements & Associated Spacecraft Telecom & Tracking Requirement Data

Architecture Loading Analysis Tool (ALAT)



Spacecraft Contact Times, Durations, and Rates by Receiving Antenna as a Function of Time for the Entire Mission Set



Simulated Tracking Schedule

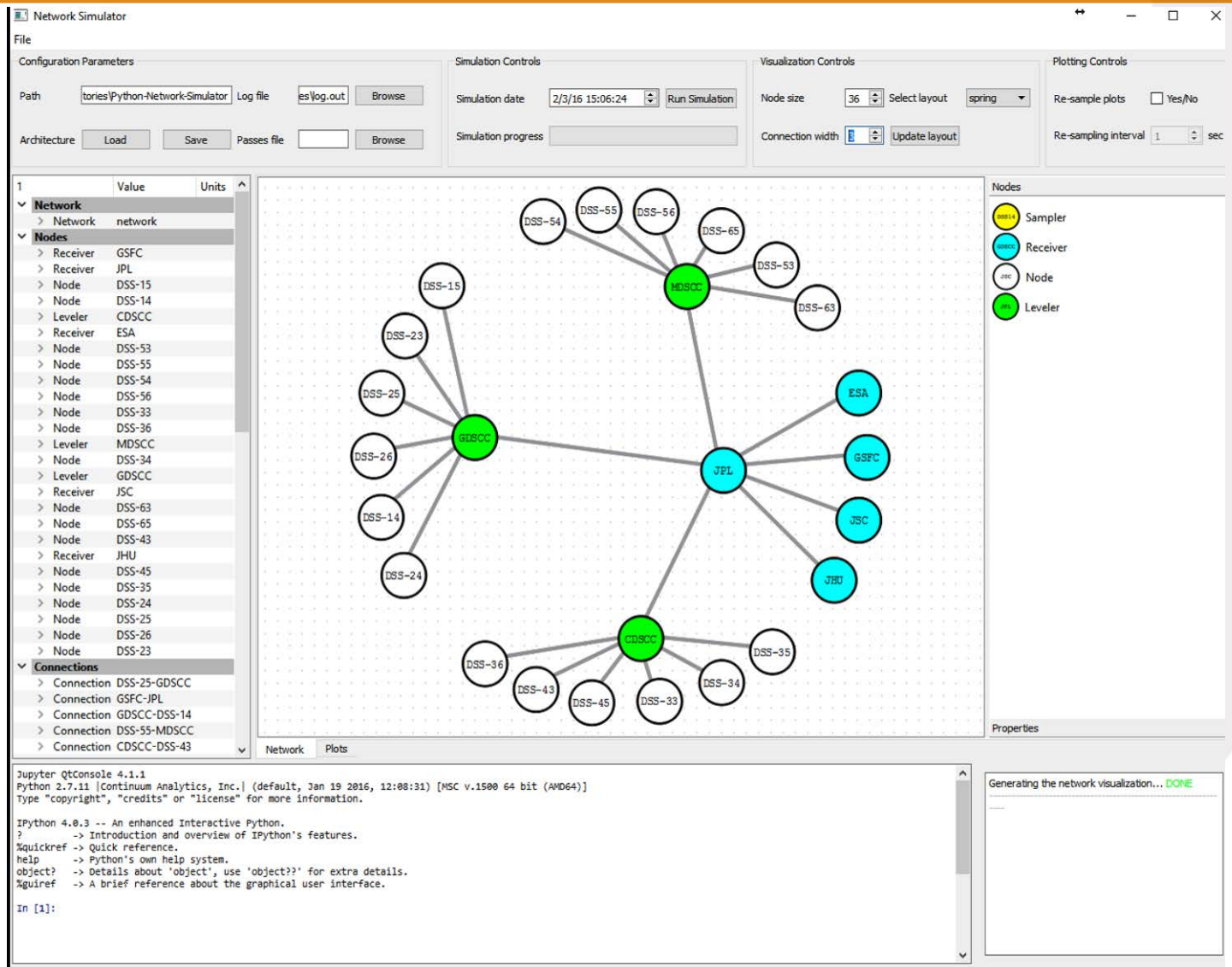
Network Traffic Modeling – ArchNet and Simulation Assumptions

