Delay Tolerant Networking &
The Interplanetary Internet

Austin Longo

University of Colorado Boulder

austin.longo@colorado.edu

CSCI 5273

05 May 2020

Abstract

The proliferation of manmade satellites and robotic exploration of the solar system has necessitated telecommunication technologies to work across highly disparate environments. Space communication poses several unique challenges and constraints, such as long propagation delays, low data rates, and intermittent connectivity. Current Internet protocols that, by and large, have been built to operate in terrestrial environments, have major shortcomings when operating under such constraints. This report presents a brief history of space communications and a survey of current protocols and implementations that seek to implement an Interplanetary Internet through the development of Delay Tolerant Networking technologies.

1. Introduction

Human exploration of the solar system is an expression of Man's innate desire for discovery; the search for the next frontier. Dating back nearly 70 years to the launch of Sputnik 1 on October 4th 1957, space exploration has been one of the fastest growing industries and has led to some of the world's greatest technological achievements. Successfully designing, building, launching, and operating a spacecraft poses innumerable challenges, not least of which are the logistics of effective communication at thousands, millions, and even billions of kilometers away.

Space communication imposes many constraints on networking, such as long and variable propagation delays, and frequent losses in connectivity. Standard Internet protocols, such as TCP, having been designed for the characteristics of terrestrial networks, possess many shortcomings when operated in the space environment. Due to these incompatibilities, the need for an InterPlaNetary Internet (IPN) was conjectured by the Internet Research Task Force (IRTF), thus forming the Interplanetary Internet Research Group (IPNRG) in 1998 [15]. The IPNRG has since released many publications on what they've dubbed Delay/Disruption-Tolerant Networking (DTN) [4] in efforts to realize the vision of the IPN.

Several standards exist today, including the Bundle Protocol [13], CCSDS File Delivery Protocol [8], and the Licklider Transmission Protocol [22]. These protocols introduce techniques that are tailored for operation in deep space, while still remaining interoperable with standard terrestrial Internet protocols.

This paper is structured as follows. Section 2 gives a background on the basics of space communication, it's challenges, and the shortcomings of Internet protocols. Section 3 gives a brief history of networking standards and protocols for space systems, discusses the objectives for a delay-tolerant suite of network protocols, and explores current protocols, standards, and implementations of DTN. Finally, section 4 explores some areas of future work to help further improve and generalize these protocols to more effectively implement the InterPlaNetary Internet.

2. Space Communication

2.1 Basics of Spacecraft Communications

Human and robotic spacecraft missions fall into two major categories when considered from the perspective of telecommunication characteristics. Near-Earth missions and deep space missions. In the former, spacecraft can be orbiting Earth in Low-Earth Orbit (LEO), ranging from 200km-2000km of elevation, in Geosynchronous Orbit (GEO), roughly 35000km, and even as far as the Moon, roughly 384000km. Sending RF signals to these spacecraft is constrained by the speed of light, 299792km/s. One Way Light Time (OWLT) to such craft range from 3ms to 1300ms. When compared to a theoretical maximum terrestrial propagation delay of 67ms between the two farthest cities on Earth (20000km), the propagation delays of these space links are within reasonable operating conditions for Internet protocols. As we look to deep space missions, such as Martian orbiters and rovers, we now must contend with distances on the order of 100's of millions of kilometers. OWLT to Mars at its closest approach to Earth is 3min, and 22min at its farthest. Pluto, one of the farthest celestial bodies in our solar system, sits an average of 3 billion kilometers from Earth, with propagation delays of nearly 3hours in one direction.

As shown in Figure 1, communication with a spacecraft typically originates from a mission operations center; which routes command and data traffic through standard terrestrial backbone networks to a ground station, or tracking gateway station. This tracking station then radiates wireless RF signals to the spacecraft, typically in X-band (8Ghz - 12Ghz) or Ka-band

(27.5GHz - 31GHz). Telemetry and data signals from the spacecraft are also received through the ground station antenna and routed back to the mission operations center.

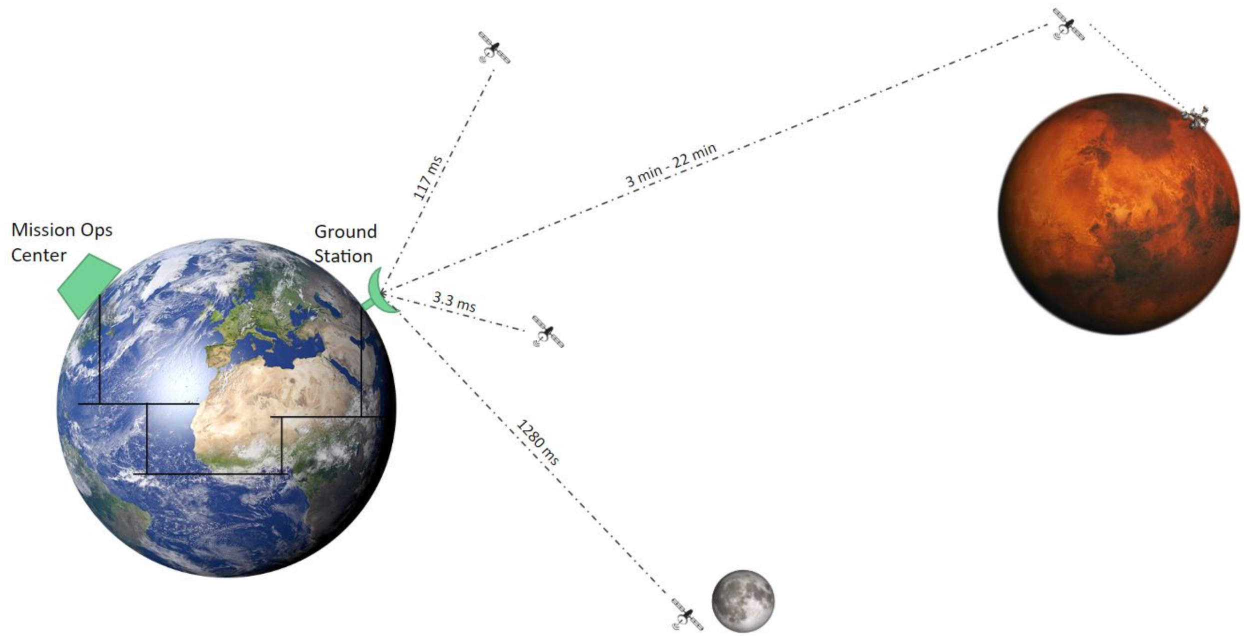

Figure 1. Basic example of spacecraft communication to various locations in the solar system

