Delay Tolerant Networking – Bundle Protocol Simulation

John SeGuí and Esther Jennings
Jet Propulsion Laboratory, Pasadena CA 91109
{ John.S.SeGui, Esther.H.Jennings}@jpl.nasa.gov

Abstract

In space exploration missions, the coordinated use of spacecraft as communication relays increases the efficiency of the endeavors. To conduct trade-off studies of the performance and resource usage of different communication protocols and network designs, JPL designed a comprehensive extendable tool, the Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE). The design and development of MACHETE began in 2000 and is constantly evolving.

Currently, MACHETE contains Consultative Committee for Space Data Systems (CCSDS) protocol standards such as Proximity-1, Advanced Orbiting Systems (AOS), Packet Telemetry/Telecommand, Space Communications Protocol Specification (SCPS), and the CCSDS File Delivery Protocol (CFDP). MACHETE uses the Aerospace Corporation's Satellite Orbital Analysis Program (SOAP) to generate the orbital geometry information and contact opportunities. Matlab scripts provide the link characteristics. At the core of MACHETE is a discrete event simulator, QualNet.

Delay Tolerant Networking (DTN) is an end-to-end architecture providing communication in and/or through highly stressed networking environments. Stressed networking environments include those with intermittent connectivity, large and/or variable delays, and high bit error rates. To provide its services, the DTN protocols reside at the application layer of the constituent internets, forming a store-and-forward overlay network. The key capabilities of the bundling protocols include custody-based reliability, ability to cope with intermittent connectivity, ability to take advantage of scheduled and opportunistic connectivity, and late binding of names to addresses.

In this paper, we report on the addition of MACHETE models needed to support DTN, namely: the Bundle Protocol (BP) model. To illustrate the use of MACHETE with the additional DTN model, we provide an example simulation to benchmark its performance. We demonstrate the use of the DTN protocol and discuss statistics gathered concerning the total time needed to simulate numerous bundle transmissions.

1. Introduction

The Internet architecture has been successfully used to connect various networks on Earth. However, the Internet protocols rely on certain assumptions that may not be true in the InterPlanetary Internet (IPN) [1]. As an effort to standardize communications for the IPN, the Delay-Tolerant Networking architecture and protocols were proposed. As work progressed, researchers observed that deep space was, in fact, a specialized domain of a larger group of challenged networks. Other examples of challenged networks include military networks running tactical protocols, and remote networks where network resources are scarce and data mules might be used to transport data. These networks all had similarities in that they experienced several of these features: asymmetric communication, noisy links, long delays, and intermittent connectivity. As a result, the network community is developing a body of research and funding has been established by both NASA and DARPA to continue work on this technology.

The network architecture and protocol design process involves analysis and implementation of the protocols, validation of their behaviors and performance evaluation. In network protocol design and evaluation, simulation tools are essential. They provide the means to test different network configurations cost effectively. For this reason, there are various network simulators available today, e.g., OPNET™, QualNet™, and ns-2 [2].

To conduct trade-off studies of the performance and resource usage of different communication protocols and network designs, JPL designed a comprehensive extendable tool, the Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE) [3].This paper discusses the

modeling and simulation effort at JPL of the Delay Tolerant Bundle Protocol (BP) [4] and Licklider Transport Protocol (LTP) [5] as it pertains to the IPN.

2. Background

Originally, to solve the issues related to interplanetary and deep space communication, members of the Consultative Committee for Space Data Systems created the CCSDS File Delivery Protocol (CFDP)[9]. CCSDS designed CFDP specifically for space communication networks characterized by long propagation delay, high error rates and predictable links. As the field developed, interplanetary networking became regarded as a sub-field of Delay Tolerant Networking. Since DTN would have a larger user base and would consequently have more industry and academic interest, many of the original IPN researchers joined and created the Delay Tolerant Networking Research Group (DTNRG). As a result of the need for greater collaboration, CFDP's functions were divided into what became the Bundle Protocol (BP) for data handling and reporting and the Licklider Transport Protocol (LTP) for reliable single hop long-haul (e.g., deep space) communication.

The IRTF-sponsored Delay Tolerant Networking Research Group (DTNRG) [6] is the primary research group studying extreme and performance-challenged communication networks characterized by opportunistic connectivity, high error rates, lack of end-to-end connectivity, highly asynchronous (or unidirectional) connectivity, and long one-way trip times. Research has shown that the traditional Internet end-to-end protocols do not work well with the aforementioned network characteristics [7]. As an architectural solution to the DTN problem, the DTNRG created the Bundle Protocol (BP) modeled after the postal system. The DTNRG publishes a publicly available reference implementation of the Bundle Protocol at their website (www.dtnrg.org).

