

Development Status of JAXA's DTN Implementation supporting BPv7

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Abstract

Interplanetary Internetworking is envisioned as a network architecture for communications between Earth and other planets in future international space exploration. The Delay and Disruption Tolerant Network (DTN) is a network technology, designed to cope with long delays and intermittent connections, and is expected to be the technology needed to realize Interplanetary Internetworking. The Bundle Protocol (BP) is one of the core protocols of the DTN, and a recommended standard for BP version 7 (BPv7) is currently being developed by the Consultative Committee for Space Data Systems (CCSDS). BPv7 is planned to be adopted for future missions, including the Artemis program. Japan Aerospace Exploration Agency (JAXA) has developed a prototype called "DTN Autonomous System Hub (DASH)" that supports the proposed BPv7 standard in CCSDS and runs in a Linux environment. We evaluated the feasibility of protocol specification, its performance, and confirmed a throughput of 700 Mbps over 10 Gigabit Ethernet between two Linux-based workstations. Finally, prior to the interoperability testing between multiple implementations at CCSDS, we internally conducted preliminary interoperability testing between DASH and NASA's Interplanetary Overlay Network (ION), focusing on the mandatory requirements of the standard. The testing was successfully completed. To assess the performance improvement of DASH on the System-on-a-Chip (SoC) from that on the Linux-based workstation, performance experiments were conducted using two DTN nodes over 10 Gigabit Ethernet. The results of these experiments showed that the average throughput of DASH on the SoC was 5.6 Gbps, which was much higher than that on a Linux-based workstation. In addition, JAXA, NASA and ESA are actively working on developing CCSDS BPv7-compliant DTN implementations. One purpose of this study is to actively contribute to international standardization efforts by conducting interoperability tests with another implementations in advance.

Keywords: DTN, Interplanetary Internetworking (IPN), SoC, FPGA, BPv7, Interoperation

Acronyms/Abbreviations

JAXA: Japan Aerospace Exploration Agency
DTN: Delay/Disruption Tolerant Networking
SoC: System-on-a-chip
BPv7: Bundle Protocol version 7
FPGA: Field Programmable Gate Array
RTOS: Real-time operating system
CCSDS: Consultative Committee for Space Data Systems
DASH: DTN Autonomous System Hub
Gbps: gigabits per second
Mbps: megabits per second
kbps: kilobits per second
MB: megabytes
KB: kilobytes

1. Introduction

DTN is an internetworking protocol suite that exhibits tolerance for delay and disruption, thereby enabling communication even in environments characterized by significant delays and interruptions. The Interagency Operations Advisory Group (IOAG) has published a document entitled "The Future Lunar Communications Architecture," in which they propose the creation of an Earth-Moon Internet-like network with a considerable latency

impact [1]. The objective of this initiative is to construct an Internet-like network in the Earth-Lunar region, where latency is particularly high.

Recently, the transmission rate of ALOS-4, an earth observation satellite launched by JAXA in 2024, was 3.6 Gbps utilizing the Ka-band [2]. This throughput was certified by Guinness World Records on July 23, 2024, as “the fastest RF direct downlink speed from an Earth observation satellite to ground stations” [3]. It has been established that high-frequency radio waves, such as the Ka-band, experience attenuation due to factors including rainfall, clouds, the atmosphere, and fog [4-9]. As a result, the bit error rate for high-frequency RF communication satellites tends to be high. In such a communication environment, TCP/IP, which is the de facto communication protocol for the internet, might not work. Therefore, DTN has been attracting attention for years as a key network technology for future lunar and Mars missions, as well as for other missions such as Low Earth Orbit (LEO) or Geosynchronous Earth Orbit (GEO) satellite systems that use Internetworking-based communications.

CCSDS is an international organization that develops standards for space data systems and communications. JAXA has been a participant in the CCSDS DTN Working Group, contributing to the standardization of the DTN recommended standards. To date, JAXA has successfully produced its own DTN protocol suite implementation domestically, which is compliant with the CCSDS recommended standards [10], and has achieved acceleration using SoC [11]. Among the protocols implemented in the DTN implementation, the Bundle Protocol (BP), the core protocol of DTN, conforms to only CCSDS Bundle Protocol Specification Recommended Standard (CCSDS 734.2-B-1) [12] (so-called Bundle Protocol version 6 (BPv6)). In 2022, the Internet Engineering Task Force (IETF), a standards organization for the Internet, has defined BPv7, which will be incompatible with BPv6. In accordance with this release, CCSDS has published the CCSDS Bundle Protocol Specification Draft Recommended Standard (CCSDS 734.2-P-1.1) [13] to make BPv7 a recommended standard and is preparing for interoperability testing to evaluate the validity of the standard.

