

Evolution of Interplanetary Internet: Technology Demonstrations for Space Network Operations

Rachel Dudukovich^{a*}, Juan A. Fraire^{bc}

^a NASA GRC, rachel.m.dudukovich@nasa.gov

^b Inria, INSA Lyon, CITI, UR3720, 69621 Villeurbanne, France

^c Universidad Nacional de Córdoba, Córdoba, Argentina

* Corresponding author

Abstract

As humanity ventures further into space, the limitations of traditional point-to-point communication systems become increasingly evident. The vast distances between celestial bodies introduce significant propagation delays, while space dynamics contribute to frequent link disruptions due to occlusion and asymmetric data rates. These challenges underscore the need for a robust, scalable, and flexible communication framework to support the future interplanetary internet.

Delay-Tolerant Networking (DTN) is a critical technology that can address these challenges. It is designed to handle the long propagation delays and intermittent connectivity that characterize interplanetary communications. By transforming isolated, point-to-point links into a resilient and interoperable network, DTN paves the way for a Solar System Internet that can enable continuous and automated communication across vast distances in space.

This paper comprehensively surveys the most relevant demonstrations of DTN technologies in the space and aeronautical communication domains. These demonstrations, including but not limited to the following experiments, are a testament to DTN's advancements.

DTN has proven its robustness in various environments, from its first space demonstration with the DMC-1G constellation to deep space validation in the DINET experiments. Projects like ESA's Multi-Purpose End-To-End Robotic Operation Network (METERON) and NASA's Lunar Laser Communications Demonstration (LLCD) further showcased DTN's capability to control remote systems and ensure reliable data transmission over optical links. The International Space Station (ISS) has also served as a critical platform for DTN experiments, including successful video downlinks over disrupted links and internetworking with the Laser Communication Relay Demonstration (LCRD) and NASA Glenn Research Center (GRC) research aircraft. Collaborative efforts like the NASA/JAXA DRTS testing and ESA's OPS-SAT CubeSat mission have continued to push the boundaries, demonstrating DTN's effectiveness in actual space operations. Additionally, a CubeSat experiment (TechEd Sat-11, led by NASA GRC and Ames Research Center) leveraging commercial networks and ground tests conducted in the DTN Engineering Network further exemplifies DTN's growing role in modern space communications.

This paper introduces a novel taxonomy that identifies gaps, challenges, and future opportunities in DTN evaluations for space by providing a comprehensive overview and comparison of these DTN demonstrations. These insights underscore DTN's pivotal role in advancing space network operations and highlight the critical steps required to realize a fully operational interplanetary internet. As we move closer to this vision, understanding and addressing these gaps will be essential in shaping the future of space communications and ensuring the seamless integration of DTN across all levels of space exploration.

Keywords: Delay Tolerant Networking, Space Communications

1 Introduction

Future Moon to Mars objectives outline the need for a robust communications architecture to enable transmission and reception of data, determination of location and orientation, and acquisition of time [1]. This Communications, Position, Navigation, and Timing (CPNT) sub-architecture will support crewed multimedia communications and scientific data collection utilizing Direct-to-Earth links, communications among surface assets and orbiting relays [2]. Delay tolerant networking (DTN) can provide the store-and-forward, reliability, security, and routing capabilities needed to integrate disparate point-to-point links into the future solar system internet.

Delay tolerant networking (DTN) has been identified as a needed technology for space communications and challenged networks since the early 2000's. Early works cited the need for network regions and gateways, naming and

addressing schemes, custody transfer, convergence layers, time synchronization, security, congestion control and an application interface[3] as features of an architecture to support disconnected networks comprised of dissimilar protocols stacks. Current visions for lunar network, outline in the LunaNet Interoperability Specification [4] include DTN protocols to support “links which are characterized by disruption/delay or where a robust end-to-end path is not available (or at full bandwidth)”.

This paper provides a summary of flight experiments which have demonstrated key aspects of DTN functionality and have matured the protocols and implementations for operational readiness. Section 2 provides a literature review of publications detailing previous DTN experiments. Section 3 provides a summary of selected recent experiments which have demonstrated new capabilities. Section 4 concludes with a summary of new capabilities which could enhance DTN for future users.

