Simulating Autonomous Telecommunication Networks for Space Exploration

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The Interplanetary Network Directorate (IND) of NASA’s Deep Space Mission System (DSMS) program identified several trends in future space exploration missions that pose new challenges for multi-mission telecommunications and navigation systems, such as: increasing number of communication links and relays, 1000-fold increase in data volumes, and growing complexity in end-to-end communications (including disruption of links). Automation and demand access are among the proposed concepts/technologies to meet these challenges.

Currently, most interplanetary telecommunication systems require human intervention for command and control. However, considering the range from near Earth to deep space missions, combined with the increase in the number of nodes and advancements in processing capabilities, the benefits from communication autonomy will be immense. Likewise, greater mission science autonomy brings the need for unscheduled, unpredictable communication and network routing. While the terrestrial Internet protocols are highly developed their suitability for space exploration has been questioned. JPL has developed the Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE) tool to help characterize network designs and protocols. The results will allow future mission planners to better understand the trade offs of communication protocols. This paper discusses various issues with interplanetary network and simulation results of interplanetary networking protocols.

Nomenclature

AOS = Advanced Orbiting System
BDP = Bandwidth delay product
BP = Bundle Protocol
Kbps = Kilo bits per second
CCSDS = Consultative Committee for Space Data Systems
CFDP = CCSDS File Delivery Protocol
DTE = Direct-to-Earth
DFE = Direct-from-Earth
DTN = Delay Tolerant Networking
IND = JPL’s Interplanetary Network Directorate
IPN = Inter-Planetary Network
LTP = Licklider Transmission Protocol
MACHETE = JPL’s Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation
RFC = Request for Comments

1. Introduction

Space exploration missions are unique due to the environment they must operate in. Cost, schedule, risk, launch opportunities, weight, volume and power consumption of the launched equipments, data storage, communications capabilities and security are just a few of the interdependent system design parameters to be considered and analyzed. The Interplanetary Network Directorate (IND) under the Deep Space Mission System (DSMS) program is responsible for enabling space science missions through design, development, operation and services. One of IND’s areas of interests is to develop new capabilities in space-based networking, with objectives to improve science return, decrease mission risk, reduce cost, and enable better support to exploration missions.

The Deep Space Mission System (DSMS) program has envisioned future missions to involve larger number of nodes and links with multi-hop relay of data to/from Earth. Relay operations had already been a proven technology

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in the Mars Exploration Mission where greater than 95% of all science data return was relayed through Mars Odyssey. In future missions, the in situ exploration landers, rovers and aerial vehicles will be mass-, power-, and volume-constrained and will depend on relay orbiters for communications to Earth. As future missions will be more complex, autonomy in network technologies can be an enabling factor to mission success and may aid in mission operation.

As networks become more complex, new behaviors emerge. A distinguishing fact of terrestrial networks versus space-based networks is the following. Terrestrial Network Engineers oftentimes have the advantage of quick replacement and possible network redesigns when undesired behaviors appear. However, Interplanetary Network Engineers, where the hardware used is thousands of kilometers from the nearest repair closet and have multi-year life expectancies, do not have this luxury. To ensure mission success, space-based network must be carefully analyzed and characterized before the launching of the mission. The performance of such network can be evaluated through simulation under different nominal and off-nominal scenarios; we may also use simulations to verify whether the design meets mission requirements and objectives.

As space-based networking differs from terrestrial networks, interplanetary communication protocols need to be designed, validated and evaluated carefully to support different mission requirements. One of the key enabling technologies is space-based network communication protocols which include a suite of CCSDS standards. Some examples of the CCSDS standards are: Telemetry, Telecommand, and Advanced Orbiting Systems (AOS), Proximity-1, CCSDS File Delivery Protocol (CFDP). Recently, Delay Tolerant Networking protocols such as Bundle Protocol (BP), Licklider Transmission Protocol (LTP) are being considered for use in upcoming missions. CCSDS Asynchronous Message Service (AMS) has also been demonstrated in terrestrial applications, in order to be considered for flight missions.

