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Validation and Demonstration of Disruption Tolerant Networking Technologies in ESA Ground Segment

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Abstract

The relevance of Delay-Tolerant Networking (DTN) technologies for ESA is growing, with application scenarios covering lunar communications, Earth observation missions and optical communication. This paper shows ESA's development and testing effort to bring DTN to an in-flight demonstration. Two CubeSats, ESA's OPS-SAT and NASA's Lunar IceCube have been chosen to demonstrate the software capabilities of the newly developed DTN software stack at ESA. The OPS-SAT and Lunar IceCube DTN demonstrations are explained, as well as the software and infrastructure needed to perform them. The OPS-SAT demonstration's goal is to show the Bundle Protocol (BP) capabilities and how it can benefit future missions. The Lunar IceCube demonstration aims to validate interoperability between four different BP implementations operated by different entities. Extensive testing has been performed in preparation of both demonstrations and the infrastructure appears to be adequate for the task. Unexpected circumstances have delayed the in-flight demonstrations for both CubeSats, nonetheless the performed demonstration trials with the OPS-SAT engineering model and interoperability testing show the readiness of ESA's ground segment implementations.

Keywords: Delay-Tolerant Networking (DTN), Bundle Protocol (BP), Ground Segment Infrastructure, Ground Station Subsystem, Interoperability

1. Introduction

Disruption Tolerant Networking (DTN) technologies are getting more and more attention in the context of future space missions and communication infrastructures. Use cases for DTN technologies include Lunar missions such as the Lunar Gateway and Lunar Communication and Navigation Infrastructure (LunaNet [1], ESA Moonlight) but also future Earth observation missions and optical communication scenarios.

ESA started the development of DTN ground software [2] a few years ago and has released the Java Bundle Protocol (BP) implementation, the DTN Assembly (DTNA) and a Licklider Transmission Protocol (LTP) implementation. Further high-rate implementations and various study activities are on-going. One focus of these activities is to research, prototype, and develop operational ground systems that can become part of the current mission operations infrastructure and can be used in routine operations with a high degree of automation. It is important to demonstrate DTN capabilities in orbit to promote DTN as a viable communication solution for future missions.

In order to validate the ground implementations as well as to gather experience in the set-up and operations of DTN networks, two demonstration activities were planned to take place in 2022 but due to external delays are still being prepared. The set-up, testing, technical challenges, and lessons learned from these demonstrations are presented in this paper.

2. Ground Segment Implementations

The relevant software and technologies are presented in this section, in particular the BP and DTNA implementations are the core ground segment software developed by ESA to support DTN in future missions. This paper expands some of the concepts already presented by Flentge [2] and provides a practical insight into the preparation effort required.

2.1. Bundle Protocol Implementation

The Bundle Protocol implementation (BPI) supports Bundle Protocol version 6 [3] and 7 [4]. It is the first ESA implementation of the protocol, and it is actively maintained as part of the ground segment software systems. Implemented in Java, it offers great flexibility in the network stack configuration and is compatible with any system running a Java Virtual Machine (JVM) with version 11 or above.

BPI implements the core functionalities of the Bundle Protocol and provides modular Convergence Layer Adapters (CLA) that are composed of Convergence Layer Elements (CLEs). Every CLE implement one or more layers of the communication protocol stack. CLEs supporting TCPCL, UDPCL, LTPCL, Consultative Committee for Space Data System (CCSDS) frames, CCSDS packets and Space Link Extension services (SLE) are currently implemented. Using the provided interfaces, a user can implement and run his own CLEs. In theory, a CLE can implement a single layer of the network stack (as the one already provided) or condense multiple layers in a single CLE, which is the case for part of the network stack of the OPS-SAT DTN demonstration (see section 2.1.1). A simplified representation of the network stack and data flow is provided in Fig. 1, where all relevant software is shown and then explained in the following sections.
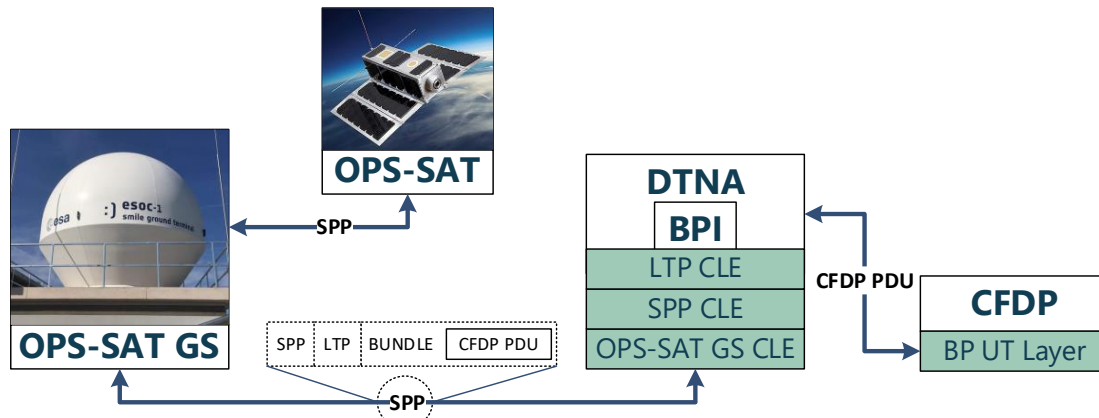
Fig. 1. CLEs stack and data flow in the OPS-SAT DTN demonstration.

