Simulation Modeling and Performance Evaluation of Space Networks

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Outline

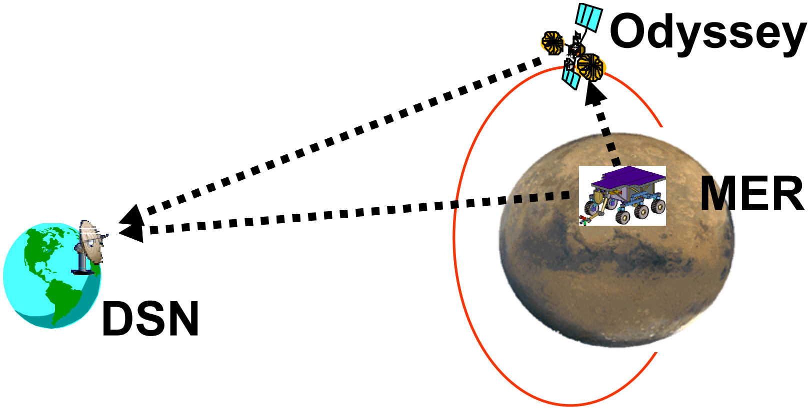
- Space-Based Networking
- MACHETE Tool Suite
- Bundle Protocol Model
- Bundle Protocol Model Benchmark
- MACHETE Development Summary
- Mars Relay Network Simulation
  - Bundle Protocol/LTP/Space-based networking protocols
  - Historical Mars Relay link characteristics
  - 8 nodes: landers, orbiters, ground stations, mission control
- Conclusion and Final Remarks
- Future work

Space-Based Networking Overview

- Delay-Tolerant Network Research Group (DTNRG)
  - Research topic: “performance challenged” networks
  - DARPA: delay and disruption tolerant networking
- Space-based communication networks (DTN subset)
  - Opportunistic connectivity
    - Lack of contemporaneous end-to-end path
  - High error rates
  - Asynchronous data rates
    - Possible unidirectional links
  - Long one-way trip times
- Reliable terrestrial protocols cannot operate
  - Expectation of end-to-end path
    - IP routing; hierarchical IP addresses; end-to-end TCP
  - Terrestrial protocols often use numerous round trips
  - Often use timer-based session management

MACHETE Background

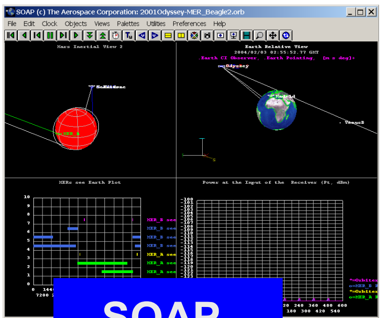
- The Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE) is a simulation tool under ongoing development to support the JPL's Interplanetary Network Directorate (IND), Mars Program Office, JPL Standards Information Office, and Space Communications Project (Code T)
- Uses:
  - Protocol and technology development
  - Performance characterization
  - Protocol verification and validation
  - Mission design and operation



Relay Network Communications

MACHETE Simulation Process

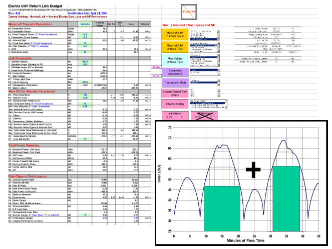
Geometric Analysis



SOAP

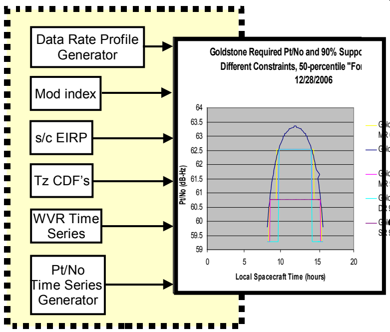
- **Generates**:
  - View Period
  - Slant Range
  - Declination
  - Connectivity
- **Models**:
  - Orbit ephemeredes
  - Lander position
  - EDL
  - Antenna patterns

Link Characterization



UHF & X-band (Excel, Matlab)