- ArchNet – a course-grain discrete-event network simulator
- Estimate the required network capacity and storage requirements as a function of the data transmitted through the system and the latency constraints of the data
- Assume all signal processing functionalities (e.g. waveform sampling, digitalization, framing, decoding, etc.) are performed at the DSN sites, and are transparent to the simulation
- All mission data are first routed to JPL for processing, prior to sending to the mission MOCs
- Store-and-forward mechanism (a.k.a. leveling) is employed at the DSN sites to reduce terrestrial network bandwidth requirements, while ensuring that spacecraft and science data latency requirements are not violated
  - ArchNet implements the two-state Markov leveling scheme in [2]

Network Traffic Modeling – ArchNet Software Description

- ArchNet software design principles
  - Provide a flexible and computationally efficient simulation environment that can operate under a wide variety of network architectures and traffic profiles
  - Facilitate the user interaction through a robust Graphical User Interface (GUI) that allows rapid visualization of the network architecture and the simulation results
  - Ensure that simulation inputs and outputs can be provided and obtained through a wide variety of standard interfaces
  - Develop a software environment that can be cheaply and easily maintained and upgraded
- ArchNet software platform and libraries
  - Implemented on the open-source Python [7]
  - Discrete-event engine uses SimPy [8]
  - Simulation and visualization environment uses PyQt [9]
  - Plotting system for simulation/visualization results uses Matplotlib [10]
  - Interactive simulation environment (middle layer between GUI and engine) uses Ipython [11]

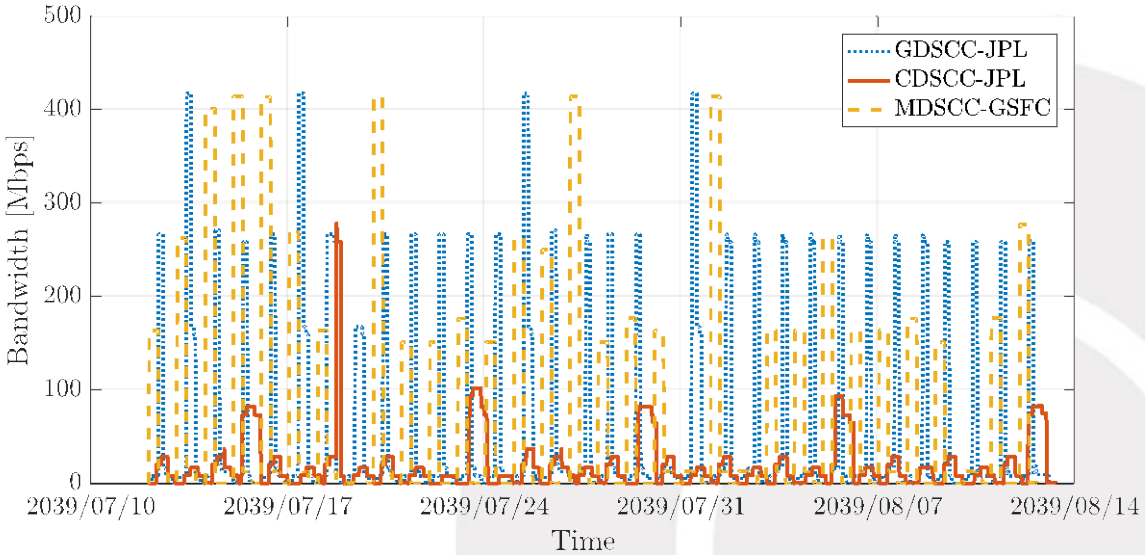
Network Traffic Modeling – ArchNet GUI Environment