The Bundle Protocol operates at a sub-application "bundle" layer providing end-to-end communication over performance-challenged networks while allowing interoperation between highly heterogeneous networks much as IP does; however, through the use of specialized convergence layers adapters [4] the bundle protocol "sits" on top each local internet's preferred transport protocol and is more flexible than IP allowing for interconnecting greater differing network types than IP. It is worth noting that BP does not replace IP but rather uses a TCP/IP convergence layer adapter when connection is needed on an IP-based network. For example BP would use TCP, LTP [5], CCSDS Proximity-1 Space Link Protocol [8] convergence layer adapters for the terrestrial Internet, the interplanetary backbone, and the planetary surface networks, respectively.

3. Related Work

In [10], Jain et al. reported a framework for evaluating routing algorithms in DTN. The simulator was written in Java; it is a discrete event simulator that simulated DTN-like store-and-forward capabilities using objects representing nodes and links. Their focus was at the network layer and above. The metrics used to evaluate performance were delay and delivery ratio. Specifically, they observed that algorithms possessing knowledge (such as network topology, queuing, and traffic demand) tend to achieve better performance. Another observation was that when the communication opportunities are plentiful, there is less need of smart routing algorithms. However, when communication opportunities are scarce, smart routing algorithms did show significant benefit.

Eriksson and Jönsson [11] presented an implementation of BP for the ns-2 simulator in C++ and used TCL scripts for runtime interfacing with the simulator. They focused on the bundle forwarding and custodial transfer capabilities of BP and did not implement security functions. The performance metrics were end-to-end delay and delivery ratio. They observed that end-to-end delay is higher with custodial transfer due to retransmissions. End-to-end delay is also higher when the bundle payload is small because custody acknowledgements would add significant overhead. Ratio of bundle delivery is influenced by bundle retransmission timer and bundle expiration time. Fast retransmission timers may cause network congestion due to unnecessary retransmissions. Short bundle expiration time would cause dropped bundles, decreasing the delivery ratio.

4. Simulation Tool – MACHETE

To simulate network protocols, we have developed a comprehensive tool MACHETE [3], tailored to unique characteristics of space networks. The architecture for MACHETE consists of (1) orbital and planetary motion kinetics modeling, (2) link engineering modeling, (3) traffic load generation and space communications protocol models, (4) external interfaces.

In a space-based network, the network nodes may be landers on the surface of a planet or spacecraft orbiting a planet. The position of these network nodes

will change with respect to planet rotation and orbital motion. The Satellite Orbital Analysis Program (SOAP) developed by Aerospace Corporation is used to model the geometry of network nodes. The tool also provides the means to model dynamic connectivity (including occultation effects) and signal loss arising from slant ranges and antenna pattern characterization. Typically, a MACHETE scenario is configured in SOAP. Running the scenario in SOAP generates connectivity and signal data. This information is then input to other MACHETE components for simulation. For example, the output of SOAP could contain information concerning link availability, signal strength, and geometric distances. Signal strength data might be input to a Link Characterization tool to produce dynamic bit error rates. Link availability and geometric distances are fed to the communications protocol simulation engine because link availability directly influences communications capability and geometric distances influences latency. Dynamic bit error rates are also fed to the communications protocol simulation engine to represent link conditions.

For link characterization, we have used models based on MATLAB, C, or Excel operating on output data created by SOAP. The link characterization models include mapping the received signal strength with the waveform modulation to generate a dynamic bit error rate process. Other examples of link characterization include adding stochastic effects to multipath fading to received UHF signal stream, capturing effects of weather on Ka-band deep space link, processing field data to represent a modified scenario. The output from link characterization models are fed to the communications protocol simulation engine as these will affect the overall networking behavior.

At the core of MACHETE is the communications protocol simulation engine QualNet™. QualNet™ is a commercial product originating from the DARPA Global Mobile Communications Networking project (GlomoSim) focusing on wireless communications and mobile nodes. QualNet™ is a discrete event simulator that provides high efficiency in simulation execution. It can be run on a single processor, or on parallel processors. The engine has a layered design similar to the five-layer TCP/IP architecture. The QualNet™ standard library already contains conventional protocols such as the IEEE 802.11/WiFi and Internet protocol standards. To support space-based networking simulation, we at JPL have developed specific space protocol models built upon QualNet™; these include the complete CCSDS protocol stack: Proximity-1, Packet Telemetry/Telecommand, AOS, SCPS and CFDP.