Telecommunications for the terrestrial part of the link utilize the standard Internet protocol stack (i.e. TCP/IP). This link is characterized by short propagation delays, high data rates, continuous end-to-end connectivity, and on-demand access. For the large majority of space missions, telecommunications for the space link have been implemented on a case-by-case basis, with each mission implementing specific packetization and unique data handling techniques. Some standardization efforts have been taken by the Consultative Committee for Space Data Systems (CCSDS), such as the Space Packet Protocol (133.0-B-1) [27].

Such standards are in efforts of normalizing communication technologies across missions and space agencies.

2.2 Challenges of Space Communications

When designing for network communications in a space environment, many unique challenges must be considered. The first, and most obvious, is the long and variable propagation delays present when communicating with spacecraft at such great distances. Not only are interplanetary distances orders of magnitude greater than anything experienced in terrestrial networks, they are also variable over time as the orbital precession of the planetary bodies expands and shortens those distances. The next most important constraint is the presence of intermittent connectivity. As satellites orbit celestial bodies and rovers rotate on the surface of planets, line of sight between the Earth and those spacecraft is lost, causing a loss of communication.

The transmission of radio frequencies over such great distances and through one, or potentially two, atmospheres results in high bit-error rates and, subsequently, high loss of information. While various on board hardware and software techniques are employed to mitigate these effects, loss still occurs with a much higher rate than it does in the terrestrial Internet. Additionally, RF technology at these distances results in extremely low data rates, ranging from 8bps - 6Mbps.

The constrained operating environment of a solar and battery powered spacecraft means that on board power is a limited commodity. To that end, power must be conservatively budgeted, especially considering that telecommunication hardware is one of the most power hungry consumers on board the spacecraft. In addition, uplink and downlink for the majority of missions is highly asymmetric, with downlink being provisioned much higher than uplink. This constraint must be closely considered when designing how protocols will exchange data. Finally, space links have centrally managed access, where users schedule access time well in advance and there is never contention for the same link simultaneously. This eliminates the concern for congestion that is present in the Internet.

To summarize, the main constraints and characteristics of space communications are as follows:

- Long and variable propagation delays
- Intermittent connectivity
- High bit-error rate (high loss)
- Low data rates (8bps - 6Mbps)
- Limited power budgets on board spacecraft
- Asymmetrical forward and reverse links (downlink >> uplink)
- Centrally managed access (no congestion)

2.3 The InterPlaNetary Internet

Given the above constraints, the vision for the InterPlaNetary Internet is a store and forward network of internets to interconnect nodes across interplanetary distances, in the presence of high error rates and frequent disruption. Figure 2 illustrates what this might look like, as provided by NASA. The key thing to note is that the vision for the IPN is one that is a network of multiple disparate internets. To that end, a successful implementation must serve as an efficient overlay that can bridge the void, literally in this case, between various internet implementations. In the illustration, one could imagine an internet very similar to that which we have on Earth today operating on a Mars colony. The IPN would then act as a bridge between the Martian Internet and the Earth Internet.