2 Background

Multiple implementations of a DTN protocol stack have been completed and exercised in both space operations and experiments. The Internet Society Interplanetary (IPNSIG)[5] maintains an list of DTN implementations and the status of key features in each implementation [6]. Key features outlined by IPNSIG include Bundle Protocol version 6 [7] and 7 [8], TCP Convergence Layer version 3 and 4 [9], UDP Convergence Layer, Licklider Transmission Protocol [10], Bundle Protocol Security [11], Contact Graph Routing [12], streaming services, Asynchronous Message Service, DTN IP Neighbor Discovery (IPND), and CCSDS File Delivery Protocol (CFDP) [13]. In addition, the Consultative Committee for Space Data Systems (CCSDS) has multiple updates to DTN specifications and drafts of new protocols in progress. As such, DTN components have a wide range of maturity and the Technology Readiness Level (TRL) [14] of a specific system can be difficult to assess. Table 1 provides a literature review of DTN experiments and operational networks including the implementation used and specific features that were demonstrated in a flight or ground operations environment. The provided summary may not include current missions which do not have publicly accessible documents at this time. Table 1 abbreviates the “Purpose” column as “Exp.” for experiments and demonstrations and “Ops.” for operations.

At this time multiple users have demonstrated Bundle Protocol version 6 in a relevant space environment. Bundle Protocol version 7 has since superseded version 6 and newer missions are beginning to utilize it in a space environment. Many space applications tend to use simplified routing although [15] and [16] have utilized CGR in a flight environment and [17], has utilized Ring Road routing. Several papers discuss the use of custody transfer, however custody transfer has been removed from the current version of Bundle Protocol version 7. There are few references to testing priority as defined in Bundle Protocol version 6 in a space environment and the approach has also been removed from Bundle Protocol version 7. New approaches to handle priority and quality of service are current drafts for possible standardization.

3 Recent Experiments

3.1 ESA’s OPS-SAT Experiment

In a real LEO environment, ESA’s OPS-SAT served as a flight validation platform for testing μ D3TN, a lightweight DTN protocol stack [24]. The experiment, described in detail in [25] and driven by D3TN GmbH (Germany), aimed to demonstrate DTN’s applicability to space communications, validating its interoperability with terrestrial networks and its ability to support application-layer services over disrupted links.

Experimental Setup The setup, illustrated in Fig 1, involved a *cold spot* (user terminal with no direct internet access), a *hot spot* (an internet-connected ground station), and ESA’s OPS-SAT acting as an in-orbit DTN relay. The communication followed a store-carry-and-forward model, employing Bundle Protocol Version 7 (BPv7) over terrestrial and space links. The key components were:

- **User Interface:** HTTP requests generated via curl were sent through an HTTP communication gateway.
- **Cold Spot Gateway:** The HTTP request was encapsulated into a DTN bundle using μ D3TN and forwarded to a dispatcher over BPv7-SPP (Space Packet Protocol).

Platform	Purpose	Software	Version	Convergence Layers	Priority / QoS	Custody	BPsec	Routing	Network Mgmt.	Data Rate
Disaster Monitoring Constellation (DMC) [18]	Exp.	"DTM Shim"/DTN2	6?	Custom, Saratoga, TCP	No	No	No	No	No	Uplink 9600 bps / Downlink 8.134 Mbps
Deep Impact Network Experiment (DINET) [15]	Exp.	ION	6	LTP	Yes	Yes	No	CGR	No	256 Kbps - 6 Mbps
EO1 [3]	Exp.	ION	6							
ISS [19]	Exp.	ION	6	Custom	No	Yes	No	Static	No	Uplink 150 bps / Downlink 400 kbps
ISS and HOSC [20]	Ops.	ION, DTN2	6	LTP, TCPCL, STCP	No	No	No	Static	Yes	Uplink 4 Mbps / Downlink 20 Mbps
OPS-SAT [17]	Exp.	μ D3TN	7	Custom TCP/SPP	No	No	No	Ring Road	No	Uplink 256 Kbps / Downlink 1 Mbps in Simulated Scenario
HDTN Aero Optical Experiment [21]	Exp.	HDTN	6	TCPCL, STCP, LTP	No	Yes	No	No	No	Optical link maximum downlink rate was 800 Mbps. DTN downlink rates: TCPCL 800 Mbps, STCP 700 Mbps, LTP 800 Mbps
Korea Pathfinder Lunar Orbiter (KPLO) [22]	Exp.	ION	-	LTP	No	No	No	No	No	Uplink 1 Kbps / Downlink 1 Mbps
Lunar IceCube Spacecraft [23]	Exp.	cFS (bplib) flight, ION ground	6	SPP, TCPCL	No	Partially	No	No	No	Not Discussed
HDTN ISS/ILT/LCR [16]	Exp.	HDTN	6/ 7	LTP	No	Yes	Yes	Yes	Partially	900 Mbps