In this paper, JAXA developed a BPv7-compatible DTN implementation called "DASH" for the purposes of interoperability testing and deployment for hardware acceleration for onboard spacecraft. The configuration of the DASH developed by JAXA is overviewed in Chapter 2. Chapter 3 describes the summary of the preliminary CCSDS BPv7 interoperability testing within JAXA prior to CCSDS. Chapter 4 presents a case study on the evaluation of the performance of DASH, in particular the throughput when it is executed on a Linux-based workstation. Chapter 5 presents the outcomes of the study of accelerating DASH on a SoC. Chapter 6 offers a comprehensive discussion of the preceding chapters, and Chapter 7 offers conclusions.

2. DTN Autonomous System Hub (DASH)

We developed DASH, which is JAXA’s DTN protocol suite implementation. DASH supports Bundle Protocol (BP), Schedule-Aware Bundle Routing (SABR) [14], Licklider Transmission Protocol (LTP) [15]. BP provides end-to-end network services, operating above the data transport services, and store-and-forward network. BP contains the ability to cope with intermittent connectivity, ability to take advantage of scheduled and opportunistic connectivity, custody transfer, and late binding of names to addresses [12]. BPv7 is the latest version of the BP defined by the Internet Engineering Task Force (IETF) as RFC9171, which is not compatible with prior versions such as BPv6 (RFC5050). Recently, CCSDS is tackling BPv7 standardization based on RFC9171 in purpose of space utilization. CCSDS entered an arrangement with the International Standards Organization (ISO) which would allow completed CCSDS standards to be processed and approved as ISO standards. Therefore, published CCSDS standards send to ISO TC20/SC13 as DIS (Draft International Standard) and vote as IS (International Standard). ISO standard is classified as a "de jure standard," defined by a national body. Consequently, to develop CCSDS recommended standards and those applicable implementations are important from the perspective of Technical Barriers to Trade in World Trade Organization (WTO). JAXA has been developing implementations based on CCSDS standards, and DASH was also developed according to the standards defined by CCSDS. Table 2-1 shows the standards of representative protocols which are implemented in DASH.

Table 2-1. Referenced standards in DASH

Protocol	Referenced Standard(s)
Bundle Protocol (BP)	CCSDS 734.2-B-1, CCSDS 734.2-P-1.1
Schedule-Aware Bundle Routing (SABR)	CCSDS 734.3-B-1 [14]
Licklider Transmission Protocol (LTP)	CCSDS 734.1-B-1 [15]

In previous reports, we successfully produced the DTN protocol suite implementation domestically [10], and the implementation achieved the maximum average throughput of 5.7 Gbps on 10 Gigabit Ethernet (57% transfer

efficiency for bandwidth) using the FPGA-based SoC [11]. Both reports are based on BPv6 as a bundle protocol standard.

3. Preliminary CCSDS-BPv7 Interoperability Testing between DASH and ION

Initially, we confirmed the interoperability of the CCSDS-BPv7 standard using two implementations. CCSDS BPv7 (CCSDS 734.2-P-1.1) is a draft recommended standard (Pink Book). In the process of upgrading from CCSDS draft proposed standard to CCSDS recommended standard, it imposes to conduct interoperability testing by different implementations to verify the reliability and conformance of the standards [16]. As a preliminary step to the interoperability testing as CCSDS organization, JAXA internally conducted interoperability testing using two different implementations of BPv7, focusing on the mandatory requirements of the standard. Initially, we confirmed the interoperability of the BPv7 standard using the implementations DASH and Interplanetary Overlay Networking (ION). ION is NASA's DTN implementation, which is open-source software and supports BPv7 [17].