2.1.1. *OPS-SAT Ground Segment CLE*

The OPS-SAT ground segment provides a specific interface for running experiments. The data must be provided to the Ground Segment (GS) as Space Packet Protocol (SPP) transmitted over a TCP connection. TCPCL is not supported. Therefore, we developed a specific CLE that is able to manage SPP inside a "pure" TCP connection. Decoupling the two layers is not easy, as the available SPP CLE expect full packets, while TCP provides a stream of data that is incompatible with the current implementation. The OPS-SAT GS CLE, shown at the bottom of the network stack in Fig. 1, provides a solution to interface the current BPI to the OPS-SAT ground segment, acting as a connection layer between the GS and the lower layers of the network.

2.1.2. *CCSDS File Delivery Protocol (CFDP) UT-layer*

The BPI CLA design is inspired by ESA's CFDP implementation [5]. There, the CFDP Unitdata Transport Layers (UT Layers) provide the same kind of flexibility and are highly customizable. One of the objectives of the OPS-SAT DTN demonstration is to perform file transfer using the CFDP protocol but BPI does not provide CFDP capabilities. A mechanism to connect CFDP to BPI was needed, and we decided to develop a specific UT Layer for CFDP. This new UT Layer utilises zeroMQ to connect to the BPI, as required by the BPI client interface. Once connected, CFDP can operate normally and use BP as any other UT-layer to send/receive data. Specifically, it can send CFDP PDUs through the zeroMQ connection and let the BPI take care of their delivery and reception.

2.2. *Licklider Transport Protocol (LTP)*

The LTP implementation has been part of the ESA DTN development effort. It is a smaller project that runs alongside the BPI and provides the functionalities of the LTP protocol as defined in RFC 5326 [6] and even some experimental features that could be relevant for future LTP versions. BPI integrates LTP with its own CLE that can be inserted into any CLA, the LTP CLE is shown at the top of the network stack in Fig. 1.

2.3. *DTNA*

The DTN Assembly (DTNA) is embedding the BPI into a prototype of an operational system which can be deployed in the ground segment. It implements ESA's standard Monitoring and Control (M&C) interfaces for integration into ESA ground stations and provides a web-based user interface for monitoring and control purposes. Providing a familiar user interface to the operators is beneficial for an

easier adoption of the system in future missions. With the DTNA user-interface an operator can monitor all the necessary BP parameters and manage CLAs.

3. OPS-SAT

Launched in 2019, the OPS-SAT CubeSat provides a unique opportunity for ESA and external experimenters to test and validate new operational software and communication protocols without the risk of damaging expensive satellites and equipment [7]. The OPS-SAT mission does not only provide these services to ESA, in fact, a publicly available experimenter platform is accessible to anyone from an ESA member, associate or cooperating state as well as national space agencies, willing to propose and run their own experiment.