Table 1: Literature Review Summary

- **Dispatcher:** A contact-aware multiplexing system schedules data transmissions based on contact opportunities with OPS-SAT.
- **OPS-SAT DTN Node:** The satellite received bundles during scheduled S-band contacts and relayed them back to the ESA ground station.
- **Hot Spot Gateway:** Upon reception, the bundle was unpacked and converted back to an HTTP request, which was

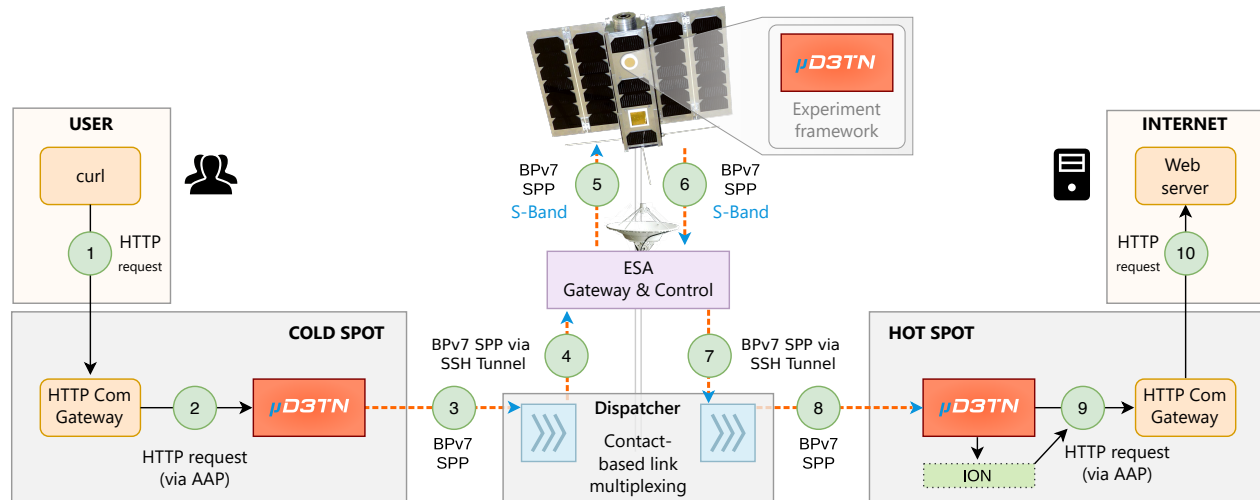


Figure 1: ESA's OPS-SAT experiment set-up [25].

then forwarded to an internet web server.

Results and Insights The experiment, executed in December 2020 and May 2021, successfully demonstrated:

1. **End-to-End DTN Communication:** HTTP requests were successfully routed across the DTN network, bridging the connectivity gap between isolated users and the internet.
2. **BPv7 Operational Validation:** This was the first in-orbit validation of BPv7, confirming its viability for space communications.
3. **Interoperability with ION:** The experiment validated interoperability between μ D3TN and NASA's Interplanetary Overlay Network (ION), enabling multi-protocol DTN operations.
4. **Bundle Fragmentation and Rate Control:** Large payloads were successfully fragmented and reassembled across disrupted links. A rate-limiting mechanism (45 packets per second) was implemented to mitigate CubeSat's communication system overloading.

More information on the OPS-SAT experiment can be found in D3TN's blog website, ESA's OPS-SAT post, and Spatium's blog site.

3.2 Cross-Agency Lunar IceCube Experiment

The Lunar IceCube mission, developed by Morehead State University and launched during NASA's Artemis-1 mission in November 2022, aimed to orbit the Moon to detect water, ice, and other resources on its surface. Unfortunately, post-launch communication with the satellite was unsuccessful.