To analyze space-based networking performance, JPL developed the Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE) tool. MACHETE captures the environmental condition of space (e.g. the link dynamics associated with communicating entities in orbit and on a planetary surface) and the network protocol stacks that such nodes employ today, and in the envisioned future. Some of the key capabilities in MACHETE are:

- QoS-aware communication: the tool models user’s ability to mark the urgency/priority requirements of their traffic and mechanisms that may be engaged at different layers to accommodate these needs while utilizing the communications resources efficiently. An example of this is the QoS-aware multi-link protocol where the algorithm dynamically switches band (X, Ka, optical, UHF) for next hop and employs priority-based queue and bandwidth scheduler in order to improve quality of service (QoS) performance such as priority, reliability, latency/time-to-live, minimum guaranteed bandwidth.
- CCSDS protocol suite: CFDP, Proximity-1, AOS link layer virtual channel, interface to AMS.
- Disruption-tolerant networking protocol suite: BP, LTP.
- Surface terrain model at fine granularity: 3D terrain obstruction and signal propagation model at 1 meter granularity. This is useful for generating or input surface terrain files, and to model surface communications.
- This tool has a High Level Architecture (HLA) interface so that it can be used in a distributed simulation. The tool can also be used in a hardware-in-the-loop setting where part of the network is emulated. Information exchange may take the form of IP packets through an IP network emulator.

The space-based networking simulation tool can be used to support trade studies, to compare alternative system designs, and may support architecture decisions. It is used to support distributed system integration laboratories where several laboratories with multiple simulation tools are interacting in a common distributed simulation.

The rest of the paper is organized as follows. In Section 2 through Section 4, we consider some characteristics of general networks, planetary surface networks and interplanetary links respectively. Section 5 gives an overview of our simulation tool. In Section 6, we present several use cases, demonstrating the use of MACHETE for analysis of interplanetary telecommunication networks. The example use cases also show how we model and simulate some for the characteristics discussed in Sections 2 to Section 4. Conclusion and future work are included in Section 7.
2. General Network Characteristics

While each network type has specific provided and environmental characteristics and protocols, there are some characteristics that need to be considered for most networks, in general. A simulation tool developer would categorize characteristics pertaining to general networks versus specific networks to implement these in modules to allow for future software re-use.

Dynamic Network Topology
A network can be represented by nodes and links where both nodes and links may be dynamically changing. For example, mobility of nodes in an ad hoc network affects the network topology, defining which nodes may be in communication range within each other. One may view traffic shaping as a form of dynamic network topology in wired networks because it affects network routing. More directly, link failures (as infrequent as they may be) can also be regarded as dynamic topology change.

Encoding
All digital communication systems use some form of digital encoding for data transmission which provides various levels of noise tolerance. IEEE 802.3 Ethernet, for instance, uses Manchester Phase Encoding whereas members of JPL’s Communications Systems and Research Section designed Turbo Codes to handle environmental characteristics of Deep Space Communication\(^3\) networks.

Traffic Patterns
Generally, application traffic patterns on all networks may be predicted by collecting statistical data. For instance, popular applications in terrestrial networks are http and ftp, while space exploration missions may use CCSDS protocols for transmission of multimedia and files (by mission design). In order to be useful, a network simulator must have representative application traffic models.

Routing
All multi-hop networks use routing or switching to transport data. Routing protocols are not omniscience and have different convergence times. Additionally, routing protocols provide different feature-sets and are designed for specific network types. Some routing protocols are proactive, sending route queries in set intervals; some are reactive, only “discovering” the network topology change when data transmission is requested. Some protocols may be a hybrid of proactive and reactive. Furthermore, multi-path routing capabilities should not be taken for granted. For example, standard Open Shortest Path First (OSPF) does not allow load-balancing across different links. Moreover, routing protocols differ in their knowledge basis and sharing methods. Some are graph driven, some are probabilistic, and others are based on distance-vectors. Routing protocols need to be chosen for particular networks; there is no single routing protocol that is best for all network types.

When designing relays, interplanetary network engineers must decide on the layer to implement the relay function. Legacy missions used a “bent-pipe” for relay, implemented at the physical layer (much like a repeater in terrestrial networks). More recent systems use link-layer relaying similar to Ethernet switching. Additional research is going on to analyze the benefits of IP layer routing in an interplanetary environment or even DTN bundle-layer relaying. However, with the exception of the DTN bundle-layer relay, none of the previous mentioned relay types will work when no end-to-end path exists. A data-mule (or store-and-forward capability) is needed. COTS IP routers cannot handle this case, however, with modifications to the buffer and routing rules one may be able to modify an IP router to act as a data mule. Nevertheless upper-layer protocols and applications expecting end-to-end connectivity would fail to operate over IP data-mules.