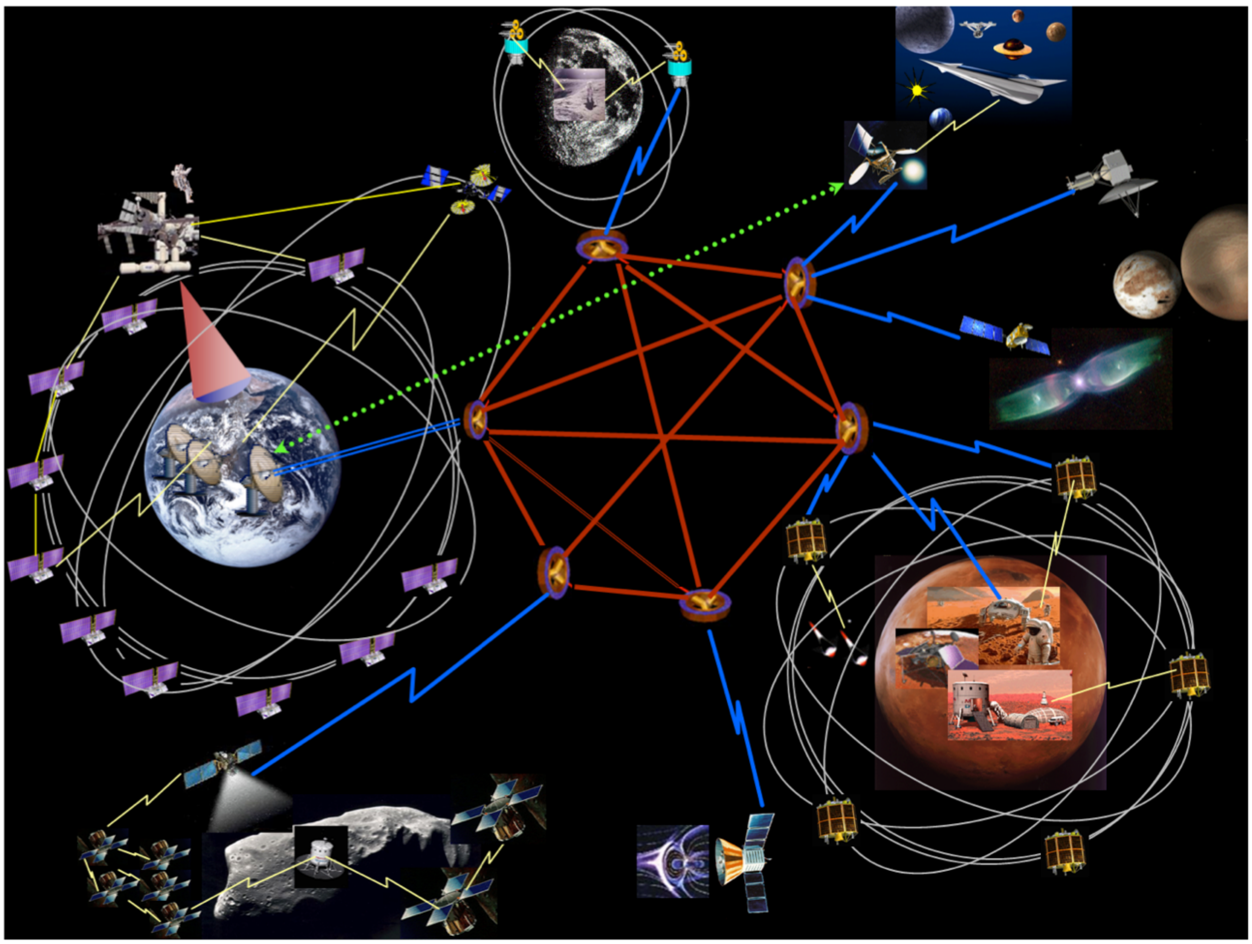

Figure 2. A hypothetical illustration of the InterPlaNetary Internet [https://www.nasa.gov/]

2.4 Shortcomings of Internet Protocols

The first thought when designing for a new infrastructure such as the IPN, is whether existing technologies can be leveraged to meet the requirements. In this case, the existing option would be the TCP/IP stack. A few of the reasons why TCP/IP does not meet the requirements of the IPN are presented here.

1. The three-way TCP handshake for establishing a connection between peers is too time consuming when dealing with long propagation delays present in deep space. Having to wait for a reply and acknowledgement before starting to exchange information wastes valuable time. Given that space links are likely to be intermittent, it's even possible that the time it takes for a single round trip handshake exceeds the total window of opportunity for communicating with the spacecraft.
2. TCP guarantees in-order delivery, exclusively. While this is ideal for terrestrial links, it is potentially too costly in the presence of long delays and intermittent connectivity. If some data has been received out of order on the destination, telling the destination node to delay delivery until all prior data has arrived could mean storing a significant amount of data on board for a length of time that could be minutes (for immediate retransmission to Mars), hours (for occultation by the satellite's parent planet), or even days (in the event of a solar conjunction event).
3. TCP's retransmission scheme relies on timely and stable feedback from the destination, retransmitting on every lost segment using a tight timeout value. In the presence of highly-asymmetric links, flooding the reverse link with ACKs

would consume valuable link bandwidth, and may not even be possible in some extreme cases.

4. Retransmissions in TCP are end-to-end; meaning the sender of the information is responsible for retaining all segments until an ACK is received, so that it can retransmit those segments should the ACK timeout. In terrestrial networks, this typically isn't an issue since delays are short and storage resources are plentiful. On most spacecraft, however, storage resources are extremely scarce. Requiring a Mars rover, for example, to retain every segment of data being transmitted back to the mission operations center for a minimum of one RTT could hinder other mission objectives, given it may only have something like 2GB of non-volatile storage [https://mars.nasa.gov/mars2020/spacecraft/rover/brains/].
5. TCP's Additive Increase / Multiplicative Decrease congestion control scheme, while effective in controlling link access for terrestrial on-demand networks, would result in severe underutilization of a space link. When time and bandwidth are valuable resources (rates for a Deep Space Network antenna are ~$1000/hr [28]), maximizing throughput is essential. The slow start of this approach would ramp up far too slowly and waste bandwidth early in the contact, while dropped packets and lengthy delays would trigger costly multiplicative decrease corrections from the protocol.

6. Finally, routing protocols in the Internet, such as BGP and OSPF, rely on timely connectivity updates to keep routing tables up to date and accurate. With long and variable delays, coupled with nominal connectivity disruptions, these protocols would result in overly pessimistic routing tables.

3. Delay/Disruption-Tolerant Networking

Given the nature of space communications and the terrestrial Internet technologies, the realization of DTN requires an overlay network to bridge between different network stacks across environment boundaries. This overlay network needs to be one with no expectation of continuous connectivity, low latency, low error rates, low congestion, high transmit rates, symmetrical links, or same-order arrival. At the same time, however, it should be able to capitalize on those characteristics, should they be present in regional networks throughout the end-to-end link.

3.1 History

The following is a brief history of major events and publications in the quest for the IPN and DTN.

- 1973 - Cerf & Kahn pioneer TCP
- 1990 - Cerf & JPL adapt Internet procolos for space missions
- 1998 - Internet Research Task Force (IRTF) launches Interplanetary Internet Research Group (IPNRG)
- 2001 - “IPN: Architectural Definition” published by IPNRG (Cerf, Burleigh, et. al.)
    - “Bundling” is born

- 2002 - “Delay-Tolerant Network Architecture: The Evolving Interplanetary Internet” published by IPNRG
    - Generalized IPN architecture; IPNRG becomes DTNRG
- 2007 - RFC 4838: “Delay-Tolerant Networking Architecture” published
    - Bundle Protocol formalized with RFC 5050
- 2007 - CCSDS 727.0-B-4: “CCSDS File Delivery Protocol (CFDP)” published
- 2008 - RFC’s 5325/5326/5327: “Licklider Transmission Protocol” published
    - Formalized DTN retransmission-based reliability; derived from CFDP
- 2008 - Flight demonstration of DTN on Deep Impact (EPOXI) mission
- 2010 - On-orbit demonstration of DTN on EO-1 spacecraft
- 2011 - NASA/JPL begin development of Interplanetary Overlay Network (ION)
    - First implementation of DTN by a space agency
- 2015 - CCSDS 734.1-B-1: “Licklider Transmission Protocol (LTP)” published
    - Standardized LTP for use in space data systems
- 2015 - CCSDS 734.2-B-1: “Bundle Protocol (BP)” published
    - Standardized BP for use in space data systems
- 2016 - ISS begins testing NASA’s DTN implementation, ION
- 2020+ - Full CCSDS standardization of protocols and deployment in all future NASA missions

3.2 Principles

The initial architectural definition published by the IPNRG in 2001 [15] set out three major principles for Delay Tolerant Networking. The first was to construct a network that operated under the premise of postal communication. In contrast to the Internet’s conversational-like communications, DTN requires operations to behave like a postal system, where data represent atomic units of work that can stand on their own. Thus, the concept of “bundles” was born.