To demonstrate the potential of Delay- and Disruption-Tolerant Networking (DTN) in space communications, NASA, ESA, and D3TN collaborated on an experiment emulating the Lunar IceCube's data transmissions. This experiment showcased interoperability among four distinct Bundle Protocol (BP) implementations:

1. **Lunar IceCube:** Utilizing NASA's bplib.
2. **ESA DTN Nodes:** Running the DTN Assembly with ESA's Java implementation.
3. **NASA JPL and Morehead State University Nodes:** Operating NASA's Interplanetary Overlay Network (ION).
4. **D3TN:** Employing their open-source μ D3TN implementation.

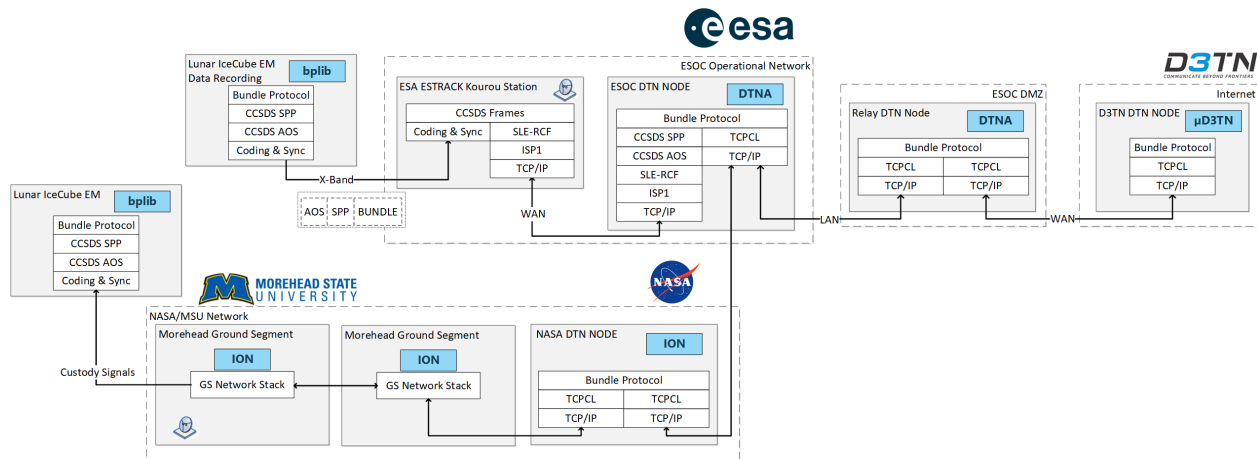


Figure 2: Cross-Agency Lunar IceCube experiment set-up (source: ESA's blog post).

Experimental Setup The Lunar IceCube DTN experiment, illustrated in Fig. 2, emulated data transmissions from the Lunar IceCube spacecraft to assess the feasibility of DTN for lunar missions. The setup integrated multiple DTN protocol implementations across ESA, NASA, Morehead State University (MSU), and D3TN infrastructure.

The experiment began with Lunar IceCube's emulated telemetry data, processed using NASA's bplib and encapsulated in Bundle Protocol (BPv7). The data was transmitted via the Morehead Ground Segment, where ION (NASA's DTN implementation) handled custody transfers and bundle forwarding. The ground station network relayed the data to NASA's DTN node, which processed it and routed it over TCPCL (TCP Convergence Layer).

ESA's involvement included the ESTRACK Kourou Station, responsible for receiving and forwarding CCSDS-formatted frames via SLE-RCF (Space Link Extension - Return Channel Frames) to the ESOC DTN node. This node converted CCSDS frames into DTN bundles and forwarded them via a Relay DTN Node operating within ESA's DMZ (Demilitarized Zone) for secure inter-network routing.

Finally, the data was routed to D3TN's μ D3TN implementation, demonstrating cross-protocol compatibility and successful end-to-end delivery across the DTN-enabled lunar communication network. This setup validated the interoperability of four distinct DTN implementations (bplib, ION, DTNA, and μ D3TN), proving that a multi-agency DTN architecture can support lunar exploration missions in the future.

