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
MACHETE Simulation Process

Geometric Analysis

- **Generates:**
  - View Period
  - Slant Range
  - Declination
  - Connectivity

- **Models:**
  - Orbit ephemerides
  - Lander position
  - EDL
  - Antenna patterns

Link Characterization

- **SOAP** (Excel, Matlab)
  - Generates:
    - Modulations
    - Fading/Noise
    - Data Rate
    - Antenna Pattern
    - Multi-path Effect
    - Coding

  - Computes:
    - Multi/single Data Rate Profile Optimization
    - Bit-error-rate

- **UHF & X-band**
  - Data Rate Profile Generator
  - View Period
  - Slant Range
  - Declination
  - Connectivity

  - **Mod index**
  - s/c EIRP
  - Tz CDF's
  - WVR Time Series

  - **P/No Time Series Generator**

- **Ka-band Optimization Tool** (Excel, C)
  - 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
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

<table>
<thead>
<tr>
<th>Bundle Option</th>
<th>Modeled</th>
<th>Excluded</th>
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<tbody>
<tr>
<td>Custody Transfer</td>
<td>X</td>
<td></td>
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<tr>
<td>Prioritization</td>
<td>X</td>
<td></td>
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<tr>
<td>Bundle Reporting</td>
<td>X</td>
<td></td>
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<tr>
<td>Fragmentation / Reassembly</td>
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<table>
<thead>
<tr>
<th>Bundle Option</th>
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<th>Excluded</th>
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<tbody>
<tr>
<td>Custody-ACK</td>
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<td></td>
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<tr>
<td>Forward-Report</td>
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</table>

- **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

- 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

<table>
<thead>
<tr>
<th>Contact % time</th>
<th>Orbiter_1</th>
<th>Orbiter_2</th>
<th>Total</th>
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<table>
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<th>DSN_3</th>
<th>Total</th>
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<td>15.20</td>
<td>40.14</td>
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<tr>
<td>Orbiter_2</td>
<td>17.69</td>
<td>13.63</td>
<td>24.98</td>
<td>56.30</td>
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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

![Diagram showing orbital elements and signal power profiles](image-url)
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**