3.1 Configurations of the interoperability testing

Fig. 3-1 shows the configuration of this interoperability test. In this interoperability testing, two implementations, DASH and ION running on Raspberry Pi (Linux OS), were utilized as DTN nodes named "DASH node" and "ION node". The test used a 10 KB dummy file generated with the dd command as the transmission file, and no delays or disruptions were set. In this test, we monitored packets between each DTN node forwarded by the switch, and the "success" or "failure" of the test was determined by observing the logs output by each node and the contents of received packets.

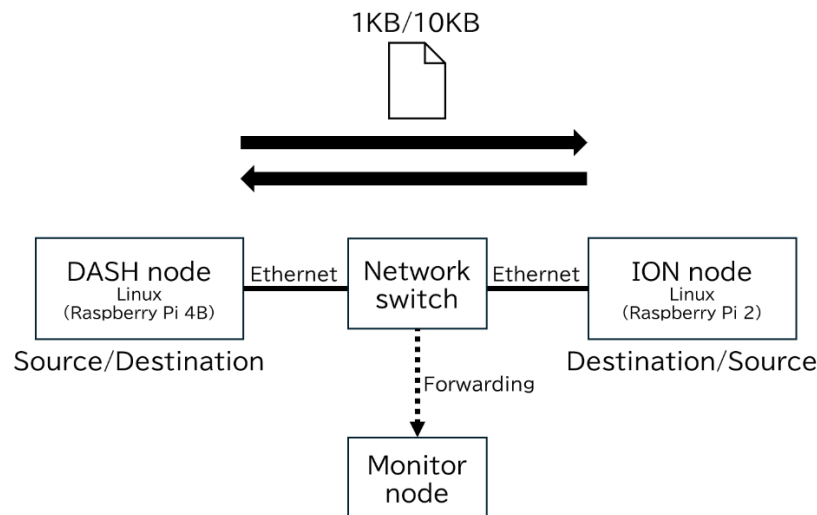


Fig. 3-1. Configuration of the interoperability testing

3.2 Test cases and result of interoperability testing

Test cases were set based on the Protocol Implementation Conformance Statement Proforma (PICS) described in the Pink Book (CCSDS 734.2-P-1.1) ANNEX A. CCSDS PICS was defined by CCSDS Implementation Conformance Statements (CCSDS A20.1-Y-1) [18]. The document adapts portions, relevant for typical CCSDS use, of the ISO/IEC 9646-7 specification for Implementation Conformance Statements. DASH has implemented all the essential features that are outlined in this Pink Book. During our preliminary interoperability testing with the ION implementation, most of interoperability based on PICS were confirmed. Especially, the "Mandatory" items in PICS were executed successfully. However, several test items are identified as "To Be Conducted (TBC)". "TBC" items were here caused by different functions which implementation had been completed and testing environment. Towards planning CCSDS interoperability test plan of the BPv7 standard, further discussion could be needed to clarify and with other implementation developers. The detail correspondence tables between the PICS, test items, and test results that we were conducted is shown in Appendix A and Appendix B. Definition in [18], mandatory is

defined that "Required for interoperability", and optional is defined that "Not necessary for interoperability". Therefore, we concluded our preliminary interoperability testing has mostly succeeded.

4. Performance Evaluation of DASH Running on Linux

We evaluated the performance of DASH running on Linux-based workstation equipped with an Intel Core-i9-10900X Processor and 64GB DDR4 SDRAM. Fig. 4-1 shows test configurations, and Fig. 4-2 shows the distribution of average throughput and LTP segment size on this test case. Each DTN node operated on a Linux-based workstation connected with 10 Gigabit Ethernet cable.

The average throughput for the different LTP segment size was observed at the node when a 10 MB file was transmitted from the source node to the destination node at a bandwidth of 10 Gbps. The average throughput was about 95 Mbps and 600 Mbps at LTP segment size = 1430 Bytes and 8900 Bytes, respectively. As with the ION in the previous study [19], we obtained a tendency for throughput to improve in response to an increase in the LTP segment. We also measured throughput performance of approximately the same order.