Results and Insights The success of this experiment underscores the importance of developing a Solar System Internet to support the increasing number of missions, especially those targeting the Moon and lunar orbits. Traditional point-to-point communication methods are becoming insufficient due to the growing demand for reliable, autonomous lunar communications and navigation services. ESA's Moonlight initiative aims to address this need by establishing the first off-planet commercial telecommunications and satellite navigation provider. Implementing DTN-based protocols is crucial to achieving flexible and efficient communication networks in space, accommodating delays, disruptions, and vast distances inherent in extraterrestrial missions.

More information on the Cross-Agency Lunar IceCube experiment can be found in D3TN's blog website and ESA's blog post.

3.3 High-rate Delay Tolerant Networking Experiment

A series of High-rate Delay Tolerant Networking (HDTN) experiments were conducted onboard the International Space Station (ISS) from May through June 2024. The experiments utilized NASA Glenn Research Center's (GRC) HDTN, open-source performance optimized DTN protocol stack [26]. The HDTN software was deployed as an onboard gateway in support of the Laser Communications Relay Demonstration (LCRD) and the Integrated LCRD LEO User Modem and Amplifier Terminal (ILLUMA-T) experiments [27]. The primary objective of the experiment was to demonstrate modern DTN protocols over the 1.25 Gbps ILLUMA-T and LCRD optical link, while demonstrating internetworking through the ground and cloud-based network.

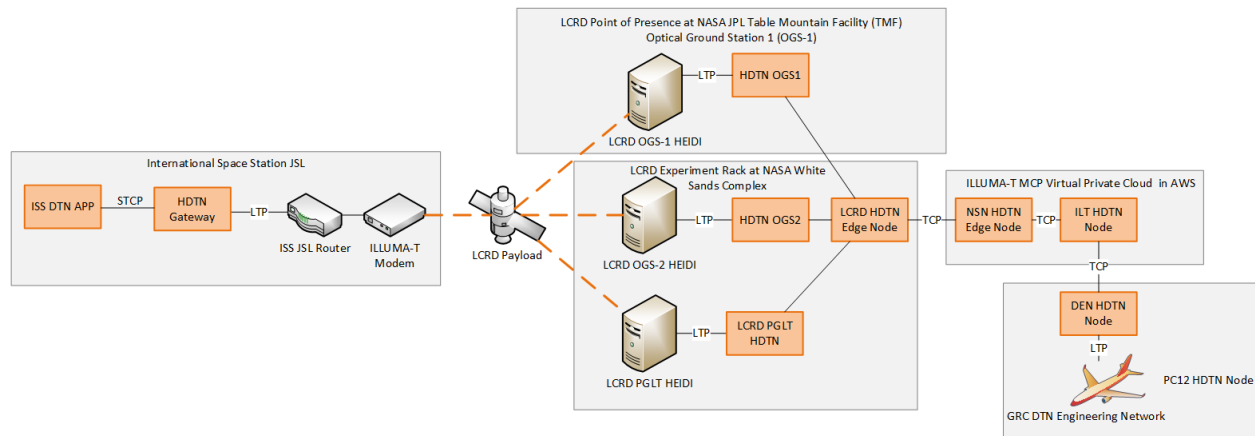


Figure 3: HDTN ISS ILLUMA-T Experiment

Experimental Setup The network consisted of the ISS (NASA Johnson Space Center), the White Sands Complex (WSC) [28], NASA Goddard Space Flight Center’s Mission Cloud Platform (MCP), NASA’s Marshall Space Flight Center Huntsville Operations Support Center (HOSC), and the GRC’s DTN Engineering Network (DEN). The ISS housed the emulated DTN payload node, the HDTN onboard gateway, Joint Station LAN equipment and the ILLUMA-T modem and related optical hardware. The ground network consists of optical ground stations, cloud-based nodes and the DEN. The hops from the cloud into the DEN allowed communication with GRC’s Pilatus PC-12 aircraft.

Results and Insights There were multiple objectives for the experiment, which successfully demonstrated:

1. **High-rate DTN:** DTN operated over 900 Mbps to/from the ISS and ground network over the ILLUMA-T and LCRD optical links.
2. **Bundle Protocol Version 7 Demonstration:** Bundle Protocol version 7 was demonstrated, which has not previously been in use on the ISS.
3. **Bundle Protocol Security Demonstration:** Bundle Protocol Security was demonstrated in space.
4. **4k Video Streaming:** Video streaming was demonstrated between the ISS and PC-12 aircraft.