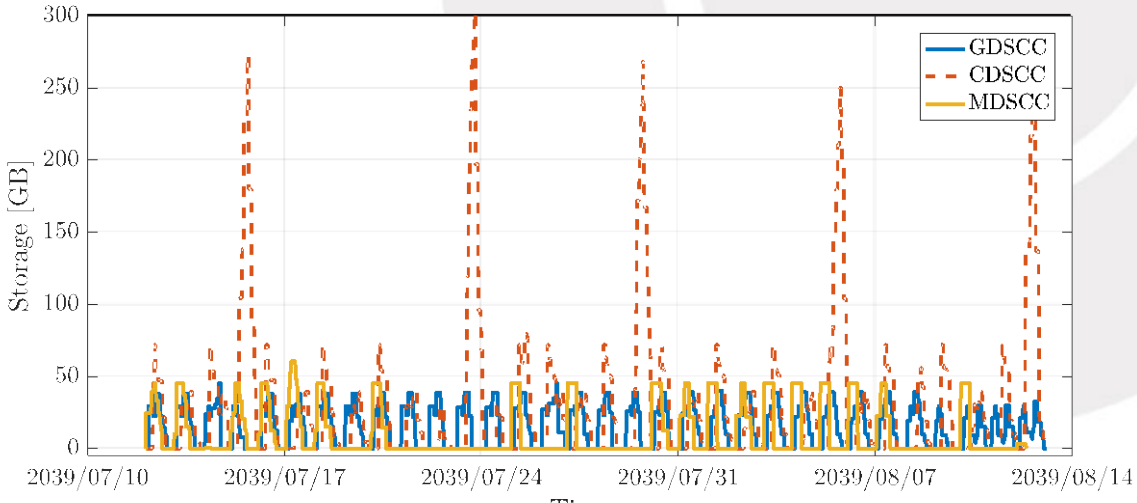


Network Traffic Modeling – Pass Types and Data Types

Mission Type	Mission Phase	Pass type	Data Type	Data Volume Fraction	Latency Requirement
Robotic	Cruise	Telemetry	Telemetry	100%	5 seconds
	Prime	Telemetry	Telemetry	100%	5 seconds
		Science	Telemetry	10%	5 seconds
			Quick-look science	5%	1 hour
			Bulk science	85%	8 hours
	Extended	Telemetry	Telemetry	100%	5 seconds
		Science	Telemetry	10%	5 seconds
			Bulk science	90%	8 hours
Human	Prime	Exploration	Telemetry	10%	5 seconds
			Quick-look science	10%	1 hour
			Bulk science	80%	8 hours
		Astronaut	Telemetry	10%	5 seconds
			Audio/Video	90%	2 seconds
		Telemetry	Telemetry	100%	5 seconds
		Audio/Video	Audio/Video	100%	2 seconds
		Science	Quick-look science	10%	1 hour
			Bulk science	90%	8 hours
Any	Any	Navigation	DDOR	100%	6 hours