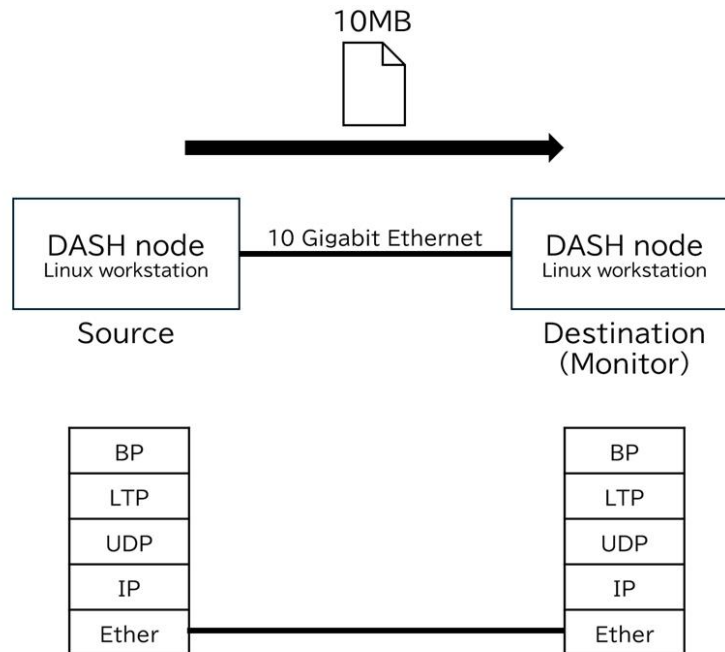


Fig. 4-1. Configuration and protocol stack of the performance evaluation of DASH running on Linux-based workstation

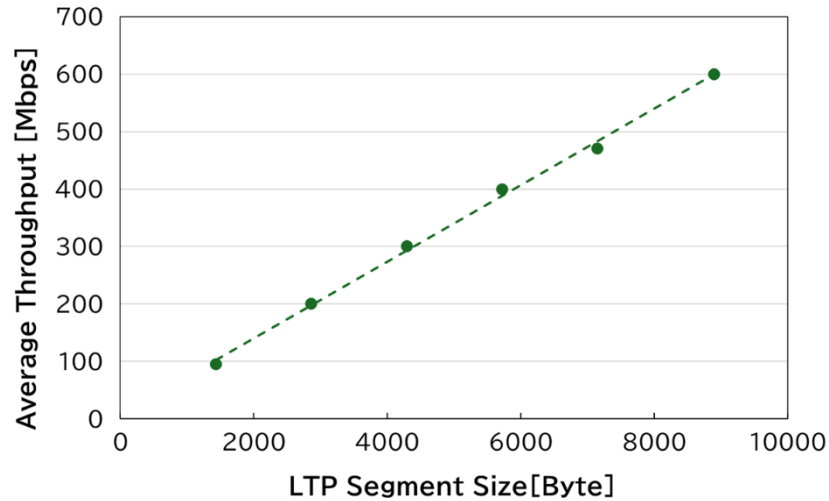


Fig. 4-2. Distribution of average throughput of DASH running on Linux-based workstation and LTP segment size

5. Development and Evaluation of DASH for SoC

FPGAs are often used in spacecraft because of their high processing speed and their ability to modify their logic circuits after deployment. JAXA has developed BPv6-compliant DTN implementations using SoC involving FPGA [11]. The deployment of CCSDS BPv7-compliant DTN implementations for DASH was also conducted with SoC utilized in our prior DTN implementations.

5.1 Implementation of DASH for SoC

The DASH running on SoC was produced by updating some of the functions of a previously developed DTN implementation [11]. Fig. 5-1 shows the implementation architecture of SoC boards used in one DASH node. Each DTN node consists of two evaluation boards: ZC706 for the DTN function and ZCU102 for the receive cache area. DTN functions were offloaded to FPGA by substituting parts of the software-based functions to FPGA. The differences between the previous version of JAXA's DTN implementation and the substituted functions are enumerated in Table 5-1. With the update from BPv6 to BPv7, the encoding and decoding method has been changed from Self-Delimiting Numeric Values (SDNV) to Concise Binary Object Representation (CBOR).