3.4 Technology Educational Satellite 11 Networking Experiment

The Technology Educational Satellite (TES) [29] series, a joint project between NASA Ames Research Center, space agencies, and educational institutions, utilizes the CubeSat platform to enable rapid development of new nanosatellite technologies and capabilities, with a strong emphasis on enhancing satellite operations. NASA Glenn Research Center and Ames Research Center (ARC) collaborated on two different CubeSat Experiments. The first was TES-13, which focused on testing experimental neuromorphic processors for high performance computing in low size, weight, and power in the space environment [30] and development of an S-band demodulation pipeline for commercial ground stations such as Amazon Web Services [31]. The second CubeSat, TES-11, added additional capabilities to the S-band demodulation pipeline, demonstrated user initiated services (UIS) and a delay tolerant networking experiment utilizing HDTN [32]. Final results from TES-11 will be detailed in future works, however a short summary is included here.

Experimental Setup The TES-11 CubeSat hosted the UIS client and the HDTN flight node which are both controlled via flight software developed by ARC, called TES-OS. The UIS and DTN experiments were completed separately in a phased approach. The DTN experiment was focused on enhancing the TES-11 onboard S-band radio interface to encapsulate network packets and enable real-time packet processing capabilities in demodulation pipeline to support a "networked" style of communication. Previously, VITA Radio Transport (VRT) encoded digital intermediate frequency (IF) samples were post-processed immediately after a pass was completed. The HDTN software was integrated into the

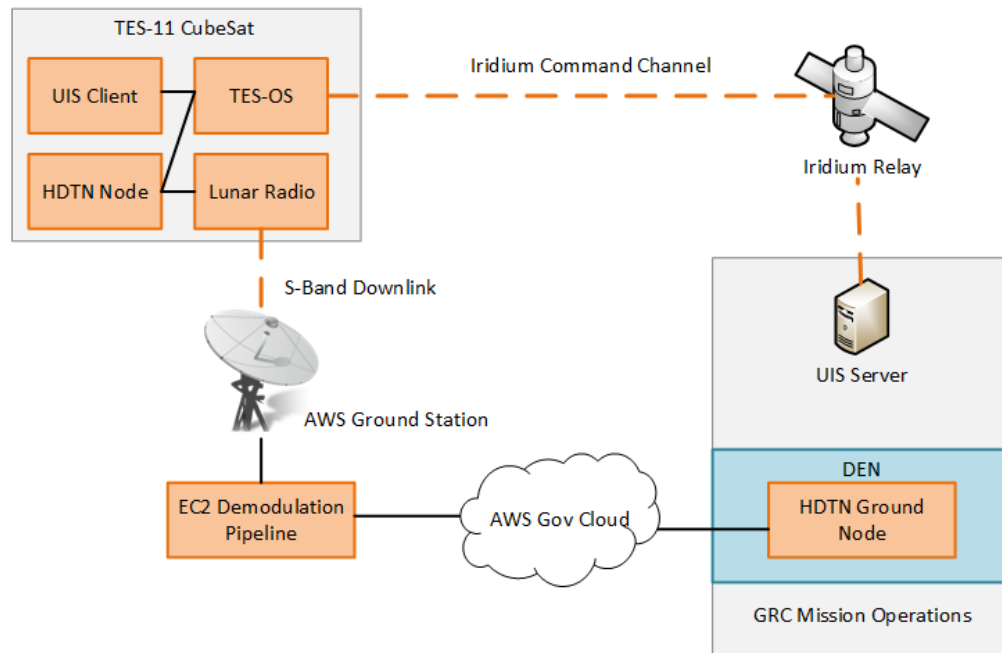


Figure 4: TES-11 Network

TES-OS framework with commands to start and stop communication and to receive contact plans. This was done to achieve the initial steps to enable DTN on TES-11. Additional goals included integrated testing with UIS to automated downlink scheduling, and adding DTN nodes to the ground network utilizing the DEN to emulate data delivery to a user from the mission operations center. The experiment concept of operations including the DEN is shown in Figure 4.