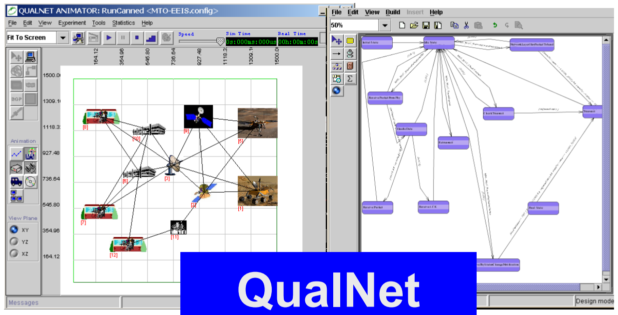
- **Accounts for:**
  - Modulations
  - Fading/Noise
  - Data Rate
  - Antenna Pattern
  - Multi-path Effect
  - Coding
- **Computes:**
  - Multi/single Data Rate Profile Optimization
  - Bit-error-rate



Ka-band Optimization Tool (Excel, C)

- **Computes:**
  - G/T profile
  - Optimized profile using 1 or multiple data rates
- **Accounts for:**
  - Historic G/T data
  - Monthly & Yearly Weather Statistics
  - Weather Forecast
  - Declination, S/C EIRP, Range, Coding

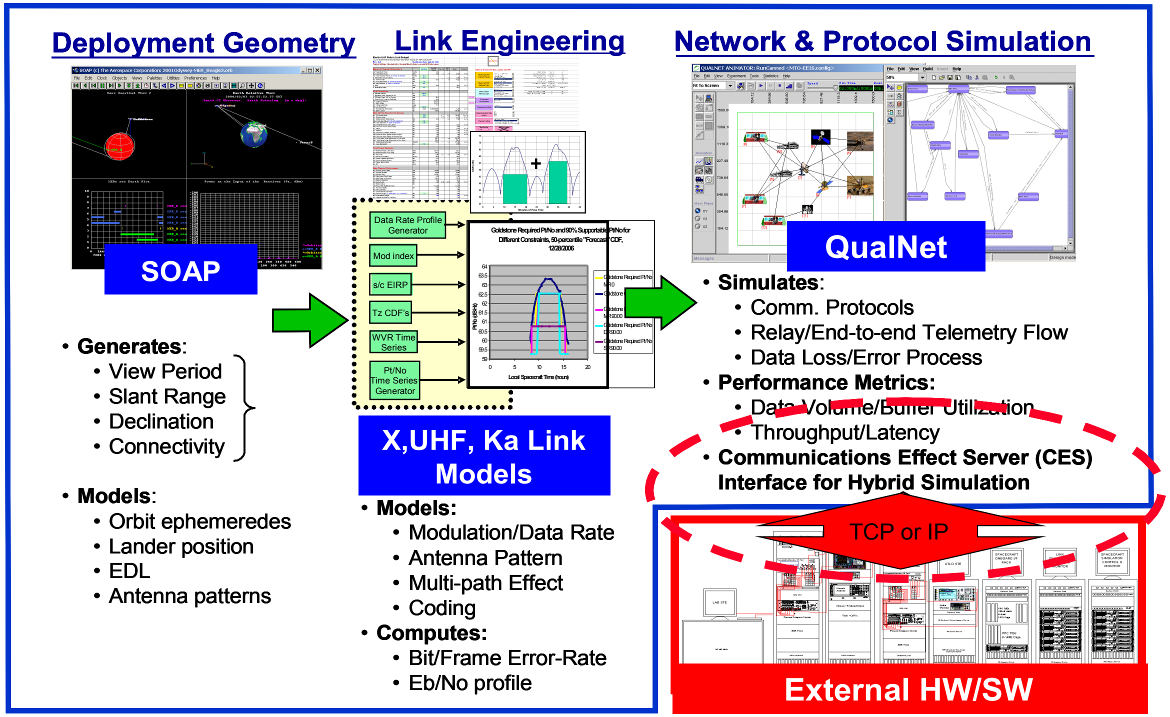
Simulation



QualNet

- **Simulates**:
  - Mission Ops Scenario
  - Onboard Data Storage/Management
  - Comm. Protocol logic & interactions:
    - TC/TM
    - Proximity-1
    - CFDP
  - End-to-end Telemetry Flow:
    - Custody Transfer
    - Frame, Packet, File tracking
  - Quality-of-Service Requirements
  - Buffer Utilization
  - Priority-based Data Handling/Policy
- **Performance Metrics Derived:**
  - Data Volume
  - End-to-End Product Latency
  - Buffer Requirement/Packet Loss
  - Quality-of-service

