Advances in High-rate Delay Tolerant Networking On-board the International Space Station

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***Abstract*—The High-rate Delay Tolerant Networking (HDTN) project at the NASA John H. Glenn Research Center (GRC) is developing a performance optimized Delay Tolerant Networking (DTN) implementation which is able to provide reliable multi-gigabit per second automated network communications for near-Earth and deep space missions. To that end, this paper provides an overview of the testing and integration efforts culminating in a high-rate DTN demonstration onboard the International Space Station (ISS). Over several years, the HDTN team has performed a series of end-to-end tests between the Software Development and Integration Laboratory (SDIL) at the Lyndon B. Johnson Space Center (JSC) and Marshall Space Flight Center's Huntsville Operations Support Center (HOSC). The testing has focused on a realistic emulation of the ISS Ku-band RF link, which operates at a maximum of 500 Mbps downlink with a 600 ms round-trip time. In this environment, the HDTN onboard gateway has been tested for interoperability with ISS payload nodes and the DTN ground gateway, store and forward capability, reliable transport using the Licklider Transmission Protocol (LTP), and successful recovery from unexpected loss of signal. In addition to integration testing, HDTN has developed a series of software engineering practices to ensure the stability and maturity of the implementation. As the result, HDTN has successfully demonstrated high-rate DTN services onboard the ISS. This paper concludes with a summary of preliminary flight testing results from the Integrated LCRD LEO User Modem and Amplifier Terminal networking experiments.**

***Index Terms*—Delay tolerant networking, optical communication, International Space Station**

I. Introduction

The High-rate Delay Tolerant Networking (HDTN) [1] project at NASA Glenn Research Center (GRC) has been developing a software suite of interplanetary networking protocols and networking framework optimized for high-rate communications. Delay tolerant networking (DTN) is a key technology focused on enabling the future interplanetary internet, supporting programs such as the International Space Station and Artemis. High-rate optical links will enable increased science data return, provide high quality multimedia capabilities essential for human space exploration, and serve as trunk lines connecting the Earth to the Moon. Future space networks are soon to become a combination of commercial service providers, NASA space assets, and international agency partners. This diverse network will require interoperable standards, services which are efficient, reliable, and secure, and solutions for scalable network management. HDTN addresses the basic challenges of the space communication environment (long round trip times, link asymmetry, intermittent connectivity) while providing a framework to address the requirements of the modern space network.

The DTN architecture creates an overlay network that is based upon a protocol data unit known as a bundle [2], [3]. A bundle agent resides at the application layer and encodes user data such as files, packets, and multimedia streams into bundles, which can then be stored to disk, forwarded to intermediate hops, or delivered to the user. The bundle layer provides a common layer among multiple nodes which can then employ a variety of lower layer protocols suitable for both space and terrestrial communication.

This paper details the testing and integration efforts leading toward future infusion of HDTN with the International Space Station (ISS). Testing was conducted at the Software Development and Integration Laboratory (SDIL) at the Lyndon B. Johnson Space Center (JSC) and Marshall Space Flight Center's (MSFC) Huntsville Operations Support Center (HOSC). The testing has focused on a realistic emulation of the ISS Ku-band RF link, which operates at a maximum of 500 Mbps downlink with a 600 ms round-trip time. Additional testing was completed at Goddard Space Flight Center and Glenn Research Center in preparation for the ILLUMA-T mission. ILLUMA-T is anticipated to operate at a maximum of 1.25 Gbps downlink with up to a 4 second round-trip time. The paper discusses the ISS network environment, HDTN flight software overview, SDIL test environment, testing criteria, and results. The paper concludes with a summary of preliminary

