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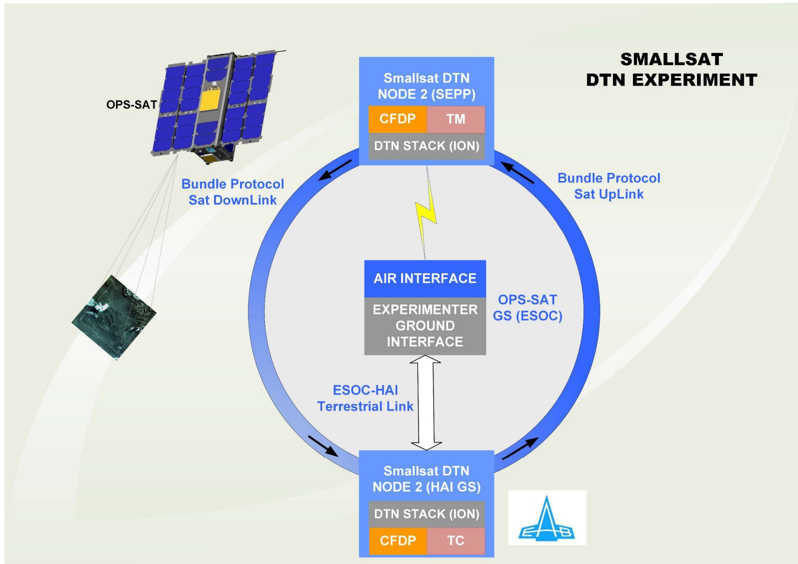

Smallsat DTN

Executive summary

Study

OSIP OPS-SAT EXPERIMENTS CAMPAIGN - STUDIES

Activity summary:

Smallsat DTN is an OPS-SAT experiment awarded funding trough ESA's OSIP, OPS-SAT campaign. The aim of the project is to investigate the benefits of CFDP and Bundle Protocol for satellite operations and their possible applications in the optical communications links, of the future ESA mission of OPS-SAT 2. The Flight Campaign of the project completed in a three-day span, successfully demonstrating the implementation of a LEO DTN network, spacecraft remote control and configuration over Bundle Protocol and CFDP imagery data distribution over multiple passes from the ground segment. Finally, benefits of DTN networking on optical links, in cloud blockage, complete miss of a pass and Variable Data Rates scenarios (relevant to OPS-SAT 2 future ESA mission) were also demonstrated.

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APPROVAL

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Authors	A. Aggelis D. Zagkos
Approved by	C. Vangelatos

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1. Introduction

1.1. Purpose

This document summarizes the work and results of Smallsat DTN ESA project on OPS-SAT. It is not intended to be an exhaustive report of the project results; an interested reader should read the Final Report deliverable of this project.

1.2. Scope

The document may be used as a reference for future mission developers willing to implement an operational DTN network architecture based on ION DTN on Space and/or Ground Segment.

1.3. Document Overview

An overview of the document's structure is given in the following paragraphs.

Section 2: Provides an introduction to the concepts of Bundle protocol (BP), LTP Convergence Layer, CFDP File Transfer Protocol and ION DTN. These are required to understand project's objectives and Smallsat DTN architecture and proposed flight demonstrators, which are also presented in this section

Section 3: Provides a brief summary of Smallsat DTN ground testing phases and methodology

Section 4: The objectives and results of the five DTN demonstration scenarios are presented
Section 5: A brief overview of conclusion, resulted from this work, is given.

Section 6: Opportunities and plans for future work, based on the results of this work are presented.

2. Smallsat DTN System Architecture & Flight Demos Scenarios on OPS-SAT

2.1. DTN Background

2.1.1. Bundle Protocol and LTP CL

The Bundle Protocol (BP [RD-2]) is a network protocol that enables communication in situations where traditional Internet Protocol (IP) communication is not feasible, such as in delay-tolerant networks (DTNs [RD-1]). DTNs are networks where end-to-end communication is not always possible due to frequent network disruptions or long delays.