MACHETE



- An integrated **space network** simulation tool suite modeling dynamics of link geometries, physical layer channel characteristics, and communications traffic and protocol behaviors (including the full CCSDS protocol stack)
- Can run simulations at orders-of-magnitude faster than real time for rapid analyses, or can interface to external test resources that generate real-time traffic and/or provide communications functions (hybrid simulation-emulation)
- Uses:
  – Characterizing system performance benefits of new or alternative protocols, services, and operations
  – Determine communications system resource requirements (e.g., bandwidth, buffer size, schedule allocations)
  – Validate new technologies for mission infusion
  – Aid mission planning and operations
- Has proven effective in use across NASA, including Mars Exploration Program, Deep Space Mission Systems, Exploration Systems
- Can leverage recent Space Communications Testbed (ESR&T) development focused on Lunar proximity and surface communications modeling for direct application to LCNS

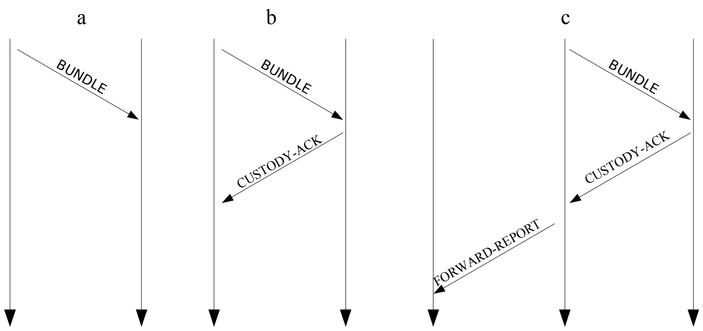
MACHETE Capabilities

- Protocol and technology development & performance evaluation. Examples include:
  - Mars Relay Network performance characterization
  - Bundle Protocol overhead analysis
  - Sensor network node placement
- Test bed & Validation
  - MACHETE provides real-time emulation functionality to facilitate performance evaluation and integration testing of flight software
- Mission design and operation
  - MACHETE provides fast-turn-around communication modeling for iterative, automated space flight mission scheduling and planning process

Bundle Protocol Model - Overview

Bundle Option	Modeled	Excluded
Custody Transfer	X	
Prioritization	X	
Bundle Reporting	X	
Fragmentation / Reassembly		X

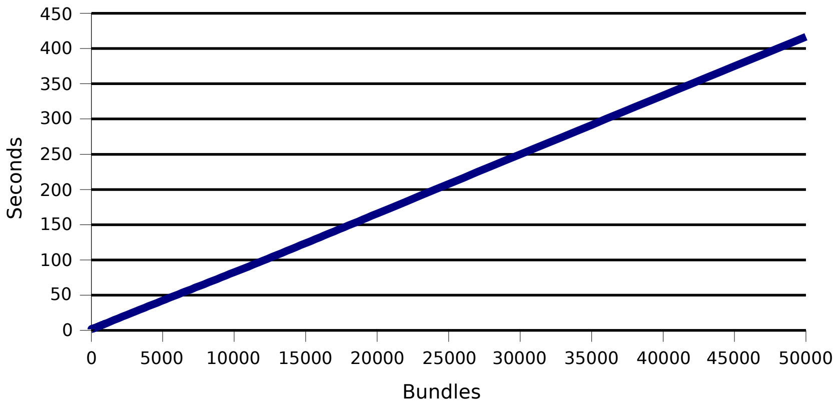
Bundle Protocol functions modeled



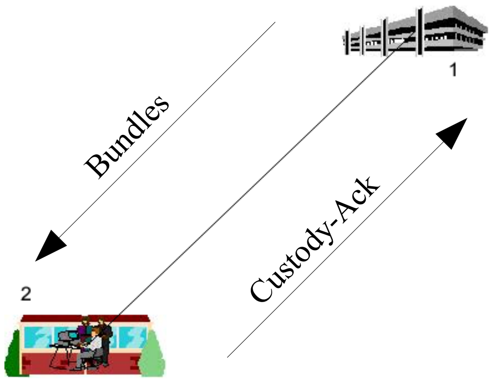
Bundle transfers a) non custodial b) custody requested c) custody and forward reporting