3.1. DTN Demonstration activities

The OPS-SAT DTN Demonstration preparation started in September 2020 while both BPI and DTNA were actively developed. The OPS-SAT flatsat provided a good testbed for validation. In combination with the NASA Interplanetary Overlay Network (ION) [8] software integration provided by Hellenic Aerospace Industries (HAI) we were able to continuously test the Bundle Protocol and LTP implementations. This activity provided active user feedback to the BPI and DTNA project during their development, which helped to steer the development into the right direction. To facilitate a broader adoption of DTNA in one of the phases of the OPS-SAT DTN demonstration it is planned to install DTNA directly as part of the ground station systems. This installation will allow to validate further the software capabilities.

The aim of the demonstration is to validate the use of CFDP Class 1 file transfer over Bundle Protocol, possibly over multiple spacecraft passes, in an operational environment. The demonstration setup has been subject to many changes and revisions during the two years of preparation as network setup and policies changed. The DTNA software is installed in a dedicated VM in the OPS-SAT ground segment (SMILE) at ESOC and can connect to the OPS-SAT ground systems and antenna terminal. Later versions of the experiment may install the DTN Assembly directly as part of the ground station and forward data via Bundle Protocol to its destination. The on-board part of the demonstration is managed by Hellenic Aerospace Industries (HAI), who run the NASA ION DTN implementation and connect it to the OPS-SAT CCSDS-based communication stack. The on-board software provided by HAI comprises a set of utilities programmed in python and C that are used to automate the experiment as much as possible as well as to debug problems.

ESA's operational CFDP ground implementation is used to transfer files during the demonstration. We use CFDP Class 1 (unacknowledged), as the LTP protocol provides the transfer reliability. The prepared setup, shown in Fig. 2, allows a bundle node, running DTNA and CFDP, to connect to the OPS-SAT ground segment and send bundles over a network stack composed of CFDP, BP, LTP, SPP and finally TCP. This network stack allows us to send and receive files from OPS-SAT in a reliable way. To accommodate the OPS-SAT ground segment interface requirements, a specific CLE has been developed, which is able to transfer SPP over a TCP connection (see section 2.1.1).
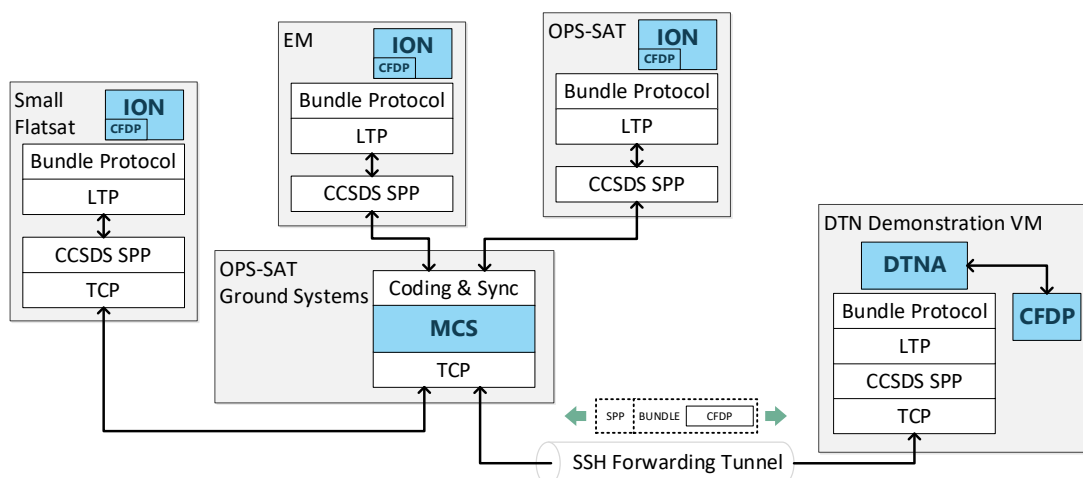

Fig. 2. Testing infrastructure for the OPS-SAT demonstration.

Fig. 2 shows the testing infrastructure for the OPS-SAT demonstration, where a connection is established from a single machine to all the testing infrastructure. The SSH connection to the OPS-SAT Ground Systems can be specifically configured to connect to the Small Flatsat for independent testing, to the Engineering Model (EM) for hardware representative testing with the supervision of the OPS-SAT flight control team, and to flying OPS-SAT itself. On-board NASA ION provides BP and LTP processing and is connected via dedicated software to the OPS-SAT SPP processing.