Simulation Results –Bandwidth Profiles & Storage Profiles



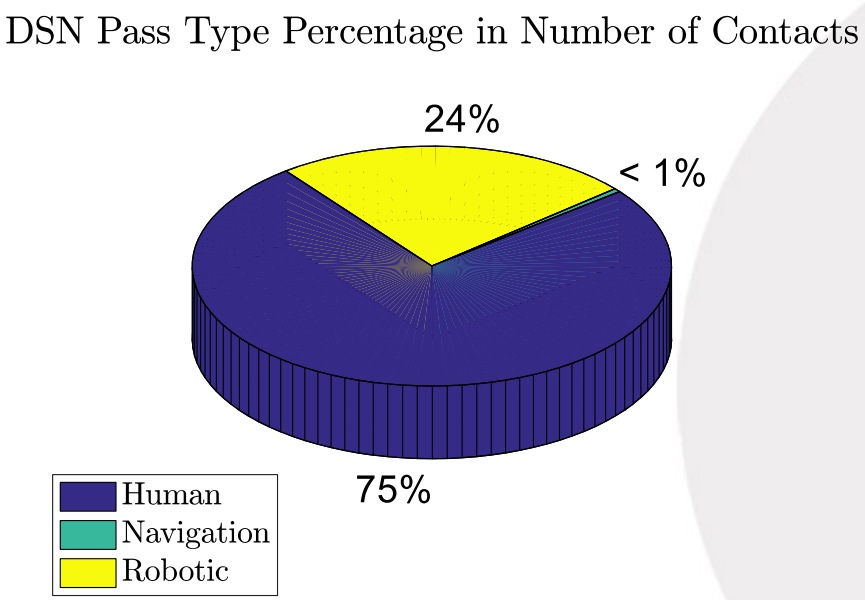


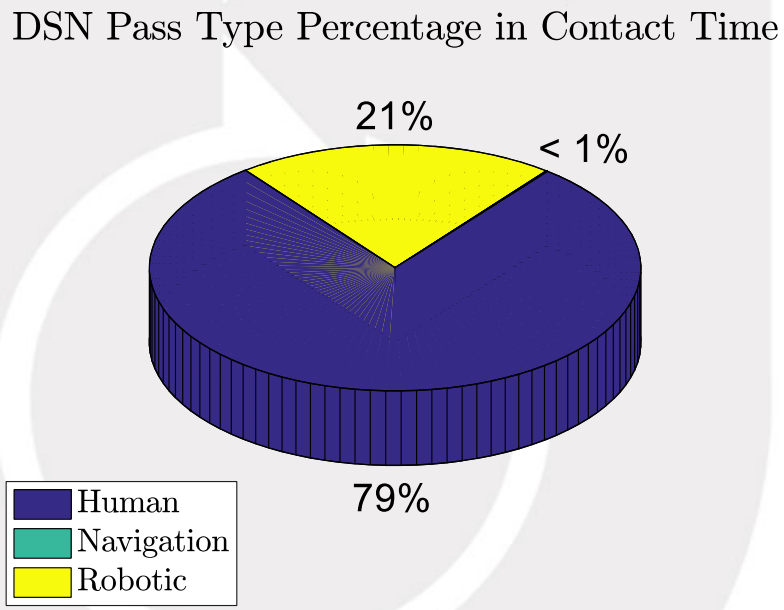
Simulation Results – % Bandwidth & Storage Requirements

Percentage (%) Bandwidth (Mbps)	85%	90%	95%	99%
GDSCC-JPL	258	260	267	418
CDSCC-JPL	28	65	82	102
MDSCC-JPL	177	263	414	414
JPL-JSC	244	244	388	395
JPL-GSFC	28.4	30.9	36.6	39.1
JPL-JHU	2.63	2.71	2.73	2.84
JPL-ESA	8.5	8.7	11	11.2

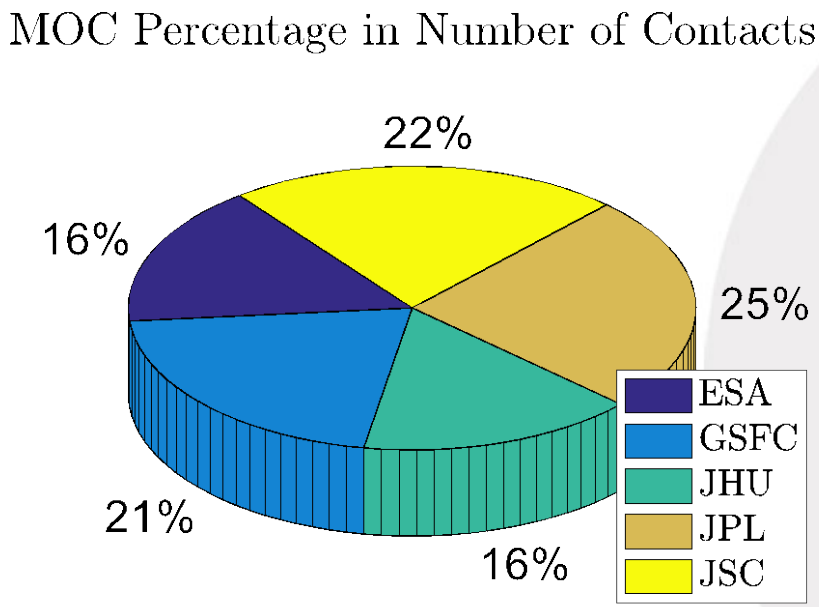
Percent (%) Storage (GB)	85%	90%	95%	99%
GDSCC	30.8	38.4	39.0	39.2
CDSCC	55.3	72.0	138.2	250.4
MDSCC	45.2	45.3	45.4	45.4

