AMERICAN MILITARY UNIVERSITY

THE INTERPLANETARY INTERNET:

Building a Delay and Disruption Tolerant Network for

Satellite and Deep-Space Communication

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INTRODUCTION

The Interplanetary Internet, also known as the Interplanetary Network or InterPlaNet (IPN), is a proposed network intended to connect stations on Earth with others in orbit around and on the surface of other planets and moons in the Solar System. It was originally conceived by Vinton (Vint) Cerf, author of the TCP/IP protocols[1] and widely recognized as "the father of the Internet"[2]. Features of the Interplanetary Internet include Earth-orbiting satellites linked to the terrestrial Internet, constellations of satellites around Mars and other bodies, as well as "Gateways" to link the different regions. The main challenge in connecting such networks is the delay caused by the speed of light limitation over the long distances separating the planets. The speed of light delay to Low Earth Orbit or even Geosynchronous Earth Orbit is a fraction of a second, but a one-way light speed trip to Mars can take from 4 to 20 minutes, depending on the relative positions of the planets[3]. This difficulty is further compounded by orbital dynamics which results in ground stations, satellites and other planets periodically out of view of each other[4]. In order to overcome these problems, new protocols based on Delay and Disruption Tolerant Networking (DTN) have been developed[5].

There have been several recent tests of DTN-based technologies, which have proven the feasibility of the Interplanetary Internet. Some of those include a DTN bundle protocol testing

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[1] Turner, Adam. "Inter-planetary Internet expands to Mars and beyond." *IT Wire*, February 21, 2007. http://www.itwire.com/science-news/space/9802-inter-planetary-internet-expands-to-mars-and-beyond (accessed April 18, 2010).

[2] Boucher, Mark. "Generation InterPlanetary Internet" SpaceRef.com, February 28, 2000 http://www.spaceref.com/news/viewnews.html?id=87 (accessed April 18, 2010).

[3] Durst, Robert C., Patrick D. Feighery, and Keith L. Scott. "Why not use the Standard Internet Suite for the Interplanetary Internet?." The MITRE Corporation. http://www.ipnsig.org/reports/TCP_IP.pdf (accessed April 17, 2010) 1.

[4] ibid.

[5] Ivancic, W., et al. "Experience with delay-tolerant networking from orbit." Draft submission. International Journal of Satellite Communications and Networking, 2008.

using a UK remote-sensing satellite and NASA's tests of DTN communication with the International Space Station and Deep Impact space probe[6]. Unfortunately, certain aspects of the IPN have been scaled back or cancelled, such as NASA's Mars Network which was based around the discontinued Mars Telecommunications Orbiter[7]. Still, development of the IPN continues.

This paper will examine the proposed architecture of the Interplanetary Internet with specific consideration of the applicability of Delay and Disruption Tolerant Networking to satellite communications.

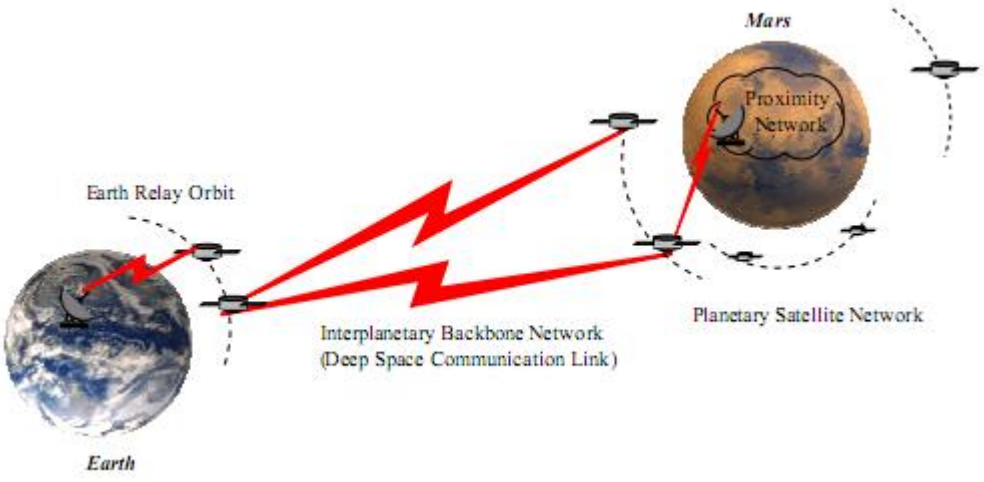

Figure 1 - Interplanetary Network - Concept[8]

[6] Clare, Loren. "Delay/Disruption Tolerant Networking for Space." Cisco Systems, Irvine, CA, 2009. http://www.innovatecalifornia.net/documents/Aug6Materials/Loren%20Clare%20DTNforSpace.pdf (accessed April 17, 2010).
[7] Turner, Adam. "Inter-planetary Internet expands to Mars and beyond." *IT Wire*, February 21, 2007.
[8] Akan, O.B., Jian Fang, and I.F. Akyildiz. "TP-Planet: A Reliable Transport Protocol for InterPlaNetary Internet." *IEEE Journal on Selected Areas in Communications* 22, no. 2 (February 2004): 348.