5. Example Bundle Protocol Stack

The DTN Bundle Protocol is an overlay above the transport layer. The objective for implementing BP in MACHETE is to simulate its interoperability with other space based protocols and to evaluate its performance for future NASA missions.

For space based networking, a possible intended use of BP is pictured in Figure 1. In this scenario, the left most stack may represent a lander on Martian surface running unacknowledged CFDP over BP, then over Proximity-1. The next box to the right may represent an orbiter. A lander communicates to an orbiter around Mars over proximity link. The orbiter may run BP over Proximity-1 when communicating to the lander on Mars surface; Proximity-1 would be responsible for reliable transmission. The third stack from the left may represent a Deep Space Network ground stations (DSN). The orbiter communicates to a DSN ground station over a deep space link, running BP over LTP where LTP ensures reliable transmission. The right most stack may represent a mission center. From the DSN ground station, the data are transferred to the appropriate mission data center via the Space Link Extension (SLE) services. Throughout this process, the CFDP is not responsible for reliable delivery of the data. Although CFDP is capable of ensuring reliable data transmission, running BP has an additional advantage of dynamic routing if an expected path suddenly becomes unavailable.

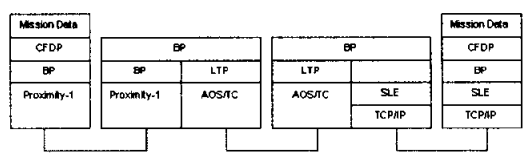

Figure 1. Example Protocol Stack of Space Based Networking

6. Bundle Protocol Model

Our modeling goal was to abstract away the non-essential features while still capturing the essential behavior. Consequently, we did not model the Bundle Security Protocol (BSP) [12, 13], the Multicast Bundle Protocol [14], or any other Bundle Protocol additions. The core behaviors of the Bundle Protocol are custody transfer, bundle prioritization, bundle reporting, and

fragmentation and reassembly. Custody transfer provides reliable end-to-end bundle transportation. Bundle prioritization provides a QoS mechanism for application agents. Fragmentation and reassembly serves to lower delivery time by allowing the use of multiple paths and allows bundles to be transmitted over convergence layers with maximum transmission units smaller than the bundle size. We did not model bundle fragmentation and reassembly..

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

Table 1. Bundle Protocol functions modeled

Each function requires additional computational power. For example a basic non-custodial bundle transfer only sends one PDU; however adding custody transfer causes the sender to wait for a custody transfer response as shown in Figure 1. Additionally requesting bundle reporting would require each hop to send a non-custodial bundle report to the specified report address.

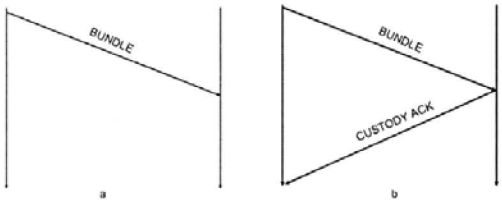

Figure 1. a) bundle transfer without custody b) bundle transfer with custody

The Bundle Protocol uses a variable length header to allow for greater flexibility. However, for simplification of simulation our model uses a fixed length header of 41 bytes.

7. Simulation Scenario

When developing simulation models, it is important to benchmark the performance of the model. Our simulator is a discreet event simulator. That is, the progress of simulation is event driven and could often run faster than real-time. To determine the scalability of our model with respect to the number of events, we ran simulations using a single link network connecting two nodes (Figure 2). By varying the number of bundles (events) in each run, we observed the growth in time required to simulate all the events. This can be used to determine whether the overhead in simulation affects the performance accuracy of the system being simulated. In our two-node simulation, traffic flows from node 1 to node 2, and custody transfer acknowledgements will flow from 2 to 1. Nodes 1 and 2 are connected via a 1Gbps simulated link with 0% error rate to allow for clean transmission without congestion. 1MB bundles are created and sent every 17 seconds also to guarantee no additional delay caused by congestion or retransmission. Custody is requested on every bundle and no reporting is requested. All bundles are sent using the lowest priority level.