- Each function adds complexity
  - Custody transfer requires an extra bundle transmission (msg switching)
  - Data prioritization requires handling functions (QoS)
  - Reporting requires an extra bundle transmission, etc. (Data management)
- Bundle fragmentation / reassembly model to be added later
  - Data currently fragmented at lower layers, but bundles still intact
  - Allows for multi-path routing
- Current model uses Long-haul Transport Protocol on all links
  - TCP convergence layer to be added
- Interface for real-time emulation
  - Application testing

Bundle Protocol Model – Simulation Benchmark



Simulation Time



Network Topology

- Simple two node topology used for benchmark
  - Virtually no limitation on network complexity
  - Commercial core can use distributed/parallel platforms
- Scalable simulation model without additional delay
  - Proportional increase in # of transfers and simulation time
- Currently no optimization work has been done
  - Performance improvements to follow

MACHETE Development Summary

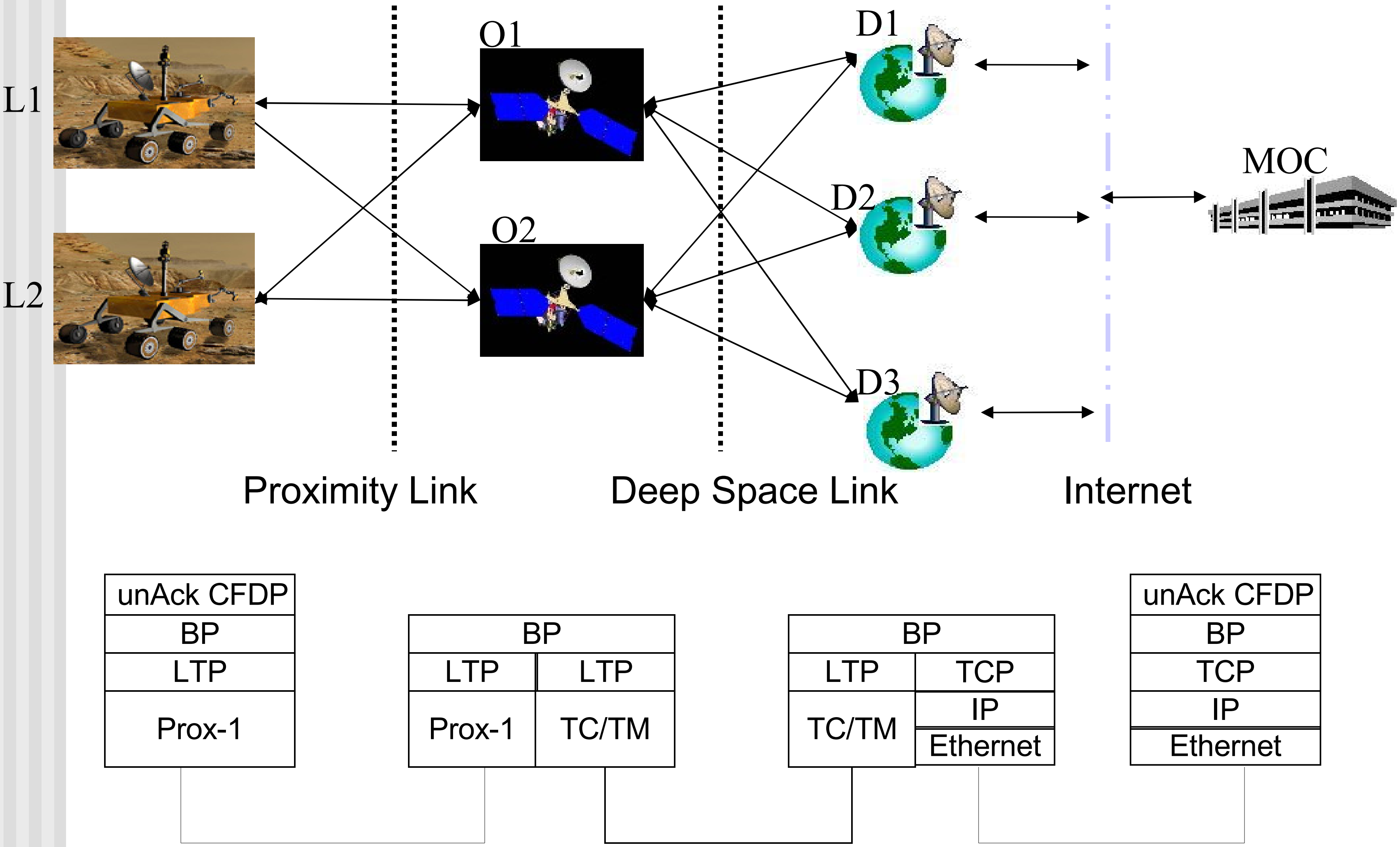
MACHETE has been developed and is effective for