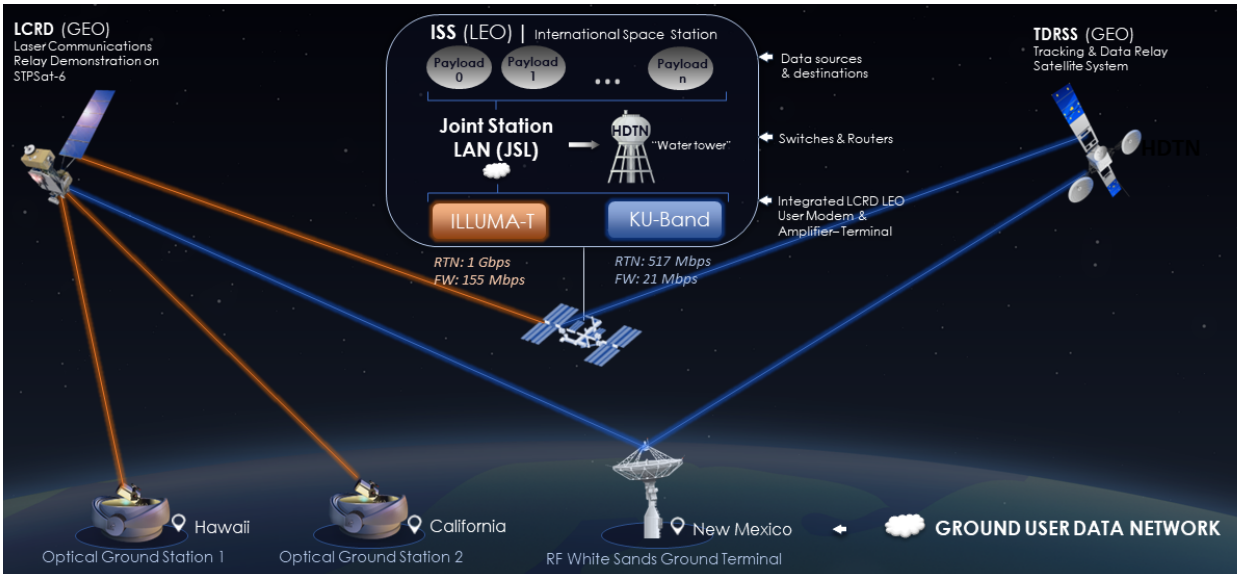

Fig. 1: HDTN ISS Concept of Operations

flight testing results since the HDTN experiment is currently being conducted on ISS at the time of writing.

II. Background

A. ISS Network Scenario

Figure 1 shows the HDTN concept of operations. DTN client nodes consisting of ISS payload science missions and station telemetry applications connect to the HDTN gateway hosted on the Joint Station LAN (JSL) [4]. HDTN stores data in the form of bundles until a communication contact is scheduled. Once a contact begins, HDTN will transmit bundles over Licklider Transmission Protocol (LTP) [5] to the ground. Currently, DTN data is transmitted over the Ku-band link through TDRS during operations, however high-rate optical communication is also available to ISS as part of the Integrated LCRD (Laser Communication Relay Demonstration) Low Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) technology demonstration [6]. The need for highly efficient bundle processing, data storage, and reliable transport required to support high-rate communications provided by ILLUMA-T has been the primary focus of HDTN.

B. HDTN Flight Software

HDTN was specifically designed to support high-rate DTN communication links (greater than 1 Gbps). Multiple implementation concepts were analyzed for efficient data processing, high-rate disk read/write capabilities, and non-blocking operations. Initial trade studies highlighted the need to separate control and data plane messaging, avoid shared memory and locking mechanisms, employ state replication based on an asynchronous message bus framework, and developing a modular and distributed architecture. The high level HDTN architecture is shown in Fig. 2.

The HDTN software package is hosted on NASA's GitHub and has been publicly available since 2021 [7]. HDTN features several applications for encoding and decoding data into bundles and supports Bundle Protocol version 6 [2] and 7 [8]. The main HDTN bundle agent consists of several modules which use a ZeroMQ message bus to exchange state information. The ingress module parses bundle information and supports multiple DTN convergence layers (TCPCL version 3 and 4 [9], UDP, LTP, and STCP). The storage module stores bundles to disk when a link is unavailable and also provides support for DTN custody transfer mechanisms. The router module reads a communication schedule know as a contact plan to determine when data should be stored and released, as well as what destination it should be sent to. The egress module manages outgoing connections and provides real-time link availability status based on a monitoring capability similar to ICMP ping. Additional implementation details regarding the HDTN software can be found in the HDTN User Guide [10].

III. Flight Experiment Preparation

This section covers the test environment and criteria that were used to prepare the HDTN software for deployment to ISS. It provides an overview of the integrated test results.