BP provides a store-and-forward mechanism that allows messages to be sent between nodes that may not be directly connected to each other. When a node receives a message, it stores it in its local buffer until it can forward it to the next node in the path towards its destination. This allows the message to be transmitted even if there are gaps in the network connectivity.

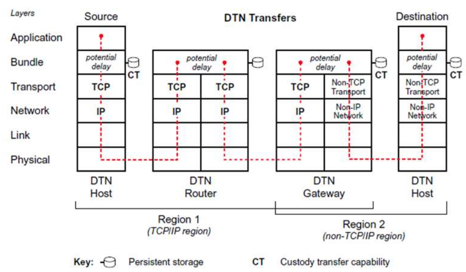

Figure 1 DTN Transfers over regional networks (source [RD-1])

Convergence Layers are a key component of the Bundle Protocol, which is envisioned to be an overlay network and provide the means of encapsulating Bundle Protocol Data over IP and non-IP networks.

One type of BP convergence layer is the Licklider Transmission Protocol (LTP [RD-3]) convergence layer. LTP is a reliable, connection-oriented protocol that is designed to operate over unreliable communication links, such as satellite links or other wireless networks. LTP is particularly well-suited for use in delay-tolerant networks (DTNs), as it can handle long delays and intermittent connectivity. LTP can support both acknowledged (RED Part) and un-acknowledged (Green part) transmission of data.

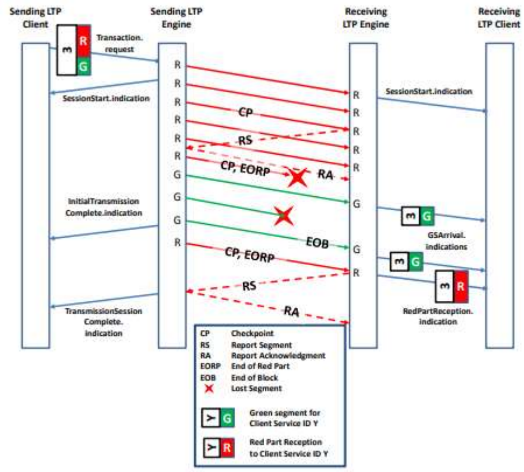

Figure 2 Overview of LTP interactions (Source RD-3)

2.1.2. CFDP over BP

The Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP [RD-5]) is a standard protocol for reliable file transfer in space and other delay-tolerant networks. CFDP defines several service classes, including the Unacknowledged Class 1 service class, which is particularly well-suited for use in conjunction with the Bundle Protocol (BP).

The Unacknowledged Class 1 service class provides a one-way, best-effort delivery mechanism for file transfer. This service class is useful in situations where network connectivity is intermittent and end-to-end acknowledgements are not possible. In this service class, the sender transmits file data to the receiver, but does not expect any acknowledgements or status reports from the receiver.

When used over the BP and a reliable Convergence Layer such as LTP, CFDP Unacknowledged Class 1 can provide reliable file transfer in situations where traditional TCP/IP-based communication is not feasible. The BP allows CFDP to be used in delay-tolerant networks, where there may be long delays or gaps in network connectivity. In this scenario, CFDP Unacknowledged Class 1 can be used to transmit files reliably from one node to another, even when network disruptions or delays are present.

2.1.3. CFDP, BP, LTP and ION DTN

The Interplanetary Overlay Network (ION) software distribution [RD-4] is an implementation of Delay-Tolerant Networking (DTN) architecture [RD-1], as described in Internet RFC 4838. It is intended to be usable in embedded environments including spacecraft flight computers. It implements

- Bundle protocol (BP) v6 (RFC 5050) and in latest version BP v7(RFC 9171)

- Implements LTP (RFC 5326) over UDP as a Convergence Layer and
- CFDP Class1 ([RD-5]) over Bundle Protocol.