The in-flight demonstration will include uplink and downlink of files using the described DTN network stack above. One of the objectives is to demonstrate downlink of a single file with parts of the files received at different ground stations. Extensive testing has been carried out with the OPS-SAT ground segment and the Engineering Model (EM) of the CubeSat, in order to understand and configure the network stack in an optimal way. The EM allowed us to simulate the demonstration with a representative on-board part and the actual OPS-SAT ground segment systems. These simulations have been fundamental to define the current network stack, as well as the protocols parameters.

Every test session on the EM needs to be scheduled in advance and is directly supported/monitored by part of the OPS-SAT flight control team. However, the BP software evolved at a rapid pace and required a more flexible testbed. The OPS-SAT team provided independent access to a flatsat running on non-representative hardware, but able to fully reproduce the software stack running on OPS-SAT. Our ability to run continuous tests with this flatsat was of paramount importance for having rapid iterations between development and testing of new functionalities. In fact, the ability to test changes resulted in expanding the demonstration objectives multiple times, e.g. from a single file transfer on a single pass to a multi-pass bidirectional transfer of multiple files.

4. Interagency DTN demonstration

Lunar IceCube [9] is a CubeSat built by Morehead State University to orbit the moon at a low altitude, searching for water ice and other resources on the Lunar surface. It has been launched as a secondary payload of the ARTEMIS-1 Moon mission in November 2022. Unfortunately, communication with the satellite could not be established which prevented the planned and prepared DTN demonstration with Morehead State University (MSU), NASA, ESA and a commercial company - D3TN. These preparation activities and intended further ground-based demonstration within the operational networks are described in the following.

The goal of this second DTN demonstration is to demonstrate interoperability between two agencies using operational networks and include more partners (NASA JPL, Morehead State University and D3TN).
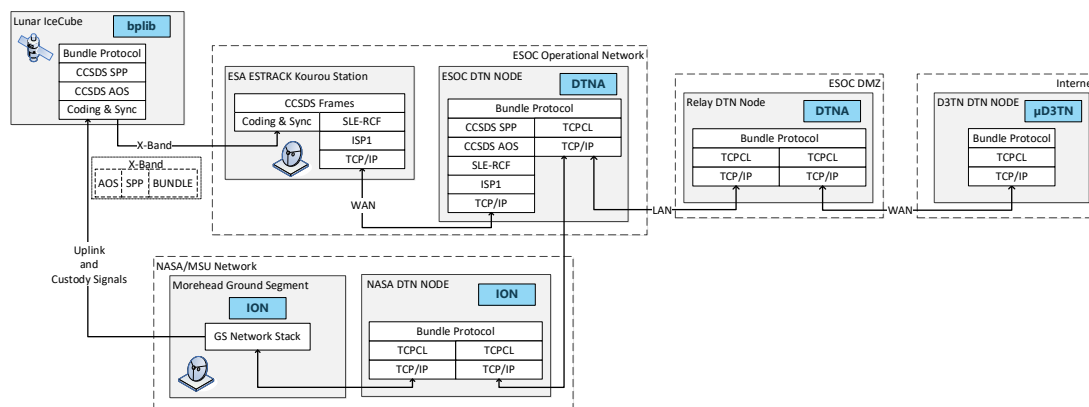

Fig. 3. Interoperability demonstration architecture and network stack

As shown in the demonstration architecture in Fig. 3, Lunar IceCube would downlink bundles in CCSDS Space Packets and AOS frames to the ESA Kourou station, where the frames will be decoded and forwarded via Space Link Extension services to the operational DTN node at ESOC. This node will extract bundles from space packets and forward bundles for NASA DTN nodes to a node at NASA JPL via a TCP Convergence Layer. The NASA node will also create Aggregate Custody Signals (ACS) as this is not supported by the ESA node. For uplinking these to the spacecraft, the signals will be forwarded to a Morehead State DTN node together with the received bundles. The received bundles will be processed and some extracted information will be forwarded back to ESA. From there, this data can be forwarded through a second ESA node in a Demilitarized Zone (DMZ) towards D3TN where some machine learning tasks will be performed on the data. The protocol stacks involve the typical CCSDS

protocols (AOS frames and space packets) on the space link and SLE for retrieving telemetry from the ground station and can be considered representative for typical cross-support scenarios. On ground, BP will make use of TCPCL for reliable bundle delivery. The setup has been quite challenging in terms of secure interconnection. The Downlink/Uplink with two separate antennas is very relevant for demonstrating how DTN can be used in an interagency context.