BACKGROUND

The incredible expansion of the Internet on Earth has occurred concurrently with the expansion of human technology across the Solar System, in the form of robotic probes and landers. Additionally, the increasing capabilities of terrestrial satellite networks have brought real time communications capability to most of the surface of the Earth. However, until recently, the networking concepts on which the Internet is based have not been extended into space. While satellite networks have been used to relay Internet Protocol (IP) traffic since the 1970s, satellites with actual IP communication capability have only recently been developed[9].

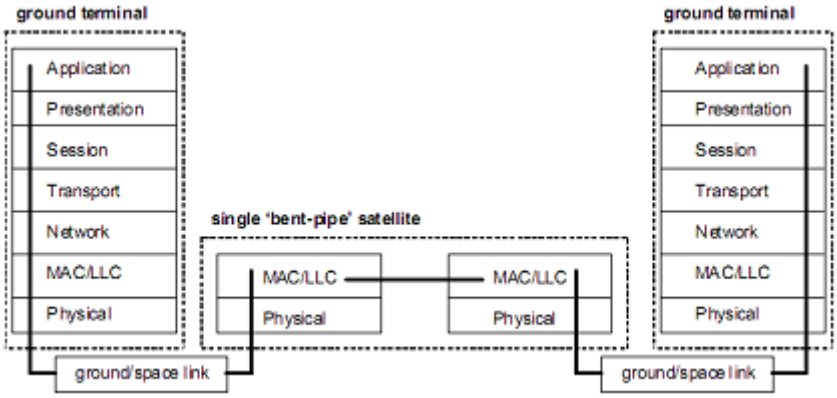

Figure 2 - Non-protocol-aware satellite repeater[10]

Some satellite constellations, such as Iridium and the cancelled Teledesic system, do provide for full networking and routing capability across ground and inter-satellite links[11]. Current deep-space communications also seem somewhat primitive by modern standards of connectivity. Typically, in order to communicate with a robotic probe in orbit around Saturn or on the surface

[9] Wood, Lloyd, et al. "Using Internet nodes and routers onboard satellites." International Journal of Satellite Communications and Networking 25, no. 2 (2007): 195.
[10] Zhang, Yongguang, ed. *Internetworking and Computing over Satellite Networks*. (Norwell, Mass.: Kluwer Academic Publishers, 2003), 18.
[11] ibid., 18.

of Mars, a NASA operations team must schedule the link ahead of time with the Deep-Space Network (DSN), and ensure that they send the correct commands and receive the correct data[12]. The craft on the other end must also know when and where to point its antenna. If communications are to be maintained for long periods of time, the operators must also select a series of ground stations to maintain contact. Further complicating this is the fact that most space missions use unique protocols to communicate, with custom designed software for each mission[13].

In 1998, Vint Cerf, along with a group of scientists at NASA's Jet Propulsion Laboratory began a program to create an "interplanetary extension to the Internet"[14]. The idea was to create a robust network of communication links across the Solar System, starting with Earth and Mars. Instead of manually configured point-to-point connections (such as with the DSN)[15], the idea was to allow spacecraft to communicate with each other, routing data along available links to any point in the Solar System. Constellations of satellites around each planet could ensure continuous transmission, limited only by the lightspeed propagation delay[16]. Initially, attempts were made to adapt the standard Transmission Control Protocol/Internet Protocol (TCP/IP) to space based communications. Immediately, problems were encountered. Internet Protocol (IP), the lower layer, is responsible for the routing of individual packets of information. Since Internet routers generally drop undeliverable packets, IP only works reliably over relatively stable links. In space, where individual hosts (spacecraft, satellites or ground stations) may not have a

[12] Page, Lewis. "NASA space tests 'interplanetary internet' protocol" *The Register*, November 19, 2008. http://www.theregister.co.uk/2008/11/19/nasa_dtn_space_test/ (accessed April 18, 2010).
[13] IEEE. "The Interplanetary Internet." *IEEE Spectrum*. http://spectrum.ieee.org/telecom/internet/the-interplanetary-internet/0 (accessed April 18, 2010).
[14] Metz, Cade. "Vint Cerf mods Android for interplanetary interwebs." *The Register*, November 5, 2009. http://www.theregister.co.uk/2009/11/05/vint_cerf_on_mobile/ (accessed April 18, 2010).
[15] Durst, Robert C., Patrick D. Feighery, and Keith L. Scott. "Why not use the Standard Internet Suite for the Interplanetary Internet?." 2.
[16] Turner, Adam. "Inter-planetary Internet expands to Mars and beyond." *IT Wire*, February 21, 2007.