- Quantifying system performance based on comprehensive considerations
  - Dynamics of link geometries
  - Physical layer channel characteristics
  - Communications traffic and protocol behaviors
  - Utilizes QualNet, SOAP & Matlab tools
- Determining system resource requirements (bandwidth, buffer size, schedule allocations, etc.)
- Characterizing performance benefits of new or alternative protocols, services, and operations
- Validating new technologies for mission infusion
- Aiding mission planning and operations

Added Bundle Protocol and Long-haul Transport Protocol models to MACHETE

- Simulated BP over LTP and other space-based networking protocols.
- Analyzed delay added by BP to InterPlanetary Network using historical mission scenario
- Currently testing future InterPlanetary Network applications

Use Case - DTN Simulation

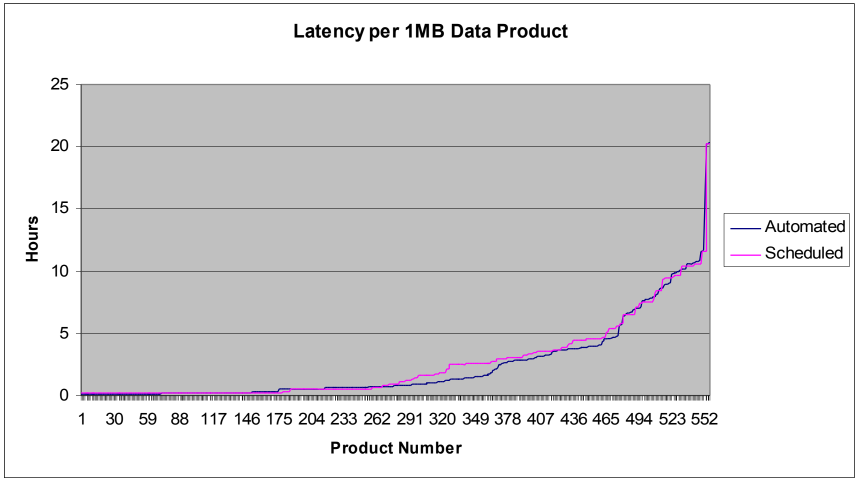


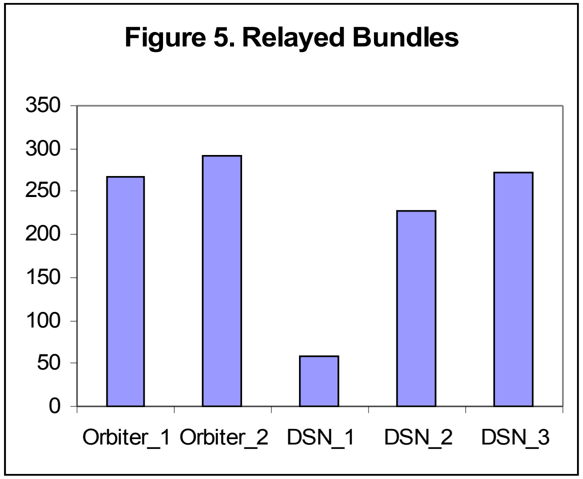
- TCP used as convergence-layer for terrestrial networks
  - overkill for Martian proximity network