Although the demonstration could not be performed with Lunar IceCube in space, the preparation and testing activities for the demonstration provide valuable findings for the interoperability aspects of DTN technologies. The activities also resulted in setting-up DTN nodes within the ESA operational networks, which are now available also for other demonstration activities. For the interoperability demonstration, the network setup has been a big challenge, mostly because it requires a connection between two operational networks from two different agencies with very stringent network security policies. The final DTN network setup, shown in Fig. 3, involves six DTN nodes and two ground stations, and has been formally specified in an Interface Control Document (ICD).

Initial testing demonstrated interoperability between four different Bundle Protocol implementations: Lunar IceCube using NASA's bplib [10], ESA DTN Nodes running the DTN Assembly with ESA's Java implementation, NASA JPL and Morehead State University nodes running NASA ION, and finally D3TN with their own µD3TN implementation. In order to assess interoperability, a series of tests have been run between DTNA and all other implementations. This kind of interoperability testing has been useful for all involved stakeholders, as it revealed problems and potential shortcomings of the involved software.

In addition, the Kourou ESTRACK station has been configured to receive Lunar IceCube telemetry data and forward it to the ESA operational DTN node via Space Link Extension (SLE) services. It is planned to perform a full end-to-end data flow test replaying Lunar IceCube telemetry recorded before the launch with a generic satellite simulator at the Kourou station. This test will cover the full data path including the ground station modem receiving recorded AOS frames from a spacecraft simulator.

5. Discussion and lessons learned

Each of the described demonstrations involved a long preparation phase comprising multiple activities and gave us insight into a variety of issues than can arise during complex multi-agencies interoperability activities.

Setting up the required network in an operational context was the most time-consuming task, with the least control from the team preparing the experiments. The network architecture design needs coordination with external entities as well as internal approval in terms of connectivity and firewalls. Specific checks on the installed DTN nodes are required before operational deployment. Finally, the required connectivity to external entities must be put in place and tested in close cooperation with network teams at the external entities.

The elaboration of an ICD is very important for having a single source of information that can be distributed to the involved entities and that provides a clear definition of the network configurations. Having clear specifications of the network architecture and routing is fundamental for understanding the data flows and for testing the setup correctly. The ICD document has been instrumental in multiple occasions for checking the software configurations in case of problems. The document has been maintained to reflect all changes to the demonstration setup in coordination with all involved entities, which ensured that all changes to the demonstration set-up are clarified and endorsed by all affected parties. Further, the document helped newcomers to understand the demonstration setup much faster.

Software testing played a major role in both demonstrations, even if it was performed with different objectives in mind. In the OPS-SAT demonstration, testing the software was part of the development effort of BP and DTNA, and provided findings for software implementation and early design problems. Testing with the spacecraft EM and simulating the relevant aspects of the demonstration before the demonstration with OPS-SAT revealed new details and issues that cannot be reproduced without representative hardware. Hence, this step is always recommended. On the other hand, interoperability testing with external DTN software has been fundamental to setup and configure a larger network of compatible DTN nodes, identify shortcomings in the various software implementations, develop solutions, and get insight into the different design philosophies.

6. Conclusions

DTN technologies are gaining popularity and becoming relevant for a number of applications, and our aim is to demonstrate that they are mature enough for broader adoption. In this paper we have reported on two experiments demonstrating use of DTN with OPS-SAT and Lunar IceCube. The different demonstration setups and systems involved have been discussed, as well as the challenges for

preparing the experiments. Follow-on work is still required to reveal the full potential of DTN through in-flight validation activities. Nevertheless, the results from the test with the OPS-SAT Engineering Model and data samples from Lunar IceCube have revealed that the system design and infrastructure setups for both demonstrations described in this paper are adequate. Hence, building upon the described technology demonstrators, the associated DTN technologies can be utilized within and across space agencies and supporting entities to augment existing and future space systems. The upcoming activities with OPS-SAT and the simulation of the Lunar IceCube demonstration will hopefully show the technology readiness for future missions.

Acknowledgements

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