A. Test Environment

The SDIL test environment was used to emulate the ISS DTN network. The topology and details of the test set up are shown in Fig. 3. The main components consist of one or more emulated onboard DTN client payload nodes, onboard gateway, ground gateway, and one or more ground user nodes. The client payload nodes consist of an HP Zbook laptop that runs the Telescience Resource Kit (TReK) [11]. TReK is used on the ISS to convert user files into CCSDS File Delivery Protocol (CFDP) [12]. TReK also provides an interface to the Interplanetary Overlay Network (ION) [13] DTN implementation which then converts the CFDP packets into bundles. ION

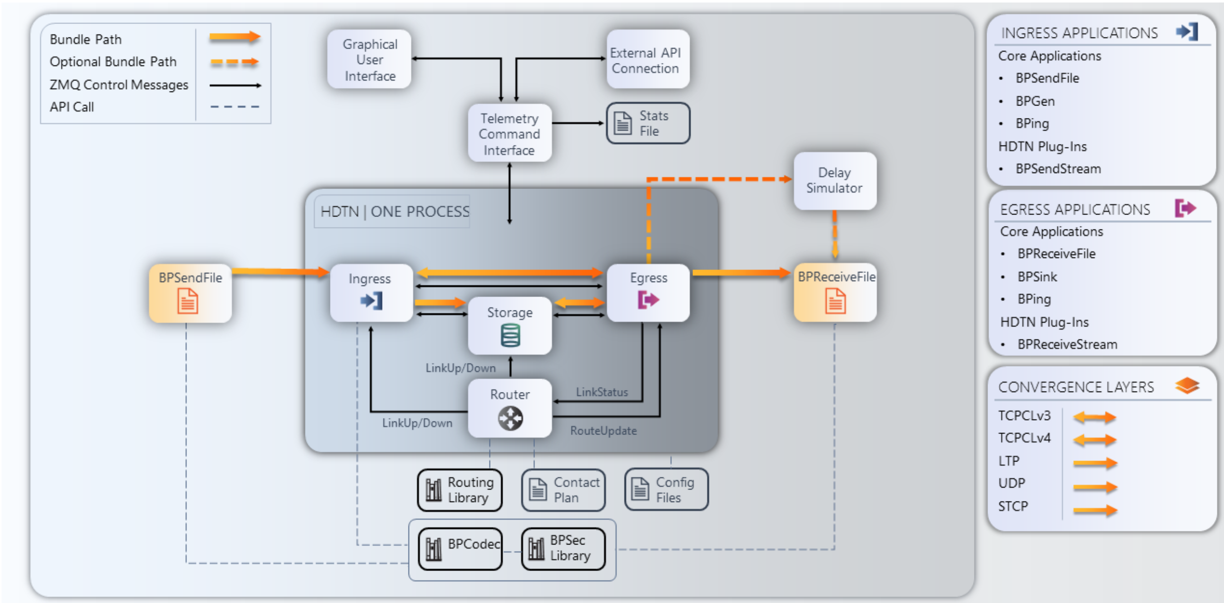

Fig. 2: High Level HDTN Architecture

then uses the STCP convergence layer to transmit bundles to the HDTN onboard gateway. The HDTN gateway uses LTP to send bundles to the DTNME [14] ground gateway. The DTNME gateway then uses the TCPCL convergence layer to deliver the bundles to a TReK ground user node. The ground node uses TReK's ION interface to receive the bundles, decode them back to CFDP and deliver the completed files to the user.

There are two types of tests which were completed. The first is called a "stand-alone" test. In this case, a Linktropy network emulator is used to represent either the Ku-band or optical space to ground link by inducing a specified delay and bandwidth limit in both directions. The space side of the emulation is as described above and the ground gateway and user nodes are similar laptop computers. This is a benchtop test and all network traffic remains in a local network within the SDIL. This type of test serves as a preliminary checkout test used for debugging new features or issues. The second type of test is an "end-to-end" test and incorporates the real HOSC DTNME gateway located at Marshall Space Flight Center. Bundles sent and received by the HDTN gateway located in the SDIL are routed through an emulated Ku-band link on the ground to the HOSC DTNME gateway and the Linktropy emulator is not used. This type of test incorporates several aspects of the real ground network that is used by the ISS. It is a much higher fidelity test and is used once basic issues have been debugged.