For Smallsat DTN, we used ION DTN as the core of our DTN network stack, since it is well suited for installation, in our ground segment as well as in the embedded Linux environment of SEPP on OPS-SAT. ION DTN is written in C and, depending on requirements, may have low memory and CPU usage footprint, making it suitable for low performance embedded systems.

2.2. Smallsat DTN Objectives & System Architecture

Smallsat DTN aimed at implementing a basic DTN network on OPS-SAT with two nodes, one being on OPS-SAT and one on HAI's Ground Segment, using as a basis the ION DTN software distribution. This network architecture is depicted in Figure 3.

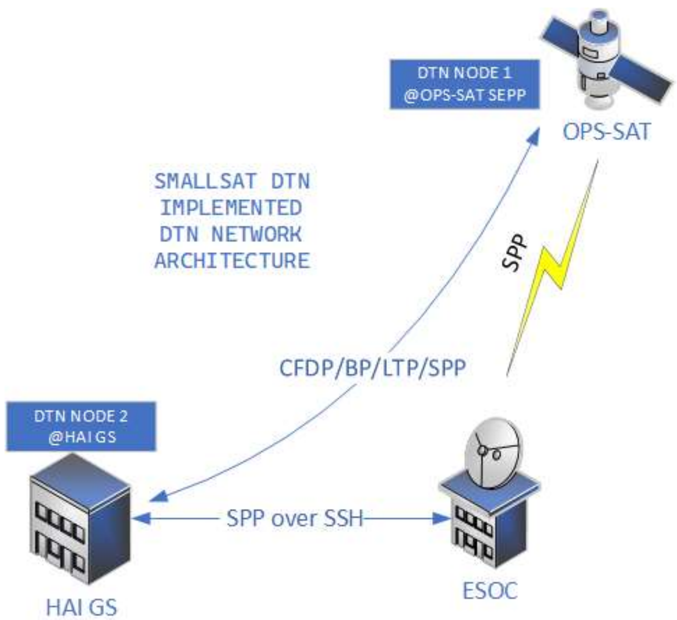

Figure 3 DTN Network of two nodes for Smallsat DTN

Although this is a simple network topology it matches exactly the architecture of the OPS-SAT mission and permits the investigation of a number of interesting Flight Demonstration scenarios for DTNs.

2.2.1. Smallsat DTN Objectives and Scenarios

Smallsat DTN high level objective is to implement on OPS-SAT, using the network presented in Figure 3, demonstration scenarios, relevant to DTN technologies like:

- Data Distribution using ION CFDP over Bundle Protocol with reliability offered by the LTP Convergence Layer
- Tolerance of ION DTN in smalls and large link disruptions
- Satellite and payload remote operations over Bundle Protocol
- Continuous operations of ION DTN stack, on ground and space, in a real operational environment.

During the initial implementation phase of the project, after communications with the ESA DTN team on ESOC, three more objectives were added, relevant to the future ESA mission of OPS-SAT 2 [RD-7]:

1. Disruption in Optical Communications (Cloud Coverage & Complete miss of a pass)
2. Variable Data Rates (VDR) on downlink
3. New generation Consultative Committee for Space Data Systems (CCSDS) protocol stack (DTN)

Although, at first sight, only the last item of the above list aligns with the original DTN objectives of the project, DTN technologies can have positive effect in the first two items also.

2.2.2. Smallsat DTN Architecture

To achieve the project objectives a number of fight demonstration scenarios were developed.

In order to implement the scenarios on the flight demo of Smallsat DTN, a number of software components needed to be developed first. These components along with ION were installed on OPS-SAT satellite On Board Computer called SEPP and in the project's Ground Segment.

The architecture of the system is depicted in the following diagrams of Smallsat DTN Ground and Space Segment.

