Simulating Autonomous Telecommunication Systems for Space Exploration

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Outline

● Space Networking Overview
● Characterization of
  – Surface Networks
  – Proximity Networks
  – Interplanetary Long-Haul Networks
● JPL's MACHETE simulation environment
  – Clearing the path for network engineering
● MACHETE Use Cases
● Conclusion
Space Exploration Network Facts

- 95% of all Mars Exploration Rover (MER) data was relayed through Mars Odyssey
  - Energy savings and data return increase using relay
- Phoenix lander has no Direct-To-Earth link
  - Lower design/development cost by using relay
- Manual relay operations gets infeasible quickly
  - Quadratic growth in network complexity
- Network automation (protocol development) builds towards autonomous exploration
Enabling Autonomy

Proximity Link
- L1
- L2
- Prox-1

Deep Space Link
- O1
- O2
- D1
- D2
- D3
- BP
- LTP
- TC/TM
- SLE
- TCP
- IP

Internet
- MOC
- unAck CFDP
- BP
- LTP
- Prox-1
- TC/TM
- SLE
- TCP
- IP
General Networking Concepts

- Various environments
- Multi-layer re-transmission systems
- Addressing capabilities
- Routing/switching protocols and traffic shaping
- Node mobility patterns and link characteristics
- Application traffic patterns
  - Application overlays
- Random: traffic, mobility, errors
Space Exploration Network Types

- Surface Networks (yellow)
- Proximity Networks (green)
- Interplanetary Networks (blue)
Surface Networks

- Wired networks or
- Constrained MANETs
  - Semi-predictable topology, limited nodes
  - Controlled mobility, occultation effects
- Protocol Examples:
  - 802.x, Frame Relay, ATM, GSM, IP, DTN Bundle
- Applications (mission specific traffic patterns):
  - HTTP, FTP, SNMP, SSH, DNS, SMTP…
Proximity Networks

- Highly predictable MANET
- Mobility: Orbital
  - Changes are expensive
- Protocols: Proximity-1, AOS, 802.11/16
- Applications: CFDP
  - Mars surface (rovers) with relay satellite(s)
  - Lunar surface with relay satellite(s)
Interplanetary Networks

- Space exploration backbone networks
- RTTs measured in minutes and hours
- Unpredictable error rates (environment)
  - Heavy link coding to improve availability
- Protocols: TC/TM, DTN Bundle Protocol, LTP
- Applications: CFDP
Terrestrial TCP Variants for Space Exploration

- Max TCP Window Size
  - RFC 1323: 1GB
- Long-term path outages cause resets
- Inefficient handling of path changes
  - Operates end-to-end. Not link optimized
  - Common in space exploration
  - Assumes all loss due to congestion
- Limited benefit from path improvements due to additive increase (steady state) operations
DTN Bundle Protocol and LTP

- Bundle Protocol
  - Began under the auspices of the InterPlaNetary Internet (IPN) working group
    - Recognized space networks are special cases of challenged networks
    - Evolved into the Delay Tolerant Networking research group
  - Provide a common unit of transfer across heterogeneous networks
  - Standardized method for store-and-forward
    - Enables interoperability
  - Overlay network on top of typical networking infrastructure
  - Does not require concurrent existence of all links on an end-to-end path
  - Tolerant to disruption and long delay
  - Delay and Disruption tolerant routing

- Licklider Transmission Protocol
  - Primary DTN reliable long-haul transmission protocol
  - Capable of reliable and expedited transmission
  - Requires in-order delivery from lower-layers
JPL's MACHETE Simulation Environment

- Purpose of such tool environment
  - Space networking is different from terrestrial networks
  - Need to design, validate and evaluate space networking protocols carefully

- Overall MACHETE architecture
  - Orbital and Planetary Motion Kinematics Modeling
  - Link Engineering
  - Traffic and Protocol Modeling
  - External Interface for Integrated Distributed Simulations

MACHETE: Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation tool
JPL's MACHETE

- 6 year project to develop network simulation models for space exploration communication
- JPL space networking models combined with commercial models
- Protocol models include: CFDP, DTN Bundle Protocol, Proximity-1, TC/TM, 802.X, IP, LTP…
- Environment models include: Ka-band, free space, 2-ray, Rayleigh, Ricean, various antenna models…
- Application models include: HTTP, FTP, VoIP, customized probability distributions…
MACHETE Environment

Deployment Geometry

Link Engineering

Network & Protocol Simulation

MACHETE – Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation
MACHETE: Use Cases
MACHETE: Data Prioritization Study
Data Prioritization: Traffic Pattern

Forward (to CEV)
S-band BW: 72 kbps
• Command: constant bit rate at 8 kbps
• Voice (correlated)
  – 2 streams
  – Gamma distribution
  – Mean talk time = 5.86 S;
  – Mean quiet time = 7.47 S;
  – Peak rate = 19.8 kbps
  – Mean conversation length = 10 minutes.

Return (to Earth)
S-band BW: 192 kbps
• Telemetry: constant bit rate at 152.6 kbps
• Voice (correlated)
  – 2 streams
  – Gamma distribution
  – Mean talk time = 5.86;
  – mean quiet time = 7.47 S;
  – Peak rate = 19.8 kbps
  – Mean conversation length = 10 minutes
## Data Prioritization: Result

<table>
<thead>
<tr>
<th>Data type</th>
<th>Peak Traffic</th>
<th>Priority (if used)</th>
<th>Peak Total % excess to BW</th>
<th>Loss % (prioritized)</th>
<th>Loss % (not prioritized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice 1</td>
<td>19.8 kbps</td>
<td>High</td>
<td>none</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Voice 2</td>
<td>19.8 kbps</td>
<td>High</td>
<td>none</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Telemetry</td>
<td>152.6 kbps</td>
<td>Medium</td>
<td>none</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Delay Tolerant</td>
<td>30 kbps</td>
<td>Low</td>
<td>7%</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>250.3 kbps 30.4%</td>
<td>23 Mb 59 Mb</td>
<td></td>
</tr>
</tbody>
</table>
CFDP and LTP’s automated repeat request (ARQ) systems are both designed for long-haul links.

CFDP’s ARQ reporting is timer driven:
- Requires precise timer configuration (administrative overhead)

LTP’s ARQ reporting is primarily event driven:
- Timeout only operates as safety net

Minor increase in data reception delay as error probability increases.
CFDP-LTP ARQ Difference Explained

CFDP and LTP's ARQ primarily differs during retransmission

During initial transmission CFDP and LTP share the same timer logic

LTP introduces additional delay when a CheckPoint segment is lost during a retransmission spurt

CFDP server has NAK timers

Note: Loss of EOF in initial CFDP spurt would have identical consequences to LTP's loss of a CheckPoint
Conclusion

- Space exploration networks are unique and highly complex environments
- Networking required for autonomous operations
- JPL developed MACHETE to characterize networked exploration systems