Secondly, a successful DTN implementation needs to have tiered functionality. That is, it needs to be able to leverage local/regional protocol stack optimizations when appropriate. Rather than creating an entirely new stack to work at all points in the network, resulting in extremely high complexity and a “weakest link” design approach, the designers found it prudent to take advantage of underlying protocols where they are best suited. Things like tiered forwarding, routing, ARQ, and even security are all tenets of DTN.

Finally, the principle of terseness is crucial in operating in constrained space environments. Bandwidth is in short supply for most deep space missions, so the protocols of DTN must minimize the total amount of data sent over the space link, even if that means requiring a bit more processing at the receiver.

3.3 Bundle Protocol

The Bundle Protocol (BP) was introduced in 2001, but formalized in 2007 via RFC 5050 [13]. The key capabilities of BP are the following:

1. Custody-based retransmission
2. Ability to cope with intermittent connectivity
3. Ability to take advantage of scheduled, predicted, and opportunistic connectivity (in addition to continuous connectivity)
4. Late binding of overlay network endpoint identifiers to constituent internet addresses

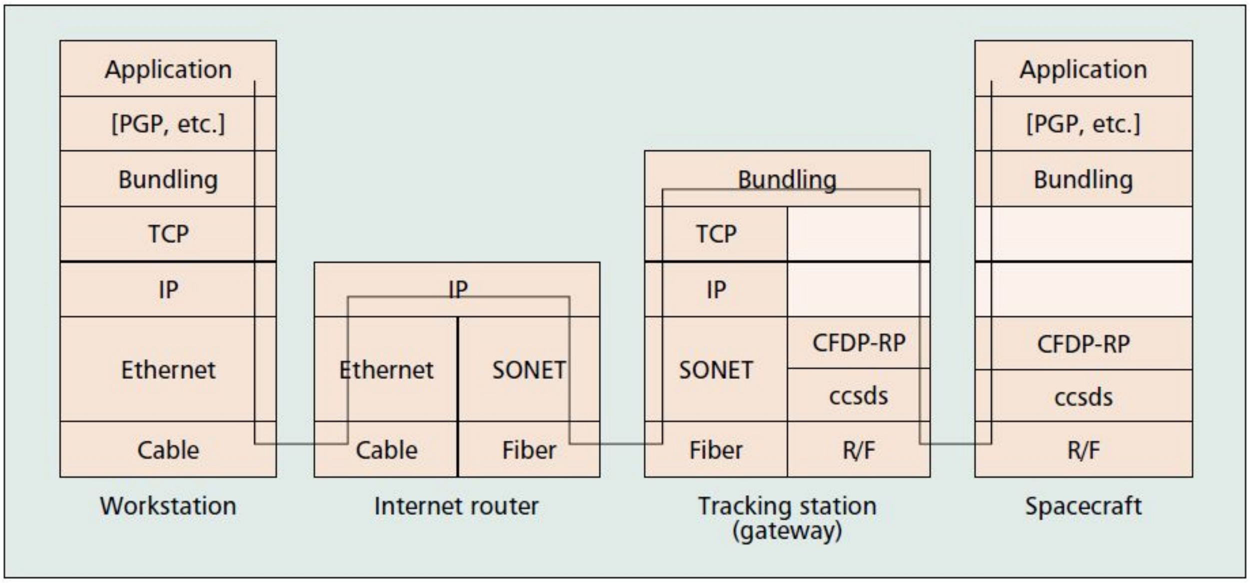

Figure 3. Example of network stacks using the Bundling protocol layer [1]

The concept of custody-based retransmission is arguably the most critical contribution of BP, and it is this topic of retransmissions in DTN that the remainder of this paper explores. With custody-based retransmission, a sending node can request the next node in the link to take custody of the bundles it is about to send to it. Should it agree, the sending node can clear bundles from its retransmission buffer once they are received and taken ownership of by the receiving node. Figure 4 shows an example of this procedure. In this current snapshot, the mission ops center has already delivered bundles 1, 2, and 3 to the tracking station, and has thus cleared them from its retransmission buffer. The tracking station, in turn, has delivered bundle 1 to the relay satellite orbiting the Moon, and only retains ownership of bundles 2 and 3. Should bundle 1 fail to get delivered any further, it is the responsibility of this relay satellite to maintain a copy of that bundle in its on-board non-volatile storage for retransmission. This achieves two things. First, it allows prior nodes in the link to free storage space by clearing bundles from their retransmission buffers once they're delivered to the next link. Second, it allows the transmission to make incremental progress throughout the link. Should a bundle transmission fail on the last leg of the link, from the Mars orbiter to the Mars rover, that bundle would only need to traverse the orbiter->rover link during retransmission, instead of the full path from the mission ops center.