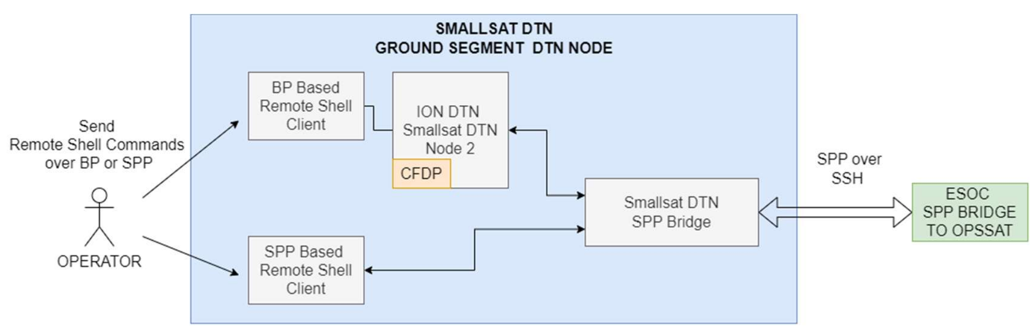

Figure 4 Smallsat DTN Ground Segment Architecture

The ground segment is composed of the following components. ION DTN software distribution, implementing the DTN node on ground. Two remote, tele-command console applications, were developed for Smallsat DTN. The first one sending tele-commands using the Bundle Protocol and ION DTN. The second one encapsulates tele-commands over plain Space Packet Protocol. The final component of the Ground Segment is the Smallsat DTN SPP Bridge that a) multiplexes ION traffic (CFDP and BP Remote Shell) with SPP Remote Shell traffic and b) encapsulates the traffic in Space Packets.

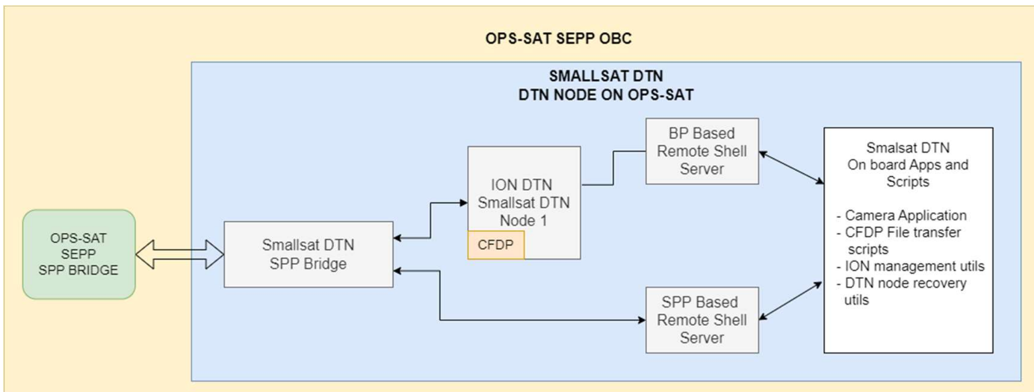

Figure 5 Smallsat DTN Space Segment Architecture

The space segment is composed from the following components. The two "remote shell servers" that receive commands from the relevant "Client" applications over BP or plain SPP. These servers can then execute, Smallsat DTN on board applications and shell scripts and finally send the results as replies to the ground segment.

The on-board Smallsat DTN applications and shell scripts, include among other, ION management remote configurations scripts, a camera application that can be programmed to capture images and send them to ground automatically via CFDP and utils that can recover ION DTN in case some or all of its subsystems fail (including the BP Remote Shell Server). The DTN subsystem, recovery commands can be sent over SPP in cases of Bundle Protocol Path unavailability.

Finally, a procedure to remotely install and configure contact plans in an un-configured ION DTN node was developed and tested successfully.

3. Ground Testing

With the completion of development and local testing of Smallsat DTN software, for the Ground and Space Segment, the ground testing continued on the Small Flatsat and on the Engineering Model (EM) of OPS-SAT (Figure 6).