Results and Insights The TES-11 delay tolerant networking experiment successfully demonstrated:

1. **Bundle Protocol Version 7:** The HDTN software successfully transmitted Bundle Protocol version 7 bundles from TES-11 which were decoded by the AWS pipeline.
2. **DTN with Commercial Ground Station:** AWS ground station and GovCloud were used to provide the ground network infrastructure utilizing HDTN as the ground and user nodes.
3. **CubeSat S-band Radio Downlink into the DEN:** Bundle were successfully received from TES-11's S-band radio through AWS services into the DEN.

4 Conclusions

Recent DTN experiments have demonstrated advanced capabilities including high-rate gigabit per second data transfer, real-time streaming of high definition video, security, automation, and integration with commercial clouds and ground stations. Additional testing could be done to demonstrate network management, additional user applications, improved quality of service and resource allocation capabilities. The current baseline of supported features including Bundle Protocol version 7 and Licklider Transmission Protocol have been demonstrated in a variety of flight scenario and platforms. DTN has been deployed to operational networks and mission, as plans for building the interplanetary internet evolve.

References

- [1] Nujoud Merancy. *Moon to Mars Architecture Executive Overview*. Tech. rep. National Aeronautics and Space Administration, 2024.

- [2] Michael Zemba et al. *NASA's Lunar Communications and Navigation Architecture*. Tech. rep. National Aeronautics and Space Administration, 2024.
- [3] Kevin Fall. “A delay-tolerant network architecture for challenged internets”. In: *Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*. SIGCOMM '03. Karlsruhe, Germany: Association for Computing Machinery, 2003, pp. 27–34. ISBN: 1581137354. DOI: 10.1145/863955.863960. URL: <https://doi.org/10.1145/863955.863960>.
- [4] NASA Space Communications and Navigation Program. *LunaNet Interoperability Specification*. <https://www.nasa.gov/wp-content/uploads/2025/02/lunanet-interoperability-specification-v5-baseline.pdf?emrc=606f95>. Accessed: 2025-3-8. 2025.
- [5] IPNSIG. *Internet Society Interplanetary Chapter*. URL: <https://ipnsig.org/>.
- [6] IPNSIG PWG. *Bundle Protocol Implementations*. <https://ipnsig-pwg.github.io/>. Accessed: 2023-12-27. 2023.
- [7] K. Scott, S. Burleigh. *Bundle Protocol Version 6*. URL: <https://datatracker.ietf.org/doc/rfc5050/>.
- [8] S. Burleigh, K. Fall and E. Birrane. *Bundle Protocol Version 7*. URL: <https://datatracker.ietf.org/doc/rfc9171/>.
- [9] B. Sipos and M. Demmer and J. Ott and S. Perreault. *Delay-Tolerant Networking TCP Convergence-Layer Protocol Version 4*. URL: <https://datatracker.ietf.org/doc/html/rfc9174>.
- [10] S. Burleigh and M. Ramadas and S. Farrell. *Licklider Transmission Protocol (LTP)*. URL: <https://datatracker.ietf.org/doc/rfc5326/>.
- [11] E. Birrane and K. McKeever. *Bundle Protocol Security (BPsec)*. URL: <https://datatracker.ietf.org/doc/rfc9172/>.
- [12] G. Araniti and N. Bezirgiannidis and E. Birrane and I. Bisio and S. Burleigh and C. Caini. *Contact graph routing in DTN space networks: overview, enhancements and performance*. URL: <https://ieeexplore.ieee.org/document/7060480>.
- [13] The Consultative Committee for Space Data Systems. “CCSDS File Delivery Protocol (CFDP)”. In: *CCSDS Blue Book* (2020). URL: <https://public.ccsds.org/Pubs/727x0b5.pdf>.
- [14] The National Aeronautics and Space Administration. *Technology Readiness Levels*. URL: <https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/>.
- [15] Jay Wyatt et al. “Disruption Tolerant Networking Flight Validation Experiment on NASA’s EPOXI Mission”. In: *2009 First International Conference on Advances in Satellite and Space Communications*. 2009, pp. 187–196. DOI: 10.1109/SPACOMM.2009.39.
- [16] Rachel Dudukovich et al. “Advances in High-Rate Delay Tolerant Networking On-Board the International Space Station”. In: *2024 IEEE Space Computing Conference (SCC)*. Los Alamitos, CA, USA: IEEE Computer Society, July 2024, pp. 9–16. DOI: 10.1109/SCC61854.2024.00008. URL: <https://doi.ieeecomputersociety.org/10.1109/SCC61854.2024.00008>.
- [17] Marius Feldmann et al. “Ring Road Networks: Access for Anyone”. In: *IEEE Communications Magazine* 60.4 (2022), pp. 38–44. DOI: 10.1109/MCOM.001.2100835.
- [18] Lloyd Wood et al. *Use of the Delay-Tolerant Networking Bundle Protocol from Space*. Technical Memorandum. Apr. 2009. URL: <https://ntrs.nasa.gov/api/citations/20090020378/downloads/20090020378.pdf>.
- [19] Andrew Jenkins et al. “Delay/Disruption-Tolerant Networking: Flight test results from the international space station”. In: *2010 IEEE Aerospace Conference*. 2010, pp. 1–8. DOI: 10.1109/AERO.2010.5446948.
- [20] Adam Schlesinger et al. “Delay/Disruption Tolerant Networking for the International Space Station (ISS)”. In: *2017 IEEE Aerospace Conference*. 2017, pp. 1–14. DOI: 10.1109/AERO.2017.7943857.
- [21] A. Hylton et al. *New Horizons for a Practical and Performance-Optimized Solar System Internet*. URL: https://ntrs.nasa.gov/api/citations/20220003634/downloads/AeroConf_2022___New_Horizons_20220228.pdf (visited on 03/01/2022).