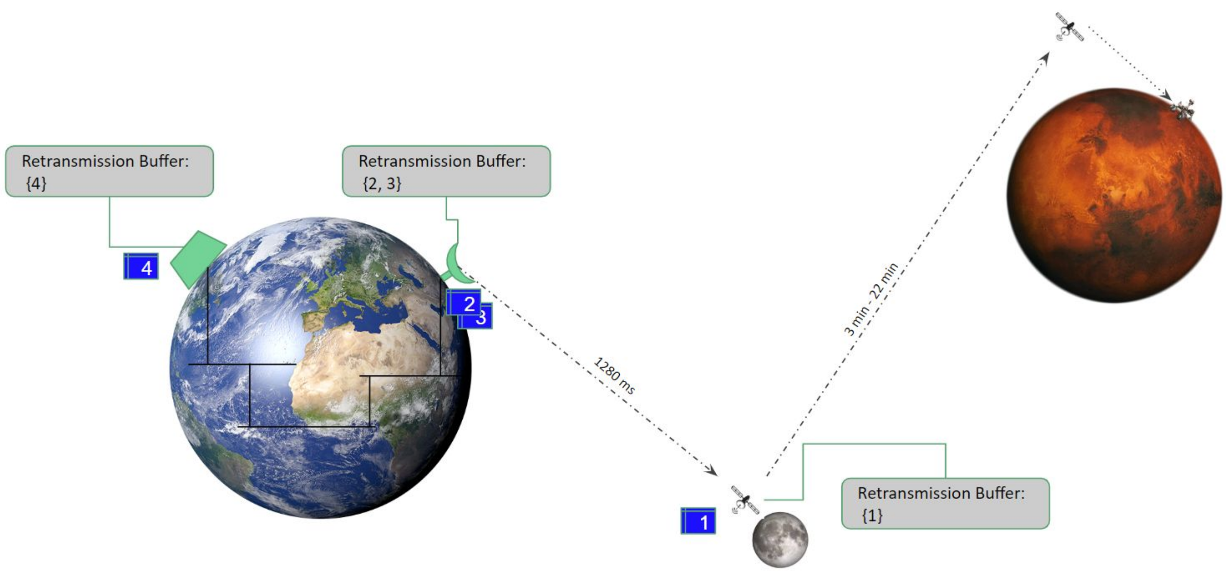

Figure 4. Example of BP's custody transfer

3.4 CCSDS File Delivery Protocol

The Consultative Committee for Space Data Systems (CCSDS) published the CFDP (727.0-B-4) [8] standard in 2007 to support file transfer and file management services in spacecraft systems. An open source implementation of this protocol is provided in NASA's core Flight System [https://github.com/nasa/CF]. The need for such a protocol was driven by the ever increasing size and complexity of spacecraft storage systems. Where, historically, spacecraft were provisioned with low capacity non-volatile storage using flat addressing schemes, capacities are growing and formatting is tending towards traditional file systems. With such advancements, manual management of on-board storage is becoming unwieldy and impractical. CFDP introduces a file transfer protocol, not dissimilar to the FTP of the Internet, to help automate data uplink, downlink, and management.

Of particular interest is CFDP's "Acknowledged Mode". This mode of operations introduces reliability through a unique retransmission scheme. One variant of CFDP's Acknowledged Mode uses the concept of Keep Alive PDUs so that the receiver can respond back with the transaction's reception progress so far. These Keep Alive PDUs can be triggered at a predefined cadence by the sender using Prompt PDUs. It is with this mechanism that the system can be configured to batch retransmissions over time so that the receiver need not respond with ACKs for every segment received. This technique was cherry picked from the protocol, and expanded upon, to form the Licklider Transmission Protocol.

3.5 Licklider Transmission Protocol

The Licklider Transmission Protocol (LTP) is a point-to-point convergence layer protocol aimed at addressing some of the challenges of Delay/Disruption-Tolerant Networking. Originally defined in RFC 5326 [22] LTP formalized and expanded upon the reliable transmission strategy of CFDP's Acknowledged mode. LTP was later re-standardized in 2015 by CCSDS in the 734.1-B-1 blue book [23]. LTP serves as a reliable convergence layer protocol specifically aimed at addressing the constraints of the RF space link. LTP sits either between the application and transport layers (as shown in Figure 5) or between the network and link layers (as is recommended in the CCSDS standard).

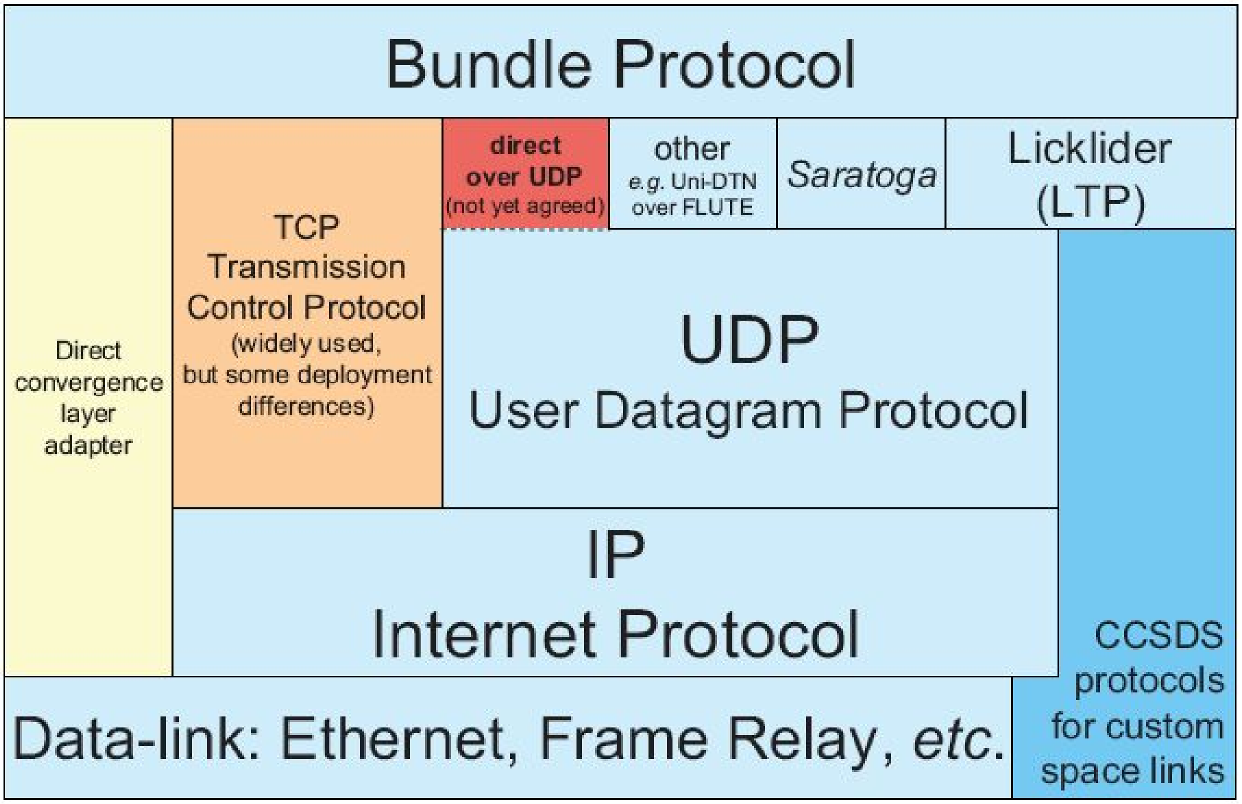

Figure 5. An illustration of a DTN node's network stack [19]

The key contributions of LTP are its selective-acknowledgement ARQ implementation, support for partial reliability, and tolerance to intermittent connectivity. With selective-acknowledgement, LTP gives control of acknowledgements to the sender. As shown in Figure 6, the sending agent can send several segments in a row to the receiver before requesting that the receiver send back a Report Segment (RS). The RS contains a list of all segments received since the last report. The sender can then determine which, if any, segments were lost and retransmit those segments. In this way, LTP effectively batches up the acknowledgements that the receiver needs to send and minimizes the traffic on the reverse link.