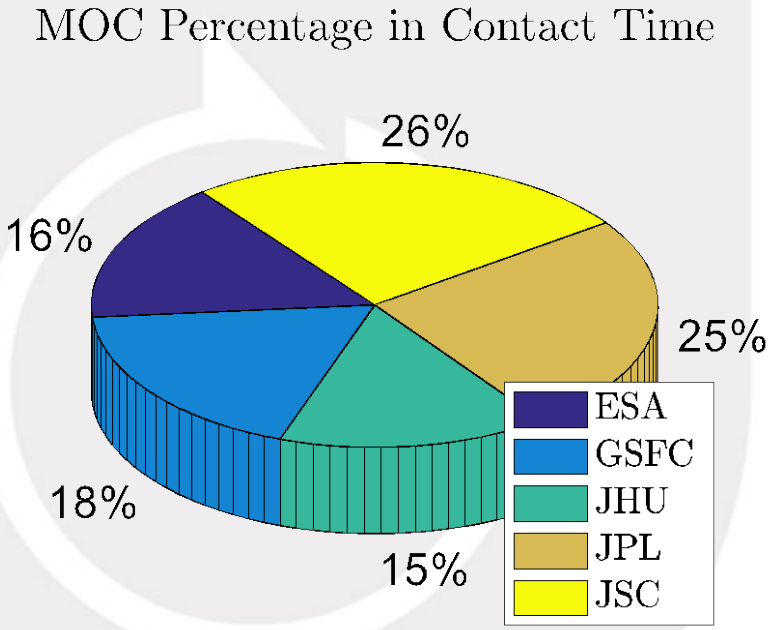
Simulation Results – Aggregated Pass Type Percentage for DSN





Simulation Results – MOCs' Pass Type Percentage





Simulation Results – Observations and Interpretations

- Simulation time of 30 days in 2039 is probably too short to provide representative statistics for the purpose of terrestrial network design and planning. But, it can be considered a stressing case for the DSN's terrestrial network requirements in the Human Mars Era.
- In this 30-day simulation, Mars visibility is northern hemisphere biased. This results in
  - Human missions being mostly tracked by Goldstone and Madrid, and robotic missions by Canberra
  - Robotic missions can tolerate higher data latency; thus, the store-and-forward mechanism in Canberra can largely reduce the required ground bandwidth compared to the Goldstone and Madrid sites (Figure 6 and Table 1).
  - Canberra's storage requirement is more than 5 times larger than Goldstone and Madrid's (Figure 7 and Table 2).
- The Human Mars missions' downlinks are dominated by high-rate low-latency audio/video.
  - Ground links from Madrid to JPL, in this scenario, exhibit a large percentage of unused time.
- Over 75% of the DSN's time is used for human missions in the 30-day period (Figure 9).
- Current DSN plan to upgrade its terrestrial network to 40 Mbps is not sufficient for this 30-day scenario, which requires a bandwidth of 100 – 400 Mbps, depending on complex.

Concluding Remarks and Future Work

- We discuss the effort to model the end-to-end traffic flow and buffering mechanism of the DSN terrestrial network in the Human Mars Era
  - Leverage on the SCMM-derived mission traffic for a 30-day period in 2039
  - Apply novel store-and-forward modeling techniques to estimate the bandwidth and storage statistics of the DSN

- Future work
  - Include optical links in addition to the RF communications
  - Generate higher-fidelity SCMM-derived mission traffic models that include lunar and Mars relay communications (RF and optical) between surface assets and the relay orbiters
    - The relay orbiters would act as the store-and-forward nodes
    - Study would provide the bandwidth and storage statistics that help to formulate the relay storage and bandwidth requirements