3. Surface Network Characteristic

Planetary surface networks consist of a wide variety of network node types. Landers are typical of initial science missions. Since they do not move much the only form of mobility is on the remote communication entities (e.g., the orbit of the relay or views of Earth). Predetermined scheduled routing is highly achievable with landers. Rovers, on the other hand, are more complex adding mobility and further occultation effects. Rover routing protocols can potentially benefit from terrain mapping and knowledge of the rovers terrain traversal paths. Weather balloons and gliders can have the most complex mobility patterns and depending on the terrain and altitude can have similar occultation issues with communication. However, fully autonomous nodes are the most complex. Hence, manned missions' communication networks are the most complex systems. One should note that all node types, depending

\(^3\)http://www331.jpl.nasa.gov/public/JPLtcodes.html
on radio frequency and power use, suffer from atmospheric interference but that varies greatly depending on the environment and is beyond the scope of this paper.

Conceivably, surface networks can use commercial-off-the-shelf (COTS) communication protocols such as IEEE 802.3 Ethernet and the 802.11/16 series wireless standards. Research has proposed using Network Coding to further improve communication efficiency using max-flow min-cut theorem to achieve maximum information flow. Terrestrial protocols are well developed and have proven useful in terrestrial environments. However, exploration surface networks tend to push hardware and software over unexpected environments. Additionally, terrestrial protocol interaction with space exploration protocols must be tested and more fully characterized before deployment.

Links between planetary surface assets and orbiters and cross-orbiter communication links together make up proximity networks. Issues in proximity networks are more controlled and predictable than surface networks. Orbits do not change frequently and cross-link communication rarely suffers occultation (no trees in orbit).

The Consultative Committee for Space Data Systems (CCSDS) standardized the Proximity-1 protocol for orbiter-lander communication. Proximity-1 offers link-layer reliability and has proven efficient for the Mars Exploration Rover to Odyssey proximity link providing twice the planned data rate. Proximity networks have the possibility of needing simultaneous communication with multiple assets over a relatively high latency link. Furthermore running TCP over a relatively high-latency proximity network has proven to be troublesome and is discussed in Section 5.

4. Inter-Planetary Communication Protocols

Inter-Planetary communication links are characterized by high latency and high error rates. Mobility is relatively minor, thus no frequent dynamic topology changes. Commanding becomes difficult due to the high latency. Forward error correction handles many of the errors, making re-transmissions rare. So, historically, Inter-Planetary communication used CCSDS’s Telecommand (TC) and Telemetry (TM) protocols. TC/TM are lightweight link-layer protocols providing data differentiation but no error detection. TC/TM rely on Forward Error Correction to resolve errors. No matter how strong the forward error correction codes, errors can still result causing discarded messages. More recently CCSDS developed the CCSDS File Delivery Protocol (CFDP) to handle reliable file transfers over long-haul links. Likewise, the IRTF developed the Licklider Transport Protocol (LTP) solely for automated retransmission (ARQ) over long-haul links without the (cross-layer) file aspect of CFDP.

The Delay Tolerant Networking Research Group (DTNRG) developed the DTN protocols for mobile, disruption tolerant networks. Inter-Planetary networks (IPNs) are considered as a special case of Delay Tolerant networks so the DTN protocols are more applicable to IPNs than terrestrial Internet protocols such as TCP, IP, or mobile IP. DTNRG developed the Bundle Protocol (BP) for handling routing, delivery and store-and-forward operations in a DTN. LTP, also developed by the DTNRG, is based on CFDP and is the default reliable transmission layer (convergence layer) for the Bundle Protocol over long-haul links.

Cisco Systems in partnership with Surrey Satellite Technology launched the Cisco router in Low Earth Orbit (CLEO) mission to develop the concept of directly using the terrestrial Internet Protocol (IP) suites in space. This project resulted in the creation of the Saratoga file transfer protocol to handle link disruption and efficiently transfer files over a proximity link.

5. Terrestrial Internet Protocols

Much research has gone into the development and optimization of the terrestrial Internet Protocols. So any new networking venture should characterize the applicability of terrestrial Internet protocols. While IPv4 is universal, researchers have developed many variants of TCP optimizing different characteristics for different network types. All variants of TCP share similar structure. First, they have a slow-start phase, and then reach steady state while attempting to avoid congestion. The major differences result in the handling of errors. For instance TCP-Tahoe waits for an ACK timeout before retransmitting while TCP-Reno retransmits a segment upon receiving three ACKS stating that all data up to the missing one was received.