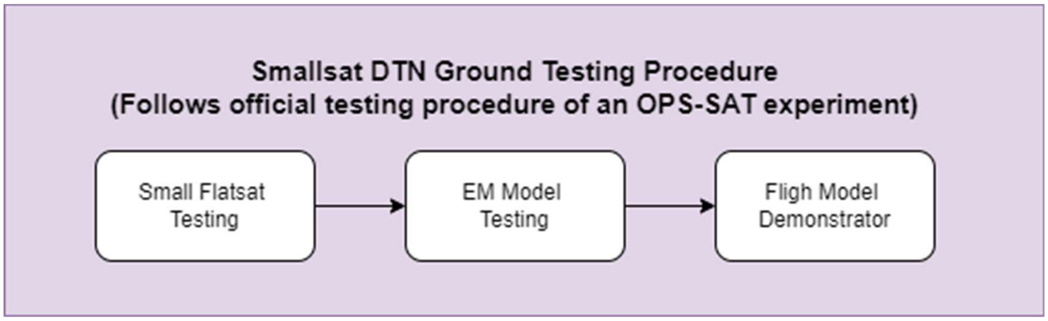

Figure 6 Smallsat DTN Ground Testing Procedure

Initial testing was performed on the Small Flatsat which is a simplified model of OPS-SAT, but its capabilities were enough for the project's functional tests. These tests completed successfully and then testing continued on the Engineering Model of OPS-SAT to tune the Smallsat DTN software for the real hardware (e.g., actual uplink and downlink rates).

During testing in EM, a limitation on the CFDP implementation of ION was encountered. ION CFDP sometimes, may not complete file transfers, in the case of late arrival of CFDP metadata.

ION Development team was contacted and a workaround based on their suggestions was implemented. The LTP convergence layer was configured for very high number of retransmissions, preventing bundle re-ordering, but the subject needs more investigation. The ION development team also mentioned that this CFDP behavior will be addressed in a future version of ION

Besides this CFDP behavior the rest of the systems worked as expected and the decision was made to move to the Flight Demonstrator.

4. Flight Demonstrator

After completing the ground testing sessions, in the Small Flatsat and EM model of OPS-SAT, the Flight Demo was scheduled for 20th of March 2023. The Flight Demonstrator duration span three days and a total of nine passes over the ground segment. During these passes the scenarios, described in the following paragraphs, were demonstrated.

4.1. Scenario 1: CFDP File transfers and BP operations automation

In this scenario a user on Smallsat DTN Ground Segment sent on the 3rd pass, commands to spacecraft, via the BP Remote Shell Client, to capture eight images and download them automatically via CFDP in the upcoming passes.

The commands were sent ahead of satellite pass and were stored in ION DTN storage waiting to be transmitted via BP on the next satellite pass over ESOC, thus demonstrating the decoupling of TM/TC creation and transmission from satellite contact times in a DTN network (BP provided automation).

The Smallsat DTN camera application on spacecraft, captured the images at the scheduled times and 'sent' them immediately to Ground Segment via CFDP. The camera application was unaware of satellite pass times over ESOC. The combination of CFDP, BP, LTP was responsible for automatically storing and forwarding the images to the project's GS, during the following satellite passes from ESOC.

In the passes used for image downloads, we managed to receive the first four of the 8 images and parts of some of the rest. One of the images captured is presented in the following figure and it's download completed on the final pass of the demonstrator.

This file transfer is important because:

- It was captured from a command sent from Ground Segment via BP
- Spanned over multiple passes
- Continued downloading while modifying in real time the ION transmission speed to the ground Segment in Variable Data Rate Scenario
- Survived link disruption in the satellite link (lossy links)
- Survived a complete miss of a pass (from the OPS-SAT 2 scenario from an unforeseen completely missing a satellite pass (OPS-SAT 2 scenario and DTN large unexpected disruptions)

- It was captured via remote command (over BP) from Smallsat DTN GS.

- Downloaded over Multiple Passes (5, 6, 7, 8, 9) automatically via CFDP/BP/LTP.

- The CFDP file transfer survived,

    - small and large RF link interruptions during passes
    - a complete miss of a pass (pass Nr. 7),
    - un-attended passes (passes Nr. 5, 6) and
    - Variable Data Rates scenario on pass 8.