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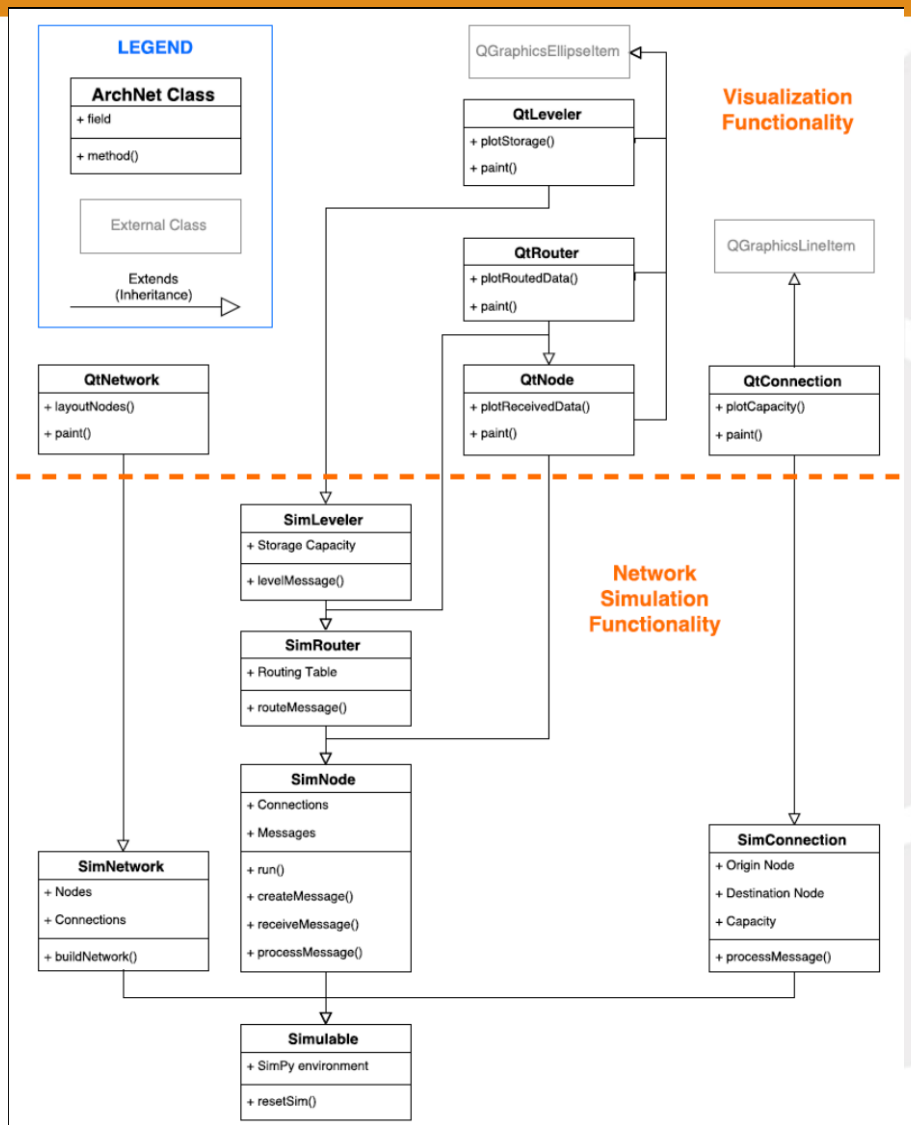
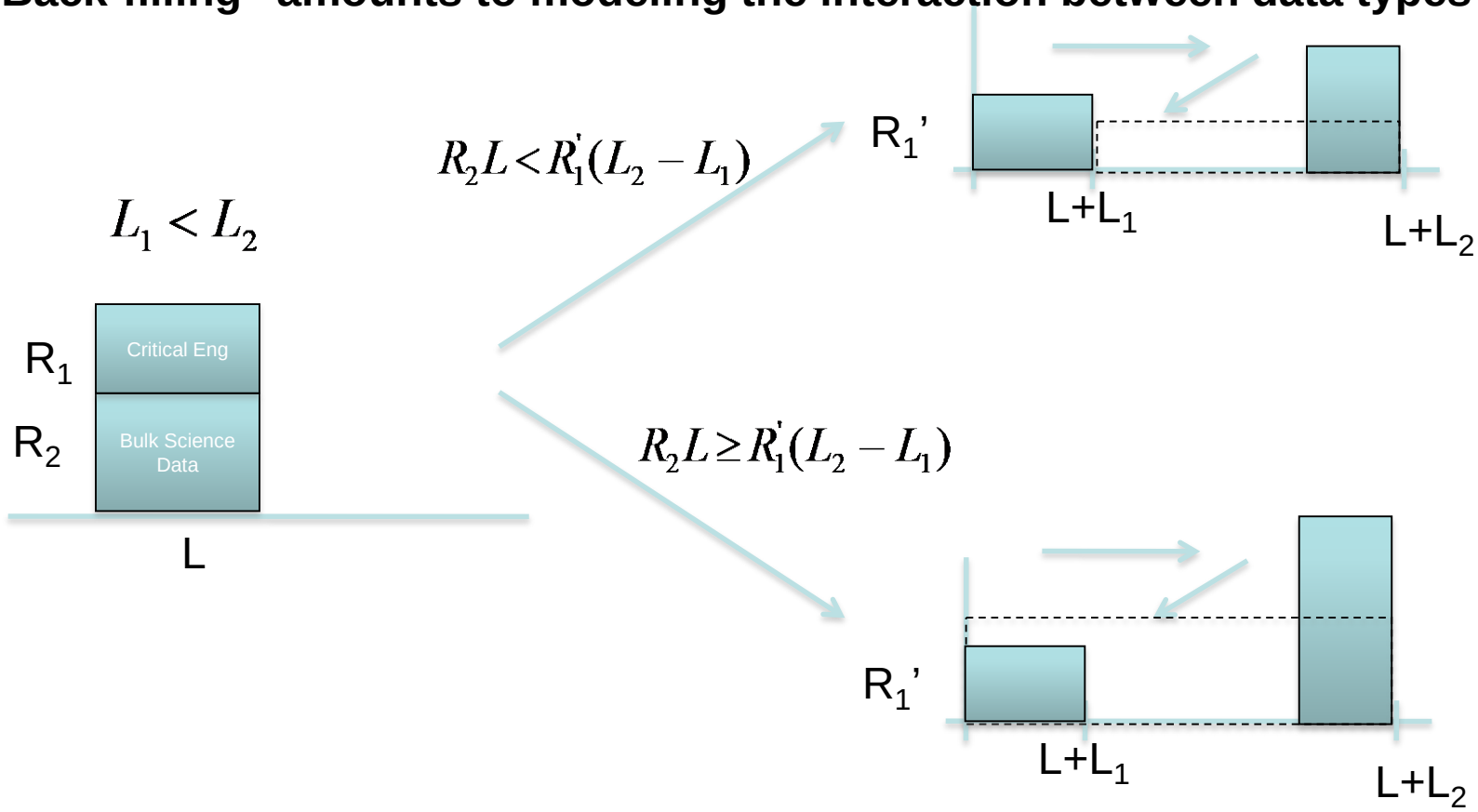
Backup