Network Simulation (cont.) - Scenario

- Orbiters have same orbits as Odyssey and MGS
- All data from landers to Earth are relayed through orbiters
  - No Direct-To-Earth/Direct-From-Earth lander links
- Lander <--> Orbiter data-rate at 128kbps
  Orbiter <--> Earth from 16kbps to 124kbps
- No bit errors -> can ignore retransmission delay
- Simple first contact routing and FIFO queuing
- Time to live effectively infinite
  - No lifetime expiration will affect statistics gathered
- Traffic: 50% link utilization
- Custody requested on all bundles
- Bundle size: 1M Byte; frame size: 1K Byte
- Proximity link delay ~ 16ms; deep space link delay ~ 4 M

Mars Relay Simulation Results and Conclusions





- Relay usage depends on orbit and data rates
- As expected the Bundle Protocol operating over common Mars Relay Network protocols did not add noticeable delay to data transportation
  - DTN routing protocols will minimize delay (future)
    - initial testing used a first contact routing “protocol”
  - Bundle Protocol provides an automated data handling protocol that does not require manual scheduling

Concluding Remarks

- Built core space-based networking protocols into the MACHETE tool
- Completed functional verification of our space-based protocol model suite
- Benchmark shows scalability of models “good-enough” for future NASA communication network research and analysis
- Simulated and analyzed Mars Relay Network multi-hop scenario with historical link characteristics
  - protocol automation did not “hurt” data delivery latency
- Integrated testing of multi-hop scenario with external testbed
- Used MACHETE to test future Mars applications in a simulated network

Future Work

- Simulation of DTN routing and flow control algorithms for space-based networking
- Further design analysis of software applications through real-time network simulation
- InterPlanetary Network topology design and testing
- Mission storage requirement estimation
- Comparisons of BP/LTP (DTN) to other delay-tolerant protocol suites
- Future Bundle Protocol model support and maintenance
  - Formal verification of models
  - Performance enhancements to model
  - Extensions: fragmentation/reassembly, security draft, multi-cast, etc.
- Potential multi-center collaboration projects
  - ECANS, Constellation, individual missions, etc.

Backup Slides

Network Simulation - Contact Times

Contact % time	Orbiter_1	Orbiter_2	Total
Lander_1	3.31	3.44	6.75
Lander_2	3.24	3.57	6.81

Contact % time	DSN_1	DSN_2	DSN_3	Total
Orbiter_1	1.72	23.22	15.20	40.14
Orbiter_2	17.69	13.63	24.98	56.30