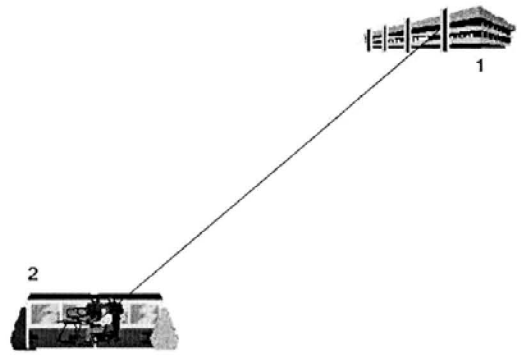

Figure 2. Simulation Topology

8. Simulation Benchmark

We ran 7 different simulations varying the number of bundles transmitted per simulation. Since MACHETE uses a discreet event simulator, the time between transmissions does not affect the real time used for simulation. Running a simulation with 0 bundles transmitted was done to show the constant overhead required by the simulator (and other protocols).

Number of 1MB bundles	Time to simulate
0	1.9 seconds
100	2.5 seconds
500	5.6 seconds
1,000	9.8 seconds
10,000	82.6 seconds
20,000	165.9 seconds
50,000	416.8 seconds

MACHETE Bundle Protocol model processing time with custody

While the Bundle Protocol has a robust feature set it adds minimal overhead with respect to state computation. Because of this most of the CPU time is actually spent processing the lower-layer protocols, particularly the convergence layer. Since MACHETE uses a discreet event simulator the time between transmissions does not affect the real time used for simulation. Consequently, the results show a linear increase in time. We have shown that our model is capable of simulating a network large enough for most IPN research projects.

8. Conclusion and Future Work

We have discussed our Bundle Protocol model and shown the time to simulate various size networks. While the BP model used in this paper is un-optimized, it performs relatively large simulations in relatively quick time. In the future we hope to compare the time to simulate the BP with our model to the time to run the reference implementation with the same number of transmissions. As funding becomes available we will complete our BP model by adding fragmentation and reassembly.

In conjunction with Johns Hopkins Applied Physics Laboratory we are using our BP model to test various network designs and compare metrics to the original CFDP.

Future projects will likely involve testing DTN routing and congestion control algorithms. Using our BP simulation tool researchers can test out innovative DTN routing algorithms in a standardized test bed.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

9. References

[1] S. Burleigh, K. Fall, V. Cerf, R. Durst, K. Scott, H. Weiss, L. Torgerson, and A. Hooke, "Delay Tolerant Networking – An Approach to Interplanetary Internet", *IEEE Communications Magazine*, June 2003.

[2] Ns-2 network simulator, April 2005. http://www.isi.edu/nsnam/ns/.

[3] J. Gao, E. Jennings, L. Clare. J. SeGui, W. Kwong, "MACHETE: A Tool for Architectural Modeling, Performance Characterization, and Technology Infusion of Space-Based Networks", *AIAA International Communications Satellite Systems Conference* (ICSSC), Rome, Italy, September 2005.

[4] K. Scott, S. Burleigh, "Bundle Protocol Specification" draft-irtf-dtnrg-arch-02.txt, July 2004.

[5] S. Burleigh, et al., "Licklider Transmission Protocol" (main protocol), draft-irtf-dtnrg-ltp-03.txt, July 2005.

[6] http://www.dtnrg.org

[7] K. Fall, " A Delay-Tolerant Network Architecture for Challenged Internets", IRB-TR-03-003, Feb., 2003.

[8] CCSDS 211.0-B-3. "Proximity-1 Space Link Protocol—Data Link Layer". Blue Book. Issue 3. May 2004.

[9] CCSDS 727.0-B-3. "CCSDS File Delivery Protocol (CFDP)". Blue Book. Issue 3. June 2005.

[10] S. Jain, K. Fall, R. Patra, "Routing in a Delay Tolerant Networking," SIGCOMM, Aug/Sep 2004

[11] Eriksson, H., Jönsson, P., "Implementation and Analysis of the Bundling Protocol for the Delay-Tolerant Network Architecture" (Master's Thesis 2005:239CIV), Department of Computer Science and Computer Engineering, Luleå University of Technology, Luleå, Sweden, April, 2005.

[12] S. Farrell, S. Symington, and H. Weiss, "Delay Tolerant Networking Security Overview", draft-irtf-dtnrg-sec-overview-01.txt, September 2006 .

[13] S. Symington, S. Farrell, and H. Weiss, "Bundle Security Protocol Specification", draft-irtf-dtnrg-bundle-security-01.txt, September 2006

[14] S. Symington, R. Durst, K. Scott, "Non-Custodial (Best Effort) Multicasting Support in DTN", draft-symington-bundle-multicast-noncustodial-00.txt, August 2006