Network Traffic Modeling – ArchNet Software Schematics



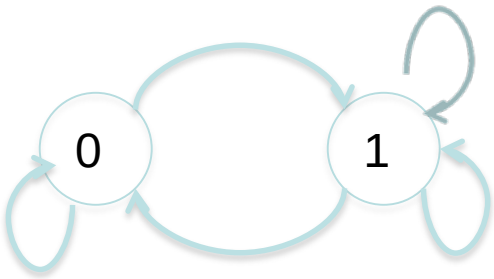
2-State Markov Modeling Scheme Observation

- **Smaller aggregated bandwidth can be achieved by back-filling the vacant timeline between $L+L_1$ and $L+L_2$ with Type 2 data (Greedy Algorithm)**
- **Example: For L=1 hour, L_1=5 second, L_2=8 hours, R_1=20 kbps, R_2=180 kbps**
  - "Straight-Forward" scheme yields 40 Kbps
  - "Back-filling" scheme yields 20.3 Kbps
- **"Back-filling" amounts to modeling the interaction between data types**

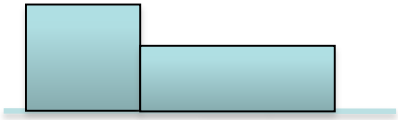


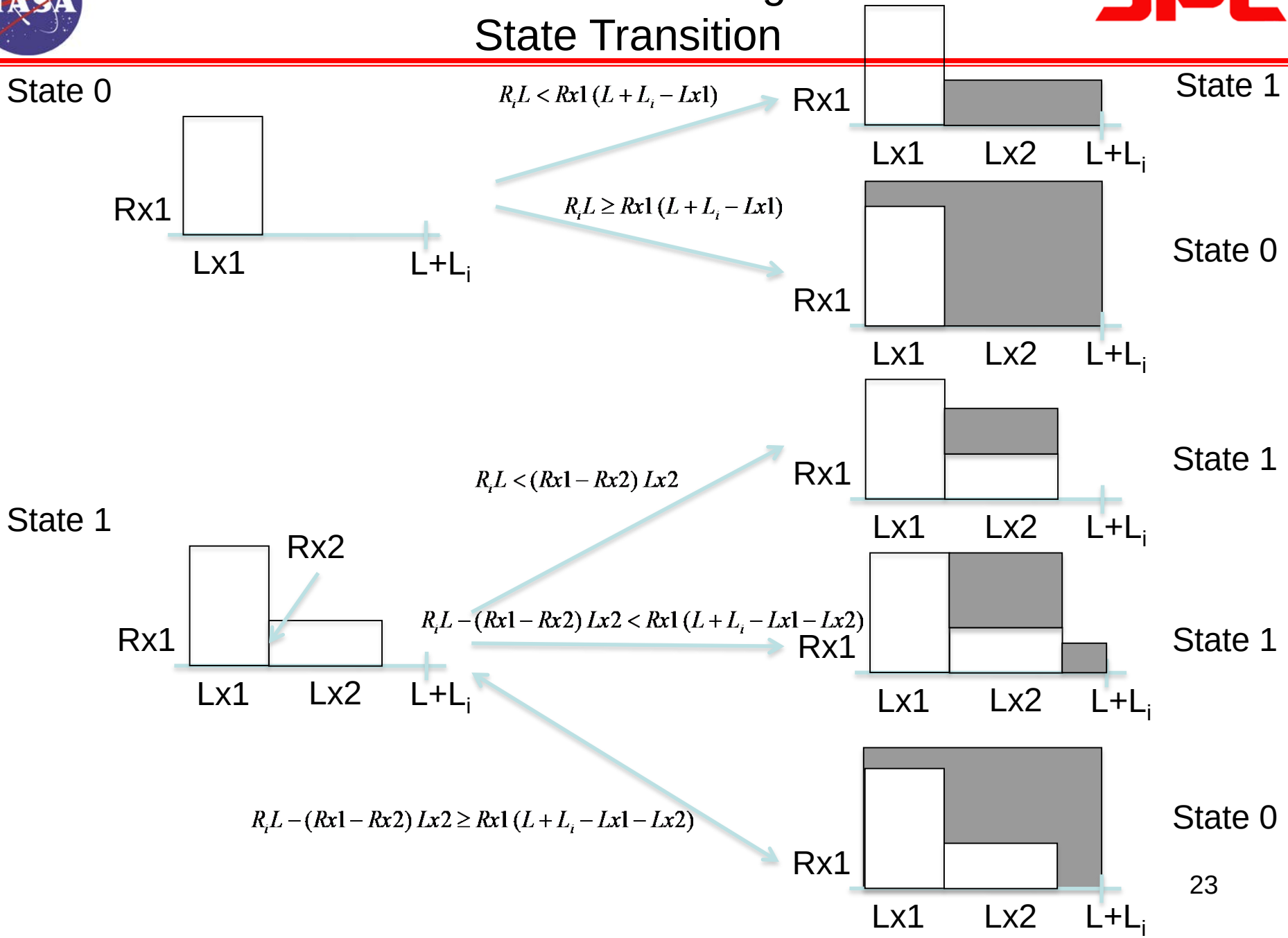
2-State Markov Modeling Scheme
State Representation

State 0



State 1



State Transition Diagram

2-State Markov Modeling Scheme
State Transition