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4 The core notion of network coding is to allow mixing of data at intermediate network nodes. A receiver sees these data packets and deduces from them the messages that were originally intended for that data sink.
Handshake and Slow-Start
TCP starts a session with a SYN, ACK, SYN/ACK handshake which takes 3 RTTs. During TCP’s slow start/exponential growth, the transmission window doubles every RTT. Reaching maximum data rate requires $\log_2(\text{data rate})$ spurts. This requirement is fine for terrestrial networks with low RTTs, but deep space networks with RTTs measured in minutes suffer underutilization with TCP. A 1Mbps link takes 23 spurts to achieve maximum throughput. With a 1,000 second RTT maximum throughput would be achieved after 23,000 seconds (6.39 hours).

TCP Send Window
TCP’s send window refers to the maximum allowed un-acknowledged segments (maximum segments in transit at any given time). Consequently TCP’s maximum throughput is directly related to its 16-bit send window. RFC1323 used scaling to expanded TCP’s send window to handle high bandwidth-delay-product (BDP) links such as high-speed fiber or high latency deep space links. Ideally the TCP send window size would equal the bandwidth delay product (BDP), but even with TCP implementing RFC1323 the maximum send window size is approximately 1 Gigabyte or 8 Gigabits. However, a 10Mbps Mars-Earth link with a 20 minute round-trip-time has a BDP of 12 Gigabits (1,200seconds * 10Mbits/second), so standard TCP would never maximize throughput on such a link.

Path Outages
TCP was designed for terrestrial networks assuming that an end-to-end would always exist. Mobile networks like space-based networks can experience short outages. These short outages would be seen as congestion by TCP and result in performance degradation or (depending on outage length) TCP connection failure.

Limited-Availability Relays
Because TCP is an end-to-end optimizing transmission protocol, its throughput will always be constrained by the lowest data rate link. However, with mobility the case can occur where a relay exists for only a short time with a network as shown in Figure 1. Assume the AB link has a much higher data rate (50Mbps) than BC (500Kbps) or AC (100Kbps). Also, assume the AB link lasts for 1,000 seconds due to occultation, while the BC link lasts for 20,000 seconds. Using an end-to-end transmission protocol, like TCP, the AB, BC path will only be used for 1,000 seconds and a maximum data rate of 500Kbps which results in a 500 Megabits or 62.5 Megabyte data volume.

However, using a store-and-forward protocol, like DTN’s BP/LTP, the AB link will get fully utilized. Node A will transmit over the AB link at a 5Mbps data rate for 1,000 seconds, resulting in a 5Gigabit AB data volume. Likewise, the BC link will transmit at 500Kbps for 10,000 seconds again resulting in a 5Gigabit data volume. The resulting AB, BC data volume would be 5Gbits as opposed to the 500Mbits using an end-to-end transmission protocol (10x more efficient).
**Link Additions**

Similarly, TCP is inefficient when switching from a low data rate path to a high rate path, mid transmission. After the slow-start phase TCP enters congestion avoidance. During congestion avoidance, the transmission window is increased by one segment per RTT. So assuming the segment size is 1,200 Bytes (10Kbits) and the path goes from a 100Kbps link to a 10Mbps link with one second latency, TCP would have reached steady-state with a 20 segment congestion window and need to arrive at a 2,000 segment congestion window. Standard TCP would take about an hour to reach 100% utilization.

**6. Simulation Tool and Environment**

To analyze and characterize novel networking protocols and system designs, NASA's JPL has developed the MACHETE network design and testing tool. The basic software architecture for MACHETE consists of four general systems: (1) orbital and planetary motion kinematics modeling, (2) link engineering modeling, (3) traffic load generation and protocol state machine modeling and execution (based on a commercial tool QualNet), and (4) user interface systems spanning all of these three core elements. The resulting combination provides an essential tool for quantifying system performance based on comprehensive considerations of different aspects of space missions. Using this tool, technology researchers and mission designers can (1) determine system resource requirements such as bandwidth, buffer size, and schedule allocations, (2) characterize performance benefits of new or alternative protocols, services, and operations, (3) validate new technologies for mission infusion, and (4) enhance mission planning and operations.