B. Test Criteria

The HDTN software was tested for both the ILLUMA-T and Ku-band use-cases. Testing for ILLUMA-T was conducted in the standalone test environment with a 1 Gbps Ethernet link to simulate the optical terminal. In addition, HDTN was rigorously tested for the Ku-band use-case over a period of multiple end-to-end tests. The test team from JSC, GRC, and MSFC completed 15 stand-alone tests and 7 end-to-end tests between 6/2021 and 5/2023. The next section discusses both high-rate stand-alone tests and end-to-end Ku-band emulation tests. Tests were done based on file transfers since file checksums can easily be used to detect that all data was received without corruption. In any case where the checksum fails, the test must be considered invalid and requiring further investigation.

C. High-rate Stand-Alone Tests

The high-rate standalone tests were conducted to support ILLUMA-T. In this case, the Linktropy network emulator was configured for 1 Gbps in both directions and a 4 second round-trip time. The 4 second round-trip time is an estimated delay characteristic of the ILLUMA-T hardware and ground components. Data rates for these tests were obtained from the Linktropy web interface statistics. Plots from the Linktropy interface are including in Section III-E Results.

Test Case	Outcome
Downlink 9 GB file	900 Mbps downlink rate
Downlink 2 files (1.8GB and 1GB) simultaneously to 2 different destinations	1000 Mbps downlink rate
Downlink two 9 GB files simultaneously to 2 different destinations	960 Mbps downlink rate
Uplink one 9 GB file	680 Mbps uplink rate

TABLE I: HDTN High-rate Stand-Alone Test Summary

Table I summarizes the basic tests that were conducted. File uplink and downlink were both tested, as well as downlink of multiple files simultaneously to different ground client nodes. There were several parameters in both the HDTN and DTNME LTP configuration settings that required tuning in