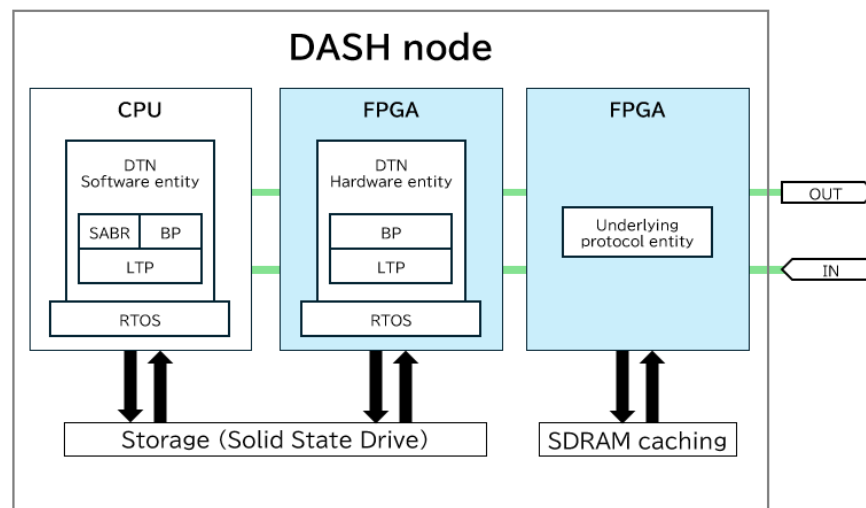


Fig. 5-1. Implementation Architecture of DASH node

Table 5-1. Differences from prior implementations and substituted DTN functions to FPGA

Protocol	Difference(s) from JAXA's prior implementations	Substituted function(s)
BP (BPv7)	Protocol Agent Bundle header generation Bundle header parsing Encode and decode (from SDNV to CBOR)	Bundle header generation Bundle header parsing CBOR encoding and decoding
LTP	-	Encoding and decoding

5.2 Performance Evaluation of DASH on SoC

The performance of DASH on SoC was evaluated with the configuration shown in Fig. 5-2. The DTN nodes were connected via a 10 Gigabit Ethernet cable, and a 10 MB file was transmitted from the source node to the destination node at a bandwidth of 10 Gbps. Fig. 5-3 shows the results of average throughput for LTP segment size using two DASH nodes running on SoCs. The average throughput for the LTP segment size was calculated based on the sending time and reception time shown in the logs of the destination node and the size of the transmitted file. According to Fig. 5-3, the average throughput at LTP segment size = 1430 Bytes and 8900 Bytes was 0.8 Gbps and 5.6 Gbps, respectively.