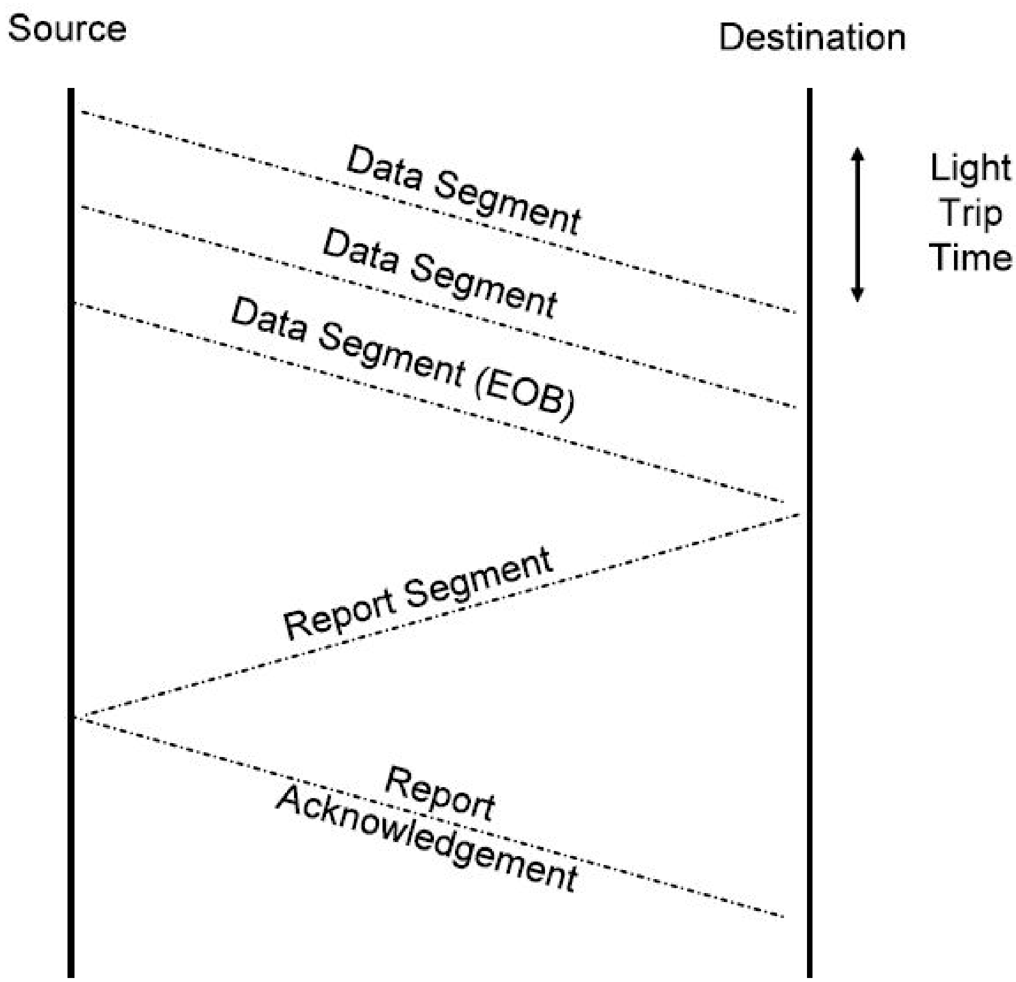

Figure 6. LTP selective-acknowledgement ARQ [19]

Furthermore, LTP supports the concept of partial-reliability; meaning only parts of the transmission are guaranteed to be delivered with the use of retransmissions. This is implemented using a "red block" and a "green block", as shown in Figure 7. Anything that is part of the red block will be retransmitted if the RS indicates it was not received. Everything that is part of the green block will simply be sent best-effort, similar to UDP. Green block data is typically something that is not required to be fully delivered to be useful. One such example is telemetry data from the spacecraft. Such data is often sent on a cadence of several seconds during a contact with the mission ops center, so if any piece of the telemetry was lost, it will be populated on the next update. This helps minimize traffic and optimize the link utilization for more critical data, such as downlinking science payload packets.