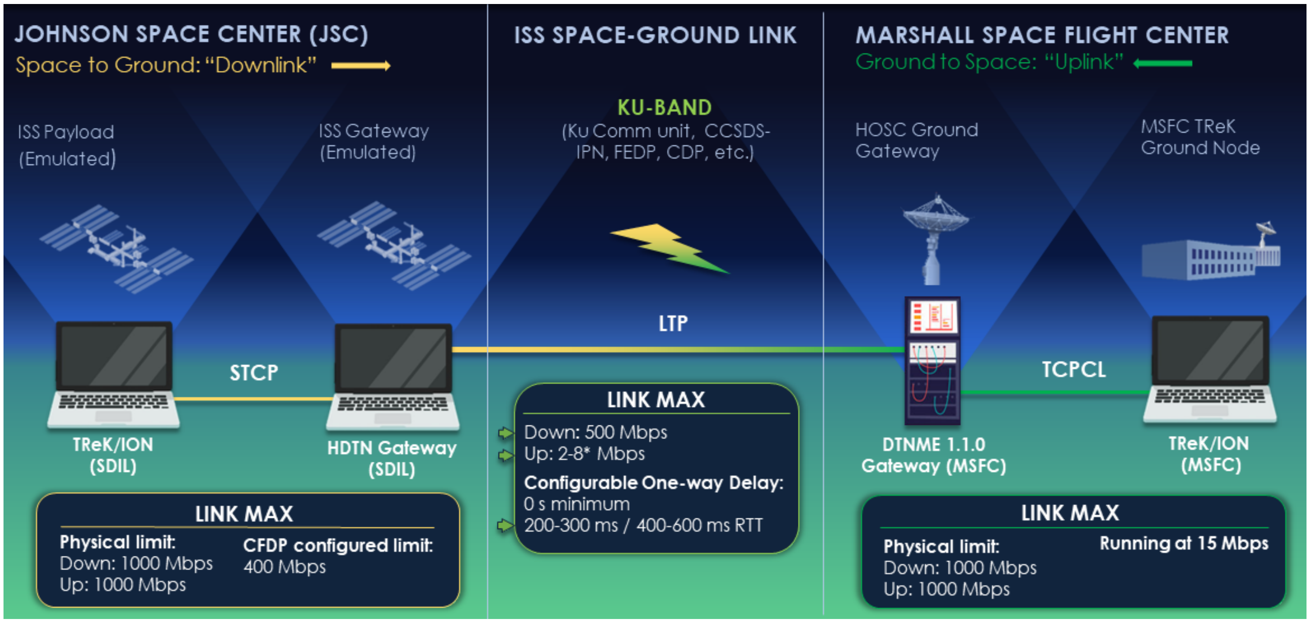

Fig. 3: SDIL Emulated Network

order to achieve optimal performance. HDTN does not currently support LTP bundle aggregation so this feature must be disabled in DTNME otherwise HDTN will report a malformed bundle. The maximum number of simultaneous LTP sessions was configured to 10,000 in HDTN. The LTP segment size was set to 1360 bytes to prevent fragmentation for file uplink from DTNME to HDTN. Also, HDTN supports 64-bit and 32-bit random numbers for LTP identifiers, however DTNME requires this to be set to 32-bits. The HDTN LTP configuration fields were updated significantly from the HDTN beta version that was used for the initial high-rate tests conducted in August of 2022 and final recommended configuration will be discussed in the results section.

The initial high-rate tests demonstrated that HDTN can saturate the 1 Gbps link and is compatible with both ION and DTNME. The next section discusses the high fidelity Ku-band SDIL emulation which was the focus of the rest of the software testing for integration with the ISS DTN network.

D. End-to-End Tests

A series of end-to-end tests were conducted using JSC's SDIL and the HOSC DTNME ground gateway to verify HDTN as much as possible in preparation for integration with the ISS network. The tests were performed at lower rates (typically around 300-425 Mbps) due to the nature of the ISS network. In many cases actual bandwidth for a particular user will be less than the full 500 Mbps Ku-band link since multiple users must share the bandwidth. In the final end-to-end test, the SDIL bandwidth limit was set to 430 Mbps and the HDTN rate limit was set to 425 Mbps as defined in the HDTN contact plan. In this configuration, the average downlink rate was around 436-400 Mbps. A file uplink test was also conducted with the SDIL bandwidth set to 2 Mbps and HDTN uplink rates were observed to be around 2 Mbps.

Table III shows the software functionality that was deemed critical for the HDTN bundle agent. Each feature was verified through end-to-end testing. In addition to interoperability between TReK/ION, HDTN, and DTNME, several features were a focus of the test. The HDTN LTP rate limit was tested from 100-425 Mbps over multiple increments to ensure that LTP traffic will not overrun other users on the network. Both large and small files transfers were conducted over a variety of sizes (25 MB up to 9 GB) to ensure the system is flexible for a variety data types.

The ISS occasionally experiences an unexpected loss of signal (LOS) and this condition was tested thoroughly. HDTN uses an "LTP ping" mechanism to detect when the ground link is available. A timer for the LTP ping is configurable and bundles will be sent to storage once the timer has been exceeded. Once the ping returns, data will begin to be released provided that an active contact is also listed in the contact plan.

E. SDIL Test Results

The results of the high-rate tests are shown in Fig. 4 and Fig. 5. Fig. 4 shows the downlink of two 9 GB files. The 1 Gbps link is fully saturated when both files are being transmitted simultaneously and then drops to around 300-500 Mbps once one file completes. Fig. 5 shows a 9 GB file uplink. The top graph shows LTP acknowledgement traffic from HDTN to DTNME at around 600 Kbps. The bottom graph show the LTP file uplink from DTNME to HDTN at 600 Mbps. Several transmissions were recorded during the plot shown.