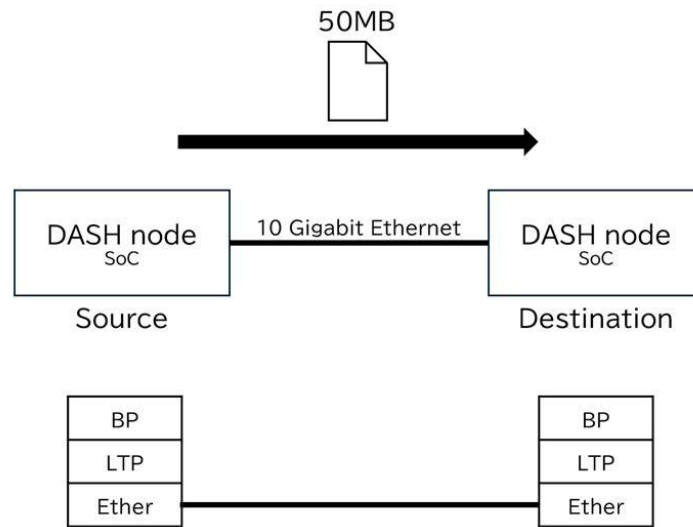


Fig. 5-2. Test configuration and protocol stack running on SoC

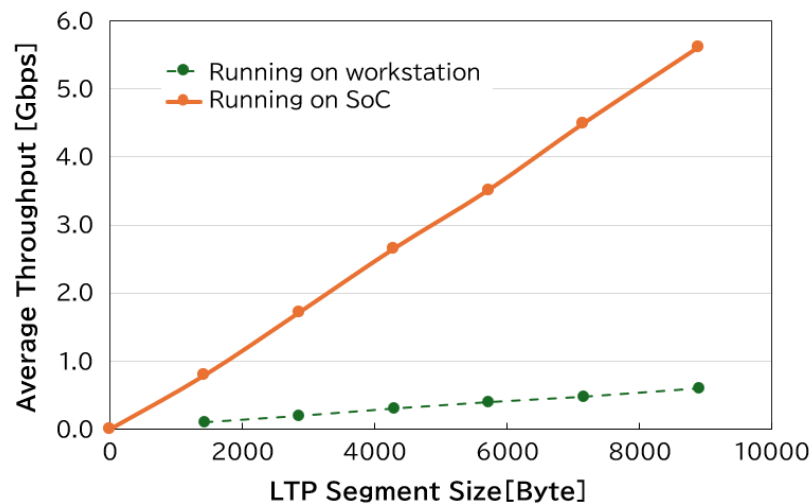


Fig. 5-3. Distribution of average throughput of DASH running on SoC (orange solid line), DASH running on workstation (green dotted line) and LTP segment size

6. Discussion

Our preliminary interoperability testing between DASH and another implementation demonstrated successful compliance with the mandatory requirements defined in CCSDS BPv7. However, it has possibility that confirmation about entire optional things at CCSDS interoperability testing. Therefore, further discussion will be needed within the standardization body regarding optional and some items that are currently identified as mandatory (e.g., MIB), which is required for comprehensive validation toward update from draft proposed standard to recommended standard regarding the CCSDS BPv7 standard. The average throughput of the Linux-based workstation and SoC versions of DASH with a line bandwidth of 10 Gbps was 0.6 Gbps and 5.6 Gbps, respectively at the LTP segment length = 8900 Bytes. The average throughput was improved by 930% by offloading some of the DTN functions. Despite the change in encoding method from SDNV to CBOR, throughput results of BPv7 implementation with SoC are equivalent to previous reports supporting BPv6 implementations [11]. Those throughput results also exceed the ALOS-4 throughput certified by the Guinness World Records. This indicates that hardware acceleration is properly achieved.

We aim to use it as part of the communications payload for unmanned spacecraft, and we intend to further explore the feasibility of implementing DTN on the on-board computer, which is power saving. At the MTU of Ethernet, the efficiency is as low as about 8% of the line bandwidth. As a future, we plan to consider increasing the range of offloading to FPGA and efficient use of CPU resources to achieve higher forwarding efficiency.

To interconnect between Interplanetary Internetwork and terrestrial network, interconnection between the internet and/or mobile telecommunications will be needed from network perspective. For that, with the intention of achieving seamless connectivity with various applications, it is desirable to have various connecting options, not only as convergence layer [12, 13], but also tunneling in-situ network over BP [20].

7. Conclusions

In this paper, we developed two types of DASH, JAXA's BPv7-compliant DTN implementation. One version runs on a Linux-based workstation, while the other runs on an RTOS using SoC.

Our preliminary interoperability testing using the ION implementation demonstrated successful compliance with the most mandatory requirements defined in CCSDS BPv7. Future collaborative efforts with other space agencies will further enhance interoperability and standardization. Furthermore, DASH implemented on the SoC platform was hardware-accelerated with the objective of spacecraft deployment. Consequently, the average throughput of 5.6 Gbps was achieved, which is higher than the throughput of ALOS-4. Furthermore, the transfer efficiency was improved by 930% compared to the version running on Linux.

In order to utilize DASH in space, we plan to continue studying how to accelerate under limited resources and how to interconnect with existed network.

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We thank Mr. Tadakatsu Abe and Mr. Susumu Tezuka for their valuable comments and fruitful discussions.

Appendix A: Correspondence Table Between PICS and Preliminary Interoperability Testing Items

Table A shows the correspondence between PICS and interoperability test items in the Pink Book (CCSDS 734.2-P-1.1).

Table A. Correspondence Table Between PICS and Interoperability Testing Items

PICS Item	Status	DASH Support	Test Item
	M: Mandatory O: Optional C: Conditional		
BP Formatting	M	Y	TC0.a, TC0.b
Previous Node	M (Receive) O (Produce)	Y	TC0.a, TC0.b
Bundle Age	M (Receive) M (Produce)	Y	TC0.a, TC0.b
Hop Count	M (Receive)	Y	TC0.a, TC0.b