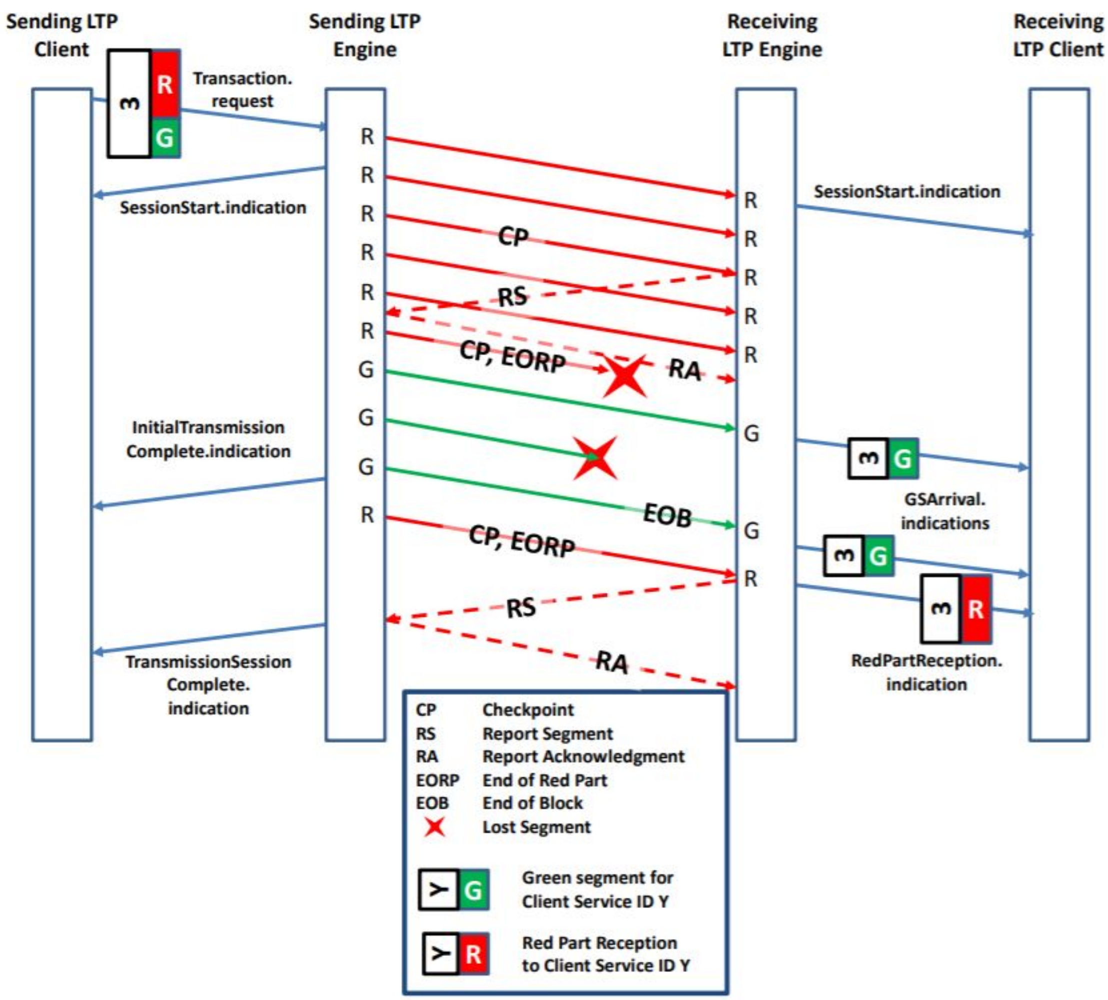

Figure 7. LTP partial reliability [23]

Finally, LTP operates in the presence of intermittent connectivity by managing timer operations of each message. The only segments that trigger timers are the Checkpoint (CP), RS, and End of Red Part (EORP) segments. EORP is an implicit CP segment, and acts as a request for the receiver to send a report segment. When a CP or EORP is sent from the sending agent, a timer is started that waits until a RS is received back from the receiving agent. If no RS is received before the timeout, a new CP or EOPR request is sent. Similarly, on the receiving agent, a timer is started when a RS is sent that waits until a Report Acknowledgement is received back from the sending agent, informing the receiving agent that it received its report. Each of these timers can be suspended when the DTN node knows that it will be experiencing a disconnection (for any of the reasons described previously) so that time spent out of contact with the spacecraft is not counted against the threshold. Upon exiting the disconnection event, the DTN node resumes the timers so that operation of the protocol may continue.

By layering LTP beneath the Bundle Protocol, a DTN transmission supports a tiered ARQ scheme. LTP handles retransmissions of individual segments within a bundle on a point-to-point link, while BP's custody transfer handles retransmissions of entire bundles across the end-to-end link, a sort of safety net.

3.6 Interplanetary Overlay Network

The Interplanetary Overlay Network (ION) [https://sourceforge.net/projects/ion-dtn/] is an open-source implementation of DTN, as described in Internet RFC 4838 [17]. It was developed by NASA and JPL and is actively maintained at Caltech. It is intended for use in embedded spacecraft environments. Also provided by the developers is a dev kit, built as an Ubuntu ISO. The dev kit includes a graphical interface called CORE; which allows for visualization of various configurations and scripting of simulations that show the behavior of DTN. An example of one such simulation is recorded here: https://youtu.be/VQtlRrnXcfg

4. Future Work

While I was unable to further investigate any of the following ideas, they are concepts that I identified as potential areas of future improvement to the DTN architecture. The first is what I've dubbed LTP Dynamic Retransmission Aggregation. Since different space links are bound to have varying properties, such as propagation delay, bandwidth, and windows of connection, it would be beneficial to dynamically adjust how many segments are batched together before a report segment is requested. This could adapt to changing parameters and adjust the amount of aggregation to better utilize the link. Currently, the CCSDS 734.1-B-1 standard for LTP Service Data Aggregation [23] achieves this, but only with preconfigured settings. It does not provide for a dynamic, real-time, adjustment.

Second would be to investigate ways for improving LTP's performance across multi-hop links. The current CCSDS standard advises LTP connections be set up point-to-point and torn down after data has reached the destination, where a new session is reestablished for the next leg of the link. A particularly difficult challenge here is compensating for heterogeneous links in a multi-hop path so that the protocol behaves correctly for each of the sub-links. A current protocol, called LTP-Transport [19], aims at overcoming this challenge, among others. This is a preliminary protocol and surely some improvements can be made.

Finally, an area that has been widely unexplored, due to the lack of a pressing need, is that of congestion control across space links. Given the current environment, congestion is not a concern when transmitting over the deep space network. In the future, however, it is not unthinkable that demand will increase and the potential for congestion along with it. As space links move from being an admission-controlled system to an on-demand commodity, a holistic form of congestion control will be required. Keeping to the principles of DTN, an implementation should be architected in a tiered fashion; leveraging congestion strategies of regional protocols, and applying an overlay strategy across the space link.

5. Conclusion

The proliferation of space-bound systems, both robotic and human-controlled, is an inevitability. As these systems grow in quantity and complexity, and as human kind's reach across the solar system expands, a unified and integrated networking solution becomes imperative. The challenges faced when communicating across the vastness of space are numerous and varied. Current Internet protocols, while highly effective for terrestrial networks, are ill-equipped to face these challenges. A new suite of protocols is necessary to bridge the void of space telecommunications in order to realize the InterPlaNetary Internet. The Delay Tolerant Networking architecture, and its associated protocols, have set the stage for this effort. Still in its infancy, however, DTN is ripe for continued research and further contributions to aid in overcoming the many challenges of space communications.