The HDTN software matured significantly during the test period between 6/2021 and 5/2023. The HDTN LTP implementation was fully debugged as the result of the tests. The

Test Criteria	Verification	Outcome
Bundle ping	Bundle ping completes round trip between specified source and destination.	Bundle pings are correctly sent/received from all points in the network.
HDTN-ION STCP interoperability	Bundles sent/received with no reported errors.	Minimal configuration required. No issues reported.
HDTN-TReK CFDP compatibility	Bundles sent/received with no reported errors.	HDTN serves as pass-through gateway at bundle layer rather than using native CFDP. No issues reported.
HDTN-DTNME LTP interoperability	Bundles sent/received with no reported errors.	Minor configuration settings required and noted.
Control LTP rate limit	HDTN outgoing data rate reaches but does not exceed the specified limit.	Rate limit tested from 100-425 Mbps for Ku-band.
Small file transfer (25 MB)	Files received with correct checksum.	File sizes tested: 25 MB, 1 GB, 2GB, 4 GB, 9 GB
Large file transfer (9 GB)	Files received with correct checksum.	HDTN is able to saturate link up to 425 Mbps for Ku-band, 1 Gbps for optical
Recover from loss of signal (LOS)	HDTN detects LOS, stores data, and resumes transmission on AOS. File received with correct checksum.	HDTN detects LOS, stores data, and resumes on AOS using LTP ping.
Transfer 2 files simulataneously (2x 2 GB)	Files received with correct checksum.	HDTN supports multiple inducts and outducts.
File Uplink (2 Mbps rate limit)	Files received with correct checksum.	Bidirectional end-to-end test completed .

TABLE II: HDTN SDIL End-to-End Test Summary

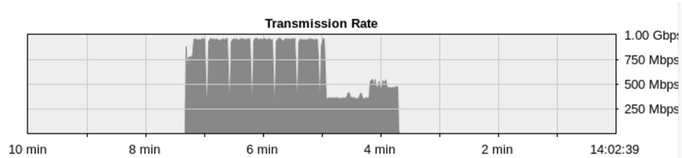

Fig. 4: High-rate Stand-Alone Test - Downlink Two Files

final DTNME configuration was to have LTP aggregation disabled and an inactivity interval of 4 seconds. The HDTN bundle pipeline source code was significantly updated to feature new parameters “maxNumberOfBundlesInPipeline” and “maxSumOfBundleBytesInPipeline” to control the queuing of data. The storage, egress, and router modules were updated to detect and handle the unexpected LOS condition. HDTN requires both the LTP ping mechanism and an active contact in order to release data. If either condition is not present, data will be stored. Several HDTN web interface pages were developed, as well as multi-level logging and statistics recording to assist with network troubleshooting. It should be noted that although HDTN implemented both Bundle Protocol version 6 (BPv6) and version 7 (BPv7), only version 6 was tested during the early flight preparation tests with SDIL. This is because the ISS team did not use BPv7 onboard at the time of testing.

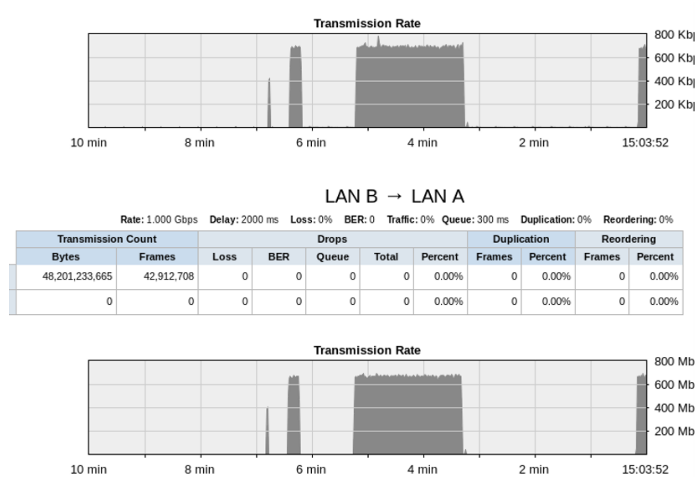

Fig. 5: High-rate Stand-Alone Test - Uplink Several Files

IV. Deployment and Flight Testing

HDTN v1.0.0 stable release was made publicly available in May 2023 as a culmination of the testing activities described in Section III. This version was loaded onto an HP Zbook laptop and configured for the flight build of the high-speed ISS DTN gateway. The laptop and software were successfully