	O (Produce)	Y	- (ION is not supported)
BPv7	M	Y	TC0.a, TC0.b
IPN_naming	M	Y	TC0.a, TC0.b
dtm:none	M	Y	TC0.a, TC0.b
IPN Node No	M	Y	TC0.a, TC0.b
IPN Service No	M	Y	TC0.a, TC0.b
Bundle Creation Metadata	M	Y	TC0.a, TC0.b
Source Node ID	M	Y	TC0.a, TC0.b
Support for dtm:none	O	Y	TC0.a, TC0.b
Registration Constraints	M	Y	TC0.a, TC0.b
Minimum Bundle Size	M	Y	TC0.a, TC0.b
Service Interface	M	Y	TC0.a, TC0.b
TCP CLA	O.1	N	-
LTP CLA	O.1	Y	TC0.a, TC0.b
UDP CLA	O.1	Y	TC0.a, TC0.b
Space Packets CLA	O.1	N	-
Generation of Administrative Records	M	Y	TC0.a, TC0.b
Bundle Transmission	M	Y	TC0.a, TC0.b
Forwarding Contraindicated	M	Y	-
Forwarding Failed	M	Y	-
	O (Return to previous node)	N	-
Bundle Expiration	M	Y	-
Bundle Reception	M	Y	TC0.a, TC0.b
Local Bundle Delivery	M	Y	TC0.a, TC0.b
Bundle Fragmentation	O(Support)	Y	-
	C(Procedure)	Y	-
Application Data Unit Reassembly	M	Y	TC0.a, TC0.b
On-Path Application Data Unit Reassembly	O	N	-
Bundle Deletion (Generation of bundle deletion status report)	O	Y	-
Bundle Deletion (Removal of retention constraints)	M	Y	-
Discarding a Bundle with no remaining retention constraints	O	Y	-
Administrative Records	M	Y	TC0.a, TC0.b
Bundle Status Reports	M	Y	TC0.a, TC0.b
MIB_state	M*	N	-
MIB_errors	M*	N	-
MIB_registration	M*	N	-
MIB_CL_info	M*	N	-
MIB_Config	M*	N	-

* The items "MIB_xxx" are discussed to remove them when the draft standard will update.

Appendix B: Preliminary Interoperability Testing Cases and Results

Table B shows preliminary test cases and their respective results.

Table B. Test cases and their respective results

Test No.	Route	Parameter(s), Confirming point(s)	Success/Fail
TC0.a	DASH -> ION	1) Application Data Unit (ADU): 1 KB, Bundle is not fragmented, LTP Convergence Layer (LTPCL), CRC none	Success
		2) ADU: 10 KB, Bundle is fragmented, UDP Convergence Layer (UDPCL), CRC-16	Success
		3) ADU: 1 KB, LTPCL, CRC-32	Success
		4) ADU: 1 KB, LTPCL, Confirm: Acknowledgement of "Bundle Processing Control Frags"	Success
		5) ADU: 1KB, LTPCL, Confirm: Bundle deletion when the bundle exceeded bundle lifetime	Success
		6) ADU: 1KB, LTPCL, Confirm: "Status Repot Request" and "Status Time" flags	TBC
		7) ADU: 1KB, LTPCL, Confirm: Support "dtn:none"	Success
		8) ADU: 1KB, LTPCL, Confirm: Handling the bundles with invalid flags	Success
		9) ADU: 1KB, LTPCL, Confirm: Handling the Block Processing Control Flag and extension block	Success
TC0.b	ION -> DASH	1) ADU: 1 KB, Bundle is not fragmented, LTPCL, CRC-32	Success
		2) ADU: 10 KB, Bundle is fragmented, UDPCL, Primary block: CRC-16, Canonical block: CRC none	Success
		3) ADU: 1 KB, LTPCL, Primary block: CRC none, Canonical block: CRC none	Success
		4) ADU: 1 KB, LTPCL, Primary block: CRC-16, Canonical block: CRC-16	Success
		5) ADU: 1KB, LTPCL, Confirm: Bundle deletion when the bundle exceeded bundle lifetime	TBC
		6) ADU: 1KB, LTPCL, Confirm: "Status Repot Request" and "Status Time" flags	TBC
		7) ADU: 1KB, LTPCL, Confirm: Support "dtn:none"	Success
		8) ADU: 1KB, LTPCL, Confirm: Handling the bundles with invalid flags	TBC
		9) ADU: 1KB, LTPCL, Confirm: Handling the Block Processing Control Flag and extension block	Success

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