**Orbital and Planetary Motion Kinematics Modeling**

There are existing orbital analysis tools that can be used to model spacecraft trajectories and orbiter motions. For example, we have used the Satellite Orbit Analysis Program by Aerospace Corporation, STK, and JPL’s proprietary TOAST telecom/orbital analysis tool, and Spice kernel to provide trajectory information.

**Link Engineering**

Multiple additional modeling tools are incorporated within MACHETE for the purpose of characterizing links. The link characterization models include mapping the received signal strength with the waveform modulation to generate a dynamic bit error rate process. Additional examples are to modify a received UHF signal stream to add the stochastic effects of multipath fading, or to capture the effects of weather on a Ka-band deep space link, or to process field data to represent a modified scenario. The data generated from these link characterization tools are fed to the QualNet simulator to incorporate them in simulations of the overall networking behavior.

**Traffic and Protocol Modeling**

We have developed QualNet models for the complete CCSDS protocol stack, including CCSDS standards Proximity-1[1], Packet Telemetry [2], AOS [3], SCPS [4], and CFDP [5]. The QualNet standard library also contains a full contingent of conventional protocols such as the IEEE 802.11/WiFi and Internet protocol standards.

For traffic generation, QualNet has the capability to model various traffic such as constant bit rate (CBR), and variable bit rate (VBR). The simulation tool can also import traffic profiles generated by other tools, such as by the SCaN traffic studies reported in [6].

**External Interface for Integrated Distributed Simulations**

MACHETE has two external interfaces: (1) High Level Architecture (HLA) interface and (2) IP Network Emulator (IPNE) interface. The HLA interface enables a simulated network to participate in a distributed simulation. Through the IPNE interface, network simulation may transmit/receive data to/from emulators in a hardware-in-the-loop simulation/emulation. In [7], MACHETE was used to support Constellation’s Distributed Systems Integration Laboratories (DSIL). DSIL project aims at developing capabilities to support systems integration, testing, and monitoring of an end-to-end distributed system architecture. The idea is to leverage existing simulators, emulators, and test-beds at different NASA centers. These simulators and emulators participate in a time synchronized distributed simulation controlled through the High Level Architecture (HLA). The mission being simulated is the lunar mission involving a Crew Exploration Vehicle (CEV), the Crew Launch Vehicle (CLV), Space Communications and Navigation Network (SCaN), Ground Systems (LCS), International Space Station (ISS), and
mission control center (MCC). The role of MACHETE is to simulate the SCaN network. While HLA provides the means to exchange status information of spacecraft positions and velocities (and time step synchronization), mission data are passed through UDP sockets, and using IPNE to inject the packets into the simulated network. SCaN performs the relay of data between CEV and MCC, adding simulated network effects and link conditions. This is used to verify whether the system can meet mission communications requirements.

7. Use Cases and Results

CFDP Performance Evaluation

In [8], MACHETE was used to evaluate the latency performance and storage requirement of CFDP in the context of a Mars Science Laboratory – Mars Telecommunications Orbiter – Deep Space Network (MSL-MTO-DSN) relay network. The application of CFDP ARQ for low latency transfers of operational data essential for daily rover activity planning was considered. Provided sufficiently low bit error rate (< 1.2x10^-7), the latency distribution stays below 1 to 3 one-way-light-time more than 99% of the time, that translate to less than one hour delay for the largest distance considered in the study. For higher bit error rates, the use of CFDP for operational data delivery, requiring around 1-hour latency, is only suitable when Mars is very close to Earth, due directly to the number of retransmission spurs required. The reliable transfer of bulk science data through high capacity but more weather-sensitive Ka-band links using CFDP ARQ was also considered to determine the storage required to meet ‘Completeness’ requirements as high as 99.99%. The study showed that the primary design driver is the pass outages due to weather event; PDU size and file size do not have significant impact. Given that buffer space as large as 25 times the daily data volume may be required to meet the most stringent completeness criteria for file-based custody transfer; however, incremental custody transfer is a possible alternative. The impact of different levels of excess link capacity on buffer size as well as full duplex operation was not considered. The study’s result provides a general upper bound on the potential buffer requirement for MTO.