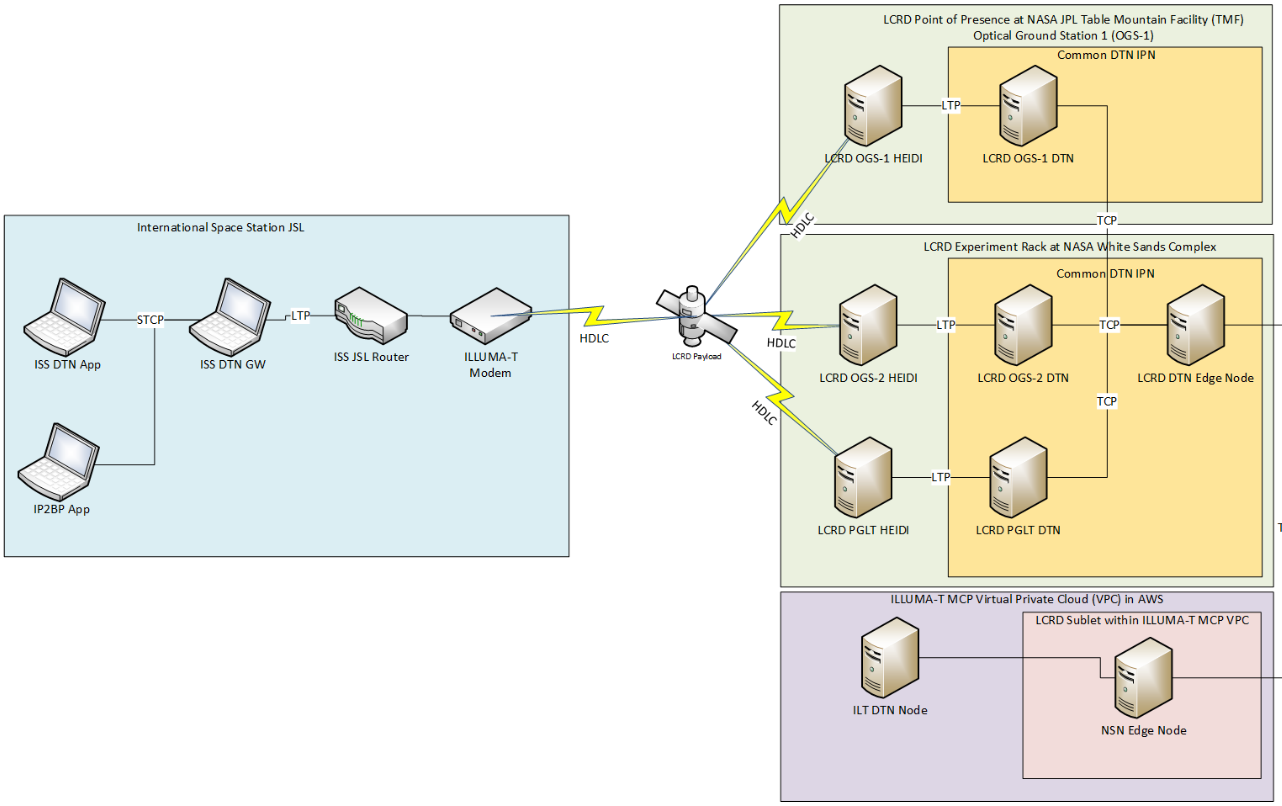

Fig. 6: ILLUMA-T Network Diagram

launched in November of 2023, installed in the ISS Joint Station LAN, and completed preliminary checkout tests. In parallel with this, a phased experiment plan was developed to support an evolving ground infrastructure [15], as well as several HDTN software updates for additional enhancements.

A. Phase 1 Experiments

Phase 1 tests were focused on establishing preliminary DTN traffic from the ISS to the LCRD ground infrastructure. Initial tests began in late March of 2024. In the very first test, HDTN's BPGen bundle generator application was used to generate high-rate test data using the UDP convergence layer. This allowed test data to flow over the optical link without requiring acknowledgements from a ground node. Phase 1 testing continued into early April with bundle pings and DTN file transfers using the LTP convergence layer and Bundle Protocol version 6 from the ISS to the LCRD ground network at the White Sands Complex (WSC). Phase 1 tests used the original ISS HDTN laptop build of HDTN v1.0.0, with only small changes to the configuration files and scripts to account for differences between the test environment and the real LCRD ground infrastructure such as node numbers and IP addresses.