References

[1] Burleigh, Scott, et al. "Delay-tolerant networking: an approach to interplanetary internet." *IEEE Communications Magazine* 41.6 (2003): 128-136.

[2] Akyildiz, Ian F., et al. "InterPlaNetary Internet: state-of-the-art and research challenges." *Computer Networks* 43.2 (2003): 75-112.

[3] Akan, Ozgur B., Jian Fang, and Ian F. Akyildiz. "TP-Planet: A reliable transport protocol for interplanetary internet." *IEEE Journal on Selected Areas in Communications* 22.2 (2004): 348-361.

[4] Cerf, Vinton, et al. "Delay-Tolerant Networking Architecture." *Internet Draft IRTF DTNRG Arch-00*, DTN Research Group - Mar. 2003. https://tools.ietf.org/html/draft-irtf-dtnrg-arch-00.

[5] Durst, R., P. Feighery, and E. Travis. "Users manual for the SCPS Transport Protocol." *WN 97W0000018, McLean, Virginia* (1997).

[6] Lawas-Grodek, Frances J., et al. "SCPS-TP, TCP and rate-based protocol evaluation for high delay, error prone links." *SpaceOps 2002 Conference*. 2002.

[7] McMahon, Alex, and Stephen Farrell. "Delay-and disruption-tolerant networking." *IEEE Internet Computing* 13.6 (2009): 82-87.

[8] CCSDS. "CCSDS File Delivery Protocol (CFDP)." *Recommended Standard - 727.0-B-4*, Blue Book - Jan. 2007. public.ccsds.org/Pubs/727x0b4.pdf.

[9] CCSDS. "CCSDS File Delivery Protocol (CFDP) - Part 1: Introduction and Overview." *Informational Report - 720.1-G-3*, Green Book - Apr. 2007. https://public.ccsds.org/Pubs/720x1g3.pdf.

[10] CCSDS. "CCSDS File Delivery Protocol (CFDP) - Part 2: Implementers Guide." *Informational Report - 720.2-G-3*, Green Book - Apr. 2007. https://public.ccsds.org/Pubs/720x2g3ec1.pdf.

[11] CCSDS. “CCSDS File Delivery Protocol (CFDP) - Part 3: Interoperability Testing Final Report.” *Informational Report - 720.3-G-1*, Green Book - Sep. 2007. https://public.ccsds.org/Pubs/720x3g1.pdf.

[12] Alhilal, Ahmad, Tristan Braud, and Pan Hui. "The Sky is NOT the Limit Anymore: Future Architecture of the Interplanetary Internet." *IEEE Aerospace and Electronic Systems Magazine* 34.8 (2019): 22-32.

[13] Scott, Keith and Scott Burleigh. “Bundle Protocol Specification.” *RFC 5050*, Network Working Group - Nov. 2007. https://tools.ietf.org/html/rfc5050.

[14] CCSDS. “CCSDS Bundle Protocol Specification.” *Recommended Standard - 734.2-B-1*, Blue Book - Sep. 2015. https://public.ccsds.org/Pubs/734x2b1.pdf.

[15] Cerf, Vinton, et al. "Interplanetary Internet (IPN): Architectural Definition." *Internet Draft IRTF IPNRG Arch-00*, IPN Research Group - May. 2001. https://tools.ietf.org/html/draft-irtf-ipnrg-arch-00.

[16] Cerf, Vinton, et al. "Delay-Tolerant Network Architecture: The Evolving Interplanetary Internet." *Internet Draft IRTF IPNRG Arch-01*, IPN Research Group - Jul. 2002. https://tools.ietf.org/html/draft-irtf-ipnrg-arch-01.

[17] Cerf, Vinton, et al. “Delay-Tolerant Networking Architecture.” *RFC 4838*, Network Working Group - Apr. 2007. https://tools.ietf.org/html/rfc4838.

[18] Mukherjee, Joyeeta, and Byrav Ramamurthy. "Communication technologies and architectures for space network and interplanetary internet." *IEEE communications surveys & tutorials* 15.2 (2012): 881-897.

[19] Tomlinson, P., et al. "Virtually Delayed: An investigation into delay tolerant networks and their emulation in a virtual environment." (2009).

[20] Srivastava, Vineet, and Mehul Motani. "Cross-layer design and optimization in wireless networks." *Cognitive Networks: Towards Self-Aware Networks* (2007): 121-146.

[21] Wu, Haitao, et al. "LTP asynchronous accelerated retransmission strategy for deep space communications." *2016 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*. IEEE, 2016.

[22] Ramadas, M., et al. “Licklider Transmission Protocol - Specification.” *RFC 5326*, Network Working Group - Sep. 2008. https://tools.ietf.org/html/rfc5326.

[23] CCSDS. “Licklider Transmission Protocol (LTP) For CCSDS.” *Recommended Standard - 734.1-B-1*, Blue Book - May. 2015. https://public.ccsds.org/Pubs/734x1b1.pdf.

[24] Lawas-Grodek, Frances J., et al. "SCPS-TP, TCP and rate-based protocol evaluation for high delay, error prone links." *SpaceOps 2002 Conference*. 2002.

[25] Durst, Robert, et al. “User’s Manual for the SCPS Transport Protocol.” *Working Note WN 97W0000018*, Washington C^3 Center - Mar. 1997. https://yazzy.org/docs/SCPS/SCPS_RI_1_1_113/docs/ri.pdf.

[26] CCSDS. “SPACE COMMUNICATIONS PROTOCOL SPECIFICATION (SCPS)—TRANSPORT PROTOCOL (SCPS-TP).” *Recommended Standard - 714.0-B-2*, Blue Book - Oct. 2006. https://public.ccsds.org/Pubs/714x0b2.pdf.

[27] CCSDS. “Space Packet Protocol.” *Recommended Standard - 131.0-B-1,* Blue Book - Sep. 2003. https://public.ccsds.org/Pubs/133x0b1c2.pdf.

[28] California Institute of Technology, JPL. “Deep Space Network Services Catalog.” Feb. 2015. https://deepspace.jpl.nasa.gov/files/820-100-F1.pdf