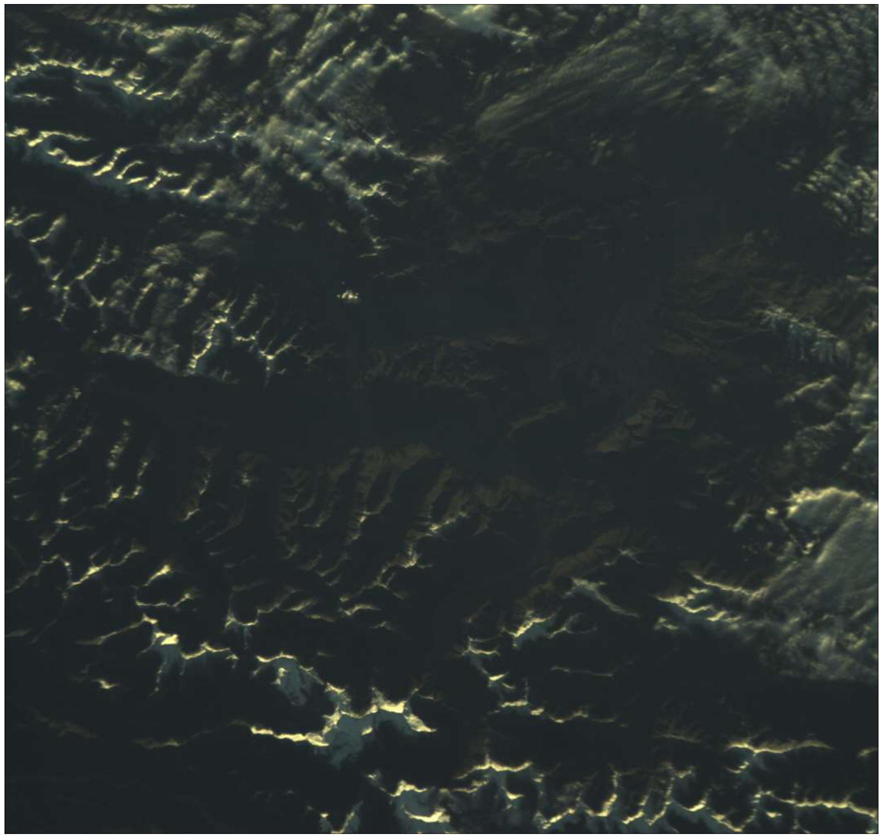

Figure 7 Image of Mountains in New Zealand. Captured via remote command (over BP) from Smallsat DTN GS. Downloaded over multiple passes (passes Nr. 5, 6, 7, 8, 9) automatically via CFDP/BP/LTP. The CFDP file transfer survived, RF link interruptions, a complete miss of a pass (pass Nr. 7), unattended passes (passes Nr. 5, 6) and Variable Data Rates scenario on pass 8.

In this scenario, a large file transfer was also started (pass Nr. 4) from the Ground Segment towards the satellite, to demonstrate multi-pass CFDP upload.

The file continued uploading for the whole demonstrator, but due to its size, the CFDP file transfer did not manage to complete in the remaining passes. Post analysis showed that the largest part of the file was uploaded.

4.2. Optical link blockage due to cloud coverage in part of a pass (OPS-SAT 2 scenario)

This is an OPS-SAT 2 scenario which aims to emulate the link disruption caused in optical links by cloud coverage. This scenario was implemented with the help of luck during the fourth pass of the demonstration.

In ESOC GS there is a specific antenna orientation, that nearby obstacles physically block the signal for several seconds during a pass. This actual link loss, conveniently emulated cloud coverage and link disruption of an optical link. The DTN network survived the disruption continuing the ongoing CFDP file transfers.