continuous connection, IP does not work as well. TCP, the higher layer protocol which is responsible for reliable end-to-end communication, depends on low-latency and relatively error-free data transfer. Once again in space the latency can be high, even for something as close as the Moon (1.7 seconds one-way), and bit error rates (BER) as high as 10^{-1} are not uncommon[17].

So what would solve the problems of TCP/IP but still allow for a robust, reusable, and standardized space network? The answer was Delay Tolerant Networking, alternately known as Disruption Tolerant Networking[18].

DELAY TOLERANT NETWORKING

At the simplest level, Delay/Disruption Tolerant Networks (DTNs) operate using "store and forward" techniques. Since an instantaneous end-to-end connection may not exist, hosts must forward data segments to the next host (when available) performing what is known as a "custody transfer", where the receiving node takes responsibility for further delivery of the data. DTNs depend on "bundle protocols", which are analogous to the Transport and Network layers of TCP/IP, but also encapsulate higher layer functionality[19].

The development of DTN was accelerated by the increasing use of standardized space data link protocols developed by the Consultative Committee for Space Data Systems (CCSDS)[20]. Currently, there are over 400 space missions that have or will use CCSDS-

[17] NASA. "Delay Tolerant Networking" http://www.nasa.gov/mission_pages/station/science/experiments/DTN.html (accessed April 18, 2010).
[18] Hooke, Adrian J. "The Interplanetary Network - a strategy for building re-usable international space communications infrastructure." Pasadena, California, 2003. http://www.ipnsig.org/reports/SMC-IT-Hooke-Keynote-15Jul03.pdf (accessed April 17, 2010).
[19] NASA. "Delay Tolerant Networking".
[20] Hooke, Adrian J. "The Interplanetary Network - a strategy for building re-usable international space communications infrastructure."

developed standards[21]. One important standard is the CCSDS File Delivery Protocol (CFDP), which was designed for reliable file transfer using a store-and-forward approach[22]. In the CFDP Basic Deployment (Build 1), two different hosts can communicate directly to send a file one-way. CFDP Advanced Deployment supports indirect communications through an intermediate host. For the IPN, the goal is to use DTN concepts to extend CFDP into its Network Deployment stage (Build 3), where a single transaction can be split and forwarded across multiple links, then reassembled at the destination[23].

DTN IMPLEMENTATIONS

In recent years, there have been several successful demonstrations of DTN protocols. Surrey Satellite Technology Ltd. (SSTL) launched the UK-DMC remote-sensing satellite in 2003, intended primarily for disaster monitoring. It included an onboard Cisco router, which was used for certain networking tests in orbit, but not for DTN transmission[24]. DTN bundle protocols were demonstrated in 2008 with the capture of an image of the Cape of Good Hope, which was then fragmented and transmitted to a ground station across multiple satellite passes, then forwarded across the terrestrial Internet. The image was successfully reassembled at NASA's Glenn Research Center[25]. The experiment proved the viability of SSTL's Saratoga DTN

[21] CCSDS. "The Consultative Committee for Space Data Systems" http://public.ccsds.org/default.aspx (accessed April 18, 2010).
[22] Burleigh, Scott C. "Operating CFDP in the Interplanetary Internet." Jet Propulsion Laboratory, 2002. http://www.aiaa.org/Spaceops2002Archive/papers/SpaceOps02-P-T5-22.pdf (accessed April 17, 2010).
[23] JPL. "Delay-Tolerant Networking," November 17, 2004. http://cwe.ccsds.org/sis/docs/SIS-DTN/DTN%20intro%20slides.ppt (accessed April 17, 2010).
[24] Wood, Lloyd, et al."Use of the Delay-Tolerant Networking Bundle Protocol from Space." Global Government Solutions Group, Cisco Systems. http://personal.ee.surrey.ac.uk/Personal/L.Wood/publications/wood-dtn-bundle-space-IAC-08.B.2.3.10.pdf (accessed April 17, 2010).
[25] Surrey Satellite Technology Ltd. "UK-DMC satellite first to transfer sensor data from space using 'bundle' protocol." http://www.sstl.co.uk/News_and_Events/Latest_News/?story=1254 (accessed April 18, 2010).

protocol. UK-DMC retains the experimental capability to handle DTN bundles without impacting normal satellite operations[26].