B. Phase 2 Experiments

Phase 2 experiments extended the network from ISS to WSC to NASA Goddard's Mission Cloud Platform (MCP). While initial ground tests were being conducted between WSC and MCP, several HDTN enhancements were in the process of being released and tested. HDTN v1.1.0 was publicly released in January 2024, which included Bundle Protocol Security, an API for updating contact plans and transmission rates, and consolidation of the scheduler and router modules. HDTN v1.1.0 was not available during the final testing and flight build for the experiment laptop that would be launched for the ILLUMA-T experiment at the end of 2023. In addition to the desired new features of HDTN v1.1.0, several smaller changes were added to support ILLUMA-T testing including disabling LTP ping when contacts are not available in the contact plan, a C++ console interface for the API, and minor bug fixes. These improvements were released as HDTN v1.2.0 and v1.2.1 in April 2024. HDTN v1.2.1 was uploaded to the ISS HDTN gateway laptop in May 2024. Prior to this, the HDTN laptop was briefly damaged by a solar event but was repaired.

Once HDTN v1.2.1 was deployed, Phase 2 experiments began in late May 2024. HDTN's BPv6 implementation was used to transfer a total of 51.50 GB of files successfully on a single day. BPv6 testing was completed with bidirectional flow of bundles with and without custody transfer. In addition, BPv7 was used for bidirectional transfer from the ISS to the Near Space Network Edge Node as shown in Fig. 6. This is the first time BP v7 has been used on the ISS and the first time it was demonstrated in space by the United States. Bundle Protocol Security (BPSec) tests are in progress at the time of this paper and will demonstrate the first use of BPSec in space.

Date	Test Milestone	Comments
June 2021	Initial SDIL test	Main HDTN modules completed, additional testing required
August 2022	Onsite SDIL end-to-end test	LTP tested with HOSC, data transmitted one way, additional testing required
May 2023	Completion of SDIL tests	All initial test criteria satisfied, release of HDTN v1.0.0
November 2023	HDTN laptop launched to ISS	Laptop successfully installed on Joint Station LAN
January 2024	Release of HDTN v1.1.0	BPSec capability made publicly available
March 2024	Phase 1 testing	Initial testing between ISS and WSC were successful
April 2024	Release of HDTN v1.2.0	Minor updates to support ILLUMA-T testing
May 2024	Begin Phase 2 tests	HDTN BPv6 and BPv7 demonstrated on ISS
May 2024	Release of HDTN v1.3.0	Provides 4k streaming capability
June 2024	Completion of Phase 2 tests	BPSec testing in progress
June 2024	Planned Phase 3 tests	Future work for 4k streaming

TABLE III: HDTN ISS ILLUMA-T Testing Milestones

C. Phase 3 Experiments

Phase 3 experiments will further extend the ground network from the MCP to the HOSC as well as from the MCP to the DTN Engineering Network (DEN)[16]. In preparation for Phase 3 experiments, HDTN v1.3.0 was released in late May 2024. HDTN v1.3.0 features a new application to stream 4k multimedia files over DTN [17], as well as the ability to edit configuration files via web interface. Streaming over DTN will be tested as part of the later stages of Phase 3 and will continue with a series of tests using the DEN and MCP connection.

V. Conclusion

HDTN is currently deployed (as of June 2024) to the ISS and is being used to conduct high-speed networking experiments as part of the Laser Communications Relay Demonstration and ILLUMA-T. Flight experiment results in this paper are preliminary and will be further expanded to include BPSec testing, 4k video streaming, and an overall discussion of the final data rates acheived during the experiments. The final results of Phase 2 and Phase 3 tests are out of the scope of this paper, which details the flight preparation tests, software development timeline, and early results. Additional testing using the DEN, MCP, NSN, LCRD, and GRC's PC-12 aircraft are planned for mid-2024. Even with preliminary results at this time, HDTN has demonstrated BP v7 onboard ISS which is a major milestone for DTN. In addition, the software is undergoing verification and validation according to NASA Procedural Requirements 7150.2D Class B to support large-scale non-human space rated systems. .

Acknowledgment

The authors would like to thank the NASA Space Communications and Navigation (SCaN) program, and in particular Philip Baldwin (NASA/HQ) for supporting this work.

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