Benefits of Data Prioritization

In [9], we study the benefit of using data prioritization to efficiently utilize limited bandwidth for data return. The focus was on the benefits of using QoS (prioritization of data) to obtain more throughput. In a 1-day lunar mission scenario, the relay is from a Crew Exploration Vehicle (CEV) through TDRS satellite to a ground station and to a mission control center (MCC). The C-band forward link bandwidth is 72 kbps and the return link bandwidth is 192 kbps. The traffic streams are one 8 kbps constant bit rate of command from MCC to CEV, two gamma distribution voice streams with peak rate at 19.8 kbps and mean conversation length of 10 minutes, one constant bit rate telemetry stream at 152.6 kbps and one delay-tolerant stream at 30 kbps. Two cases were run. In the first case (Case_A), command and voice streams are assigned the highest priority. Telemetry is assigned medium priority and delay-tolerant traffic is assigned low priority. The queue sizes for high, medium and low priorities are set at 10,000 bytes, 30,000 bytes and 10,000 bytes respectively. In the second case (Case_B), the traffics are the same as Case_A; however, all traffic streams are of the same priority and the queue size is 50,000 bytes (which is equal to the sum of the queue sizes in Case_A).

On the return link, adding the peak rates of the two voice streams and telemetry results in 192.2 kbps; which would saturate the return link. However, since there are times when the voice stream is quiet, the bandwidth can be used for other types of traffic. By adding another 30 kbps of low priority delay tolerant traffic, the total peak traffic is 222.2 kbps which is 15.7% in excess of the 192 kbps bandwidth.

With prioritization, Case_A shows that we could fit another 27 kbps of low priority traffic without loss to any other traffic. More specifically, 93% of the 30 kbps low priority traffic and 93% went through. Without prioritization, Case_B lost 4% of telemetry and approximately 2% on each of the voice streams on the return link. However, comparing the total bit loss in Case A and Case B, the loss in Case A is approximately 23 megabits while in Case B, it is 59 megabits. Thus, using data prioritization could increase the total throughput.

LTP and CFDP Comparison

JPL originally characterized CFDP’s retransmission system over four different error rates [8], and while LTP’s heritage traces from the CFDP, LTP uses a message driven retransmission system whereas CFDP uses a combination of messages and timers. Using a message drive ARQ was done to easy LTP deployment and simplify management. Timer-driven ARQ requires foreknowledge of latency and increases management overhead.

LTP’s ARQ system is Sender driven. To request error reporting the Sender tags data segments (DS) with
Checkpoint (CP) flags and starts a CP-Ack timer. The receiver responds to the checkpoint with a CP_ACK and a Report Segment (RS). The RS lists all received blocks. Upon reception of the report segment the Sender retransmits all missing data segments. LTP does not recommend a strategy for CP flagging as this is environmentally dependant.

During simulation we noticed an increase in latency for the high error rate case with LTP compared to CFDP (Figures 1 and 2). While moving from timer-driven CFDP to message-driven LTP simplifies management, it also (slightly) decreases performance. When a checkpoint (CP) segment is lost as in figure 2 the sender waits for the CP_ACK timeout, say 2 * RTT. Upon CP_ACK timeout, the sender resends the CP segment. On the other hand, a CFDP receiver has an inactivity timer that signals sending of a reception report (equivalent to an LTP Report Segment). Since LTP flags standard data segments as checkpoint the probability of loss of checkpoint is equal to the product of the BER and segment size. The probability of increased latency is minor, but its effects can be seen in figure 3.
Figure 2 – LTP Checkpoint Loss Effects

Figure 3 – CFDP (left) file transfer latency compared to LTP (right)
8. Conclusion and Future Work

As can be seen, Inter-Planetary Network Engineering is highly complex. Engineers need the means to characterize the trade-offs of different protocol stacks or even test the feasibility of a certain stack. MACHETE provides these means.

Terrestrial engineers looking at Inter-Planetary Networks usually first ask the question: why not use the Internet protocols such as TCP and IP? While there is merit to this question, the design of terrestrial Internet protocols does not include delay and disruption tolerant networks. Primarily, most terrestrial Internet protocols assume end-to-end paths, low latencies and relatively low error rates.

We can extend the LTP analysis by comparing LTP's ARQ system with that of Proximity-1. Proximity-1 includes a reliable mode which retransmits corrupted frames. However, Proximity-1 uses a Go-Back-N ARQ while LTP uses a more bandwidth/energy efficient Selective Repeat (SR) system.

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