Also in 2008, the EPOXI spacecraft from the Deep Impact mission was used to test NASA's DTN implementation known as ION. The craft successfully transferred image files to JPL from a distance of 80 light-seconds[27]. In 2009 NASA, in concert with University of Colorado's BioServe Space Technologies again demonstrated DTN technology using a "Commercial Generic Bioprocessing Apparatus" (CGBA) on the International Space Station (ISS). The CGBA was configured to send and receive DTN bundles to and from the University's Boulder campus[28].

These experiments have shown that the Interplanetary Internet is ready to take the next step into space.

THE FUTURE OF INTERPLANETARY NETWORKING

While the reality of the Interplanetary Internet has not advanced nearly as quickly as the vision[29], it is apparent that the fundamental technology of Delay Tolerant Networks has matured to the point that Cerf's predictions will come true sooner rather than later. If NASA funding remains adequate, DTN will increasingly be used for practical purposes in Earth orbit and beyond. A further advantage is that DTN is being standardized for international use, and the ION

[26] Wood, Lloyd, et al."Use of the Delay-Tolerant Networking Bundle Protocol from Space."
[27] NASA. "NASA Successfully Tests First Deep Space Internet." http://www.nasa.gov/home/hqnews/2008/nov/HQ_08-298_Deep_space_internet.html (accessed April 18, 2010).
[28] NASA. "NASA and University Test New 'Space Internet' Protocols," July 2, 2009. https://www.spacecomm.nasa.gov/spacecomm/programs/technology/dtn/press_release.cfm (accessed April 18, 2010).
[29] Cerf, Vint. "The Internet is for Everyone." Speech presented at the Computers, Freedom and Privacy Conference, Washington, D.C., April 7, 1999. https://www.itu.int/ITU-D/ict/papers/witwatersrand/Vint%20Cerf.pdf.

implementation is "open source"[30]. The more developed that the space communications infrastructure becomes, the easier it will be to design and build future missions.

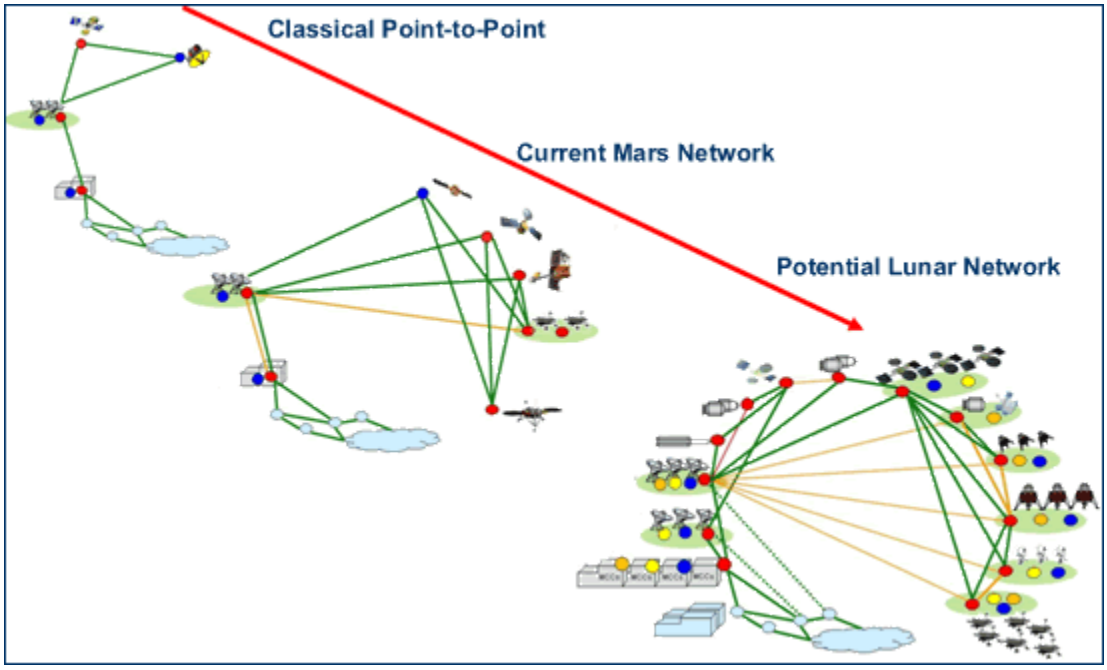

Figure 3 - Possible Future IPN[31]

[30] Clare, Loren. "Delay/Disruption Tolerant Networking for Space."
[31] NASA. "NASA Space Communications: Technology" https://www.spacecomm.nasa.gov/spacecomm/programs/technology/dtn/default.cfm (accessed April 18, 2010).

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