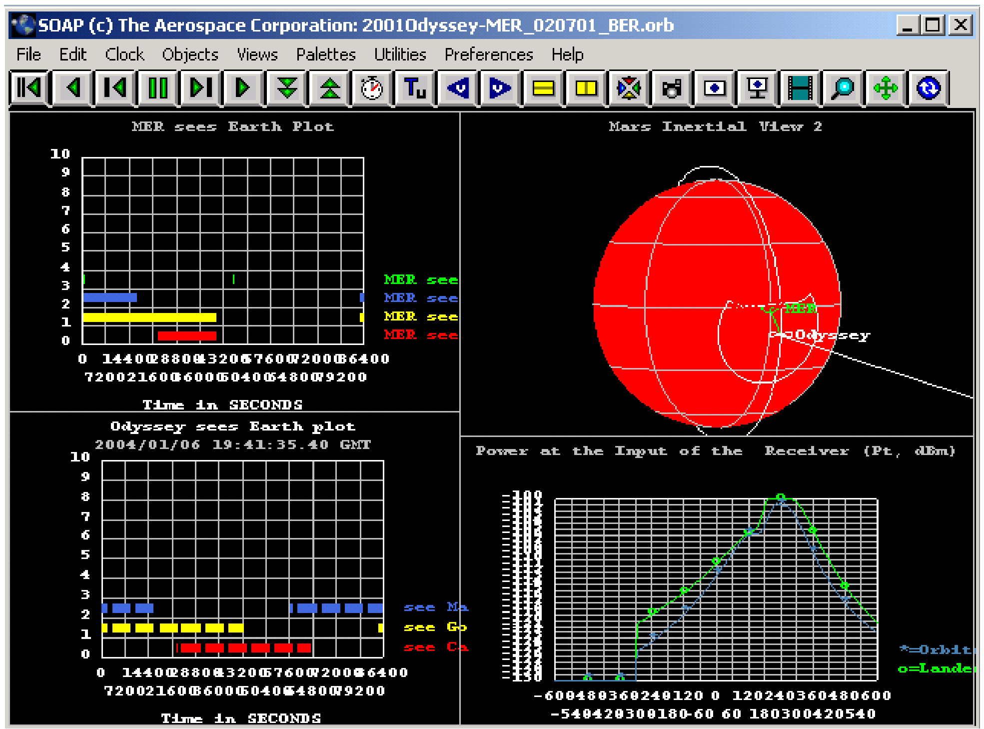
Orbital Modeling with SOAP

INPUT:

- Orbital elements
- Surface asset positions
- Telecom parameters (e.g., transmit power levels)
- Antenna patterns
- Mission scenario duration

OUTPUT:

- Received signal power profiles
- Inter-spacecraft ranges (propagation delays)
- View periods and feasible passes communications



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Traffic and Protocols Simulation

Input:

- Schedules for communications passes
- Bit error rates, propagation delays, and data rate profiles
- Parameters for traffic generation processes
- Protocol parameters (e.g., QoS policies)

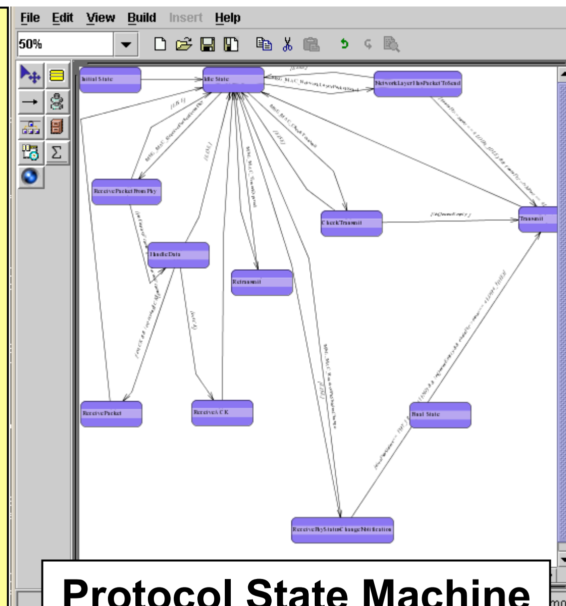
Output:

Time-dynamic processes and statistics for

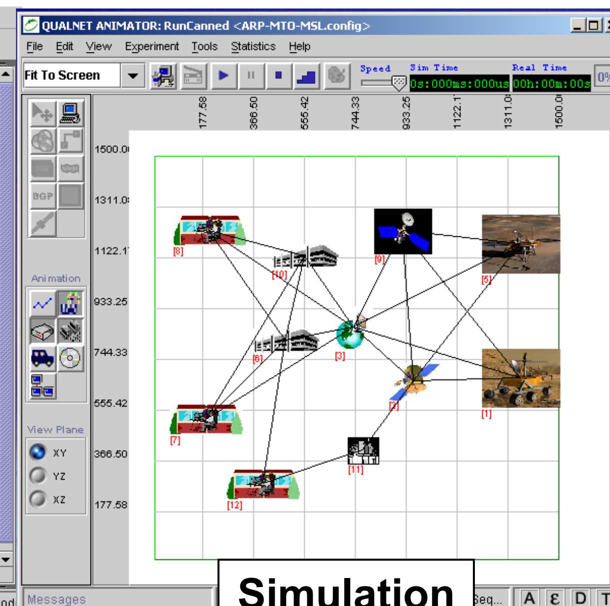
- Data transfer volumes
- Data delivery latencies
- Queue lengths

QualNet Models

- Traffic generation
- Executes behavioral models of communications protocols (including queuing disciplines)
- Statistics collection of performance metrics



Protocol State Machine



Simulation

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