- [22] Inkyu Kim, Sang Ik Han, and Dongsoo Har. “Operational Tests for Delay-Tolerant Network between the Moon and Earth Using the Korea Pathfinder Lunar Orbiter in Lunar Orbit”. In: *Electronics* 13.15 (2024). ISSN: 2079-9292. DOI: 10.3390/electronics13153088. URL: <https://www.mdpi.com/2079-9292/13/15/3088>.
- [23] D3TN. *A Milestone in Space Communication: Successful Interoperability Testing with the Lunar IceCube*. Accessed on 2-14-25. 2023. URL: <https://d3tn.com/blog/posts/2023-08-31-lunaricecube-experiment/>.
- [24] Felix Walter et al. “The Architectural Refinement of μ D3TN: Toward a Software-Defined DTN Protocol Stack”. In: *2024 IEEE 10th International Conference on Space Mission Challenges for Information Technology (SMC-IT)*. IEEE, 2024, pp. 161–170.
- [25] Marius Feldmann et al. “Ring road networks: Access for anyone”. In: *IEEE Communications Magazine* 60.4 (2022), pp. 38–44.
- [26] NASA Glenn Research Center. *High-Rate Delay Tolerant Network*. URL: <https://github.com/nasa/HDTN>.
- [27] Alan Hylton et al. “The International Space Station, Optical Communications, and Delay Tolerant Networking: Towards A Solar System Internet Architecture”. In: *41st International Communications Satellite Systems Conference (ICSSC) and 29th Ka and Broadband Space Communications Conference (KaBSC)*. 2024.
- [28] Alan Hylton, David Israel, and Mikael Palsson. “Laser Communications Relay Demonstration: Experiments With Delay Tolerant Networking”. In: *40th International Communications Satellite Systems Conference (ICSSC)*. 2023.
- [29] Gianine Figliozzi and Frank Tavares. *What are NASA’s Technology Educational Satellites?* Accessed on 2-18-25. 2022. URL: <https://www.nasa.gov/centers-and-facilities/ames/what-are-nasas-technology-educational-satellites/>.
- [30] Nayim Rahman et al. “Neuromorphic Hardware in Outer Space: Software Defined Networking Executed on an In-Orbit Loihi Spiking Processor”. In: *2023 IEEE Cognitive Communications for Aerospace Applications Workshop (CCAAW)*. 2023, pp. 1–5. DOI: 10.1109/CCAAW57883.2023.10219299.
- [31] Adam Gannon et al. “Cloud-Based Demodulation and Data Distribution of a Satellite Downlink”. In: *2023 IEEE Cognitive Communications for Aerospace Applications Workshop (CCAAW)*. 2023, pp. 1–5. DOI: 10.1109/CCAAW57883.2023.10219312.
- [32] Rachel Dudukovich et al. “TechEdSat-11: Prototyping Autonomous Communications in Orbit”. In: *2024 Small Satellite Conference*. 2024.