4.3. Scenario 3: Full miss of a pass in space-to-ground optical links (OPS-SAT 2 scenario)

This is also an OPS-SAT 2 scenario. In OPS-SAT 2 optical communications, optical link to the ground segment may be missed completely, if the on-board and ground optical terminals of the GS fail to establish a link during the first twenty seconds of a pass.

This scenario was also demonstrated, with the help of an unforeseen event. Due to poor RF-Link at the 7th pass of the campaign, ESOC GS failed to establish connectivity with OPS-SAT and the pass was completely missed.

The DTN network compensated for this unexpected event, because the LTP subsystem was configured for disruptions larger than a typical pass over the ground segment of a LEO satellite.

4.4. Scenario 4: Variable Data Rates during pass (OPS-SAT 2 scenario)

This is the final OPS-SAT 2 related scenario. Currently flying and planned optical LEO DTE systems transmit at a constant data rate. This approach does not exploit optimally the channel capacity [RD-7]. Instead, Variable Data Rates approach, splits the pass of a LEO pass in sectors and optimizes the data rate in each of them.

ION DTN has the capability to modify on the fly, in real time, the transmission rate of its LTP Convergence Layer, without affecting its current data transfers. This configuration change can be triggered by third party software.

During the 8th pass of the demonstrator, in parallel to active CFDP uploads and downloads, the transmission rate of ION DTN on spacecraft was remotely modified on the fly three times with commands sent from the ground segment.

The remote configuration was applied successfully and the modification of data rate on the downlink was immediately visible in the real time TM/TC console of Smallsat DTN Ground Segment.

4.5. Scenario 5: Continuous operation and remote configuration of the DTN network

The goal of this scenario was to run an operational DTN network in a continuous way. This included remote modification of the running ION configuration in addition to being able to recover from unexpected error conditions in a real mission environment.

Some of these concepts were part (and demonstrated) in previous scenarios. E.g., in the VDR scenario ION DTN on spacecraft was remotely configured to alter its running transmission rate of the LTP convergence layer.

One special operation in an ION DTN network, is the update of ION's contact plan. ION software must be informed, ahead of time, with the future contact times to the Ground Station.

For the Flight Demonstrator, ION on spacecraft was originally configured for only the first four passes over the Ground Station (ESOC). To continue operations in the next five passes of the demonstrator, their contact times needed to be uploaded and applied in ION configuration, before the end of the 4th pass.

The new contact plans, were uploaded reliably to spacecraft using ION CFDP at the 3rd pass, and remotely applied at 4th pass of the demonstrator, using project's BP based shell.

One important issue that we encountered during Ground Testing and Flight Demonstrator is that BP based remote commands, even if configured with the highest priority, had significant delays in the presence of parallel CFDP (bulk) traffic. This is something that we did not expect and needs further investigation.

As a workaround Smallsat DTN operations relied on project SPP based shell, to send commands via this alternate path, when real time response was needed. The drawback of this method was that SPP based shell did not provide reliable transfer and either commands, command replies or both may be lost and need to be re-sent.

It is important to notice that since SPP based commanding is unreliable (and commands may be reissued), care was taken that commands changing Smallsat DTN status on Space were idempotent.

Finally, being self-sufficient and autonomous for the operational needs of this experiment, was an important part of this scenario. In case of a crashed DTN stack on OPS-SAT, where BP communications would be lost, a failover procedure was developed. Via project's SPP shell, Smallsat DTN GS could remotely restart the DTN stack and continue BP operations. This was not needed in the flight demonstrator, but it was available in any case. This procedure was demonstrated successfully during ground testing.

5. Conclusions

The scope of this project covered a lot of operational DTN scenarios and its original goals were accomplished. Generic benefits of DTN and CFDP concepts (reliability, tolerance in disruptions, network automation, reliable multi-pass file transfers) in an operational environment were demonstrated, along with three scenarios of DTN usage for the future OPS-SAT 2 mission.

Some problems in the ION-DTN implementation were encountered (CFDP errors when delayed metadata, bundle priorities not working as expected) and workarounds were applied. In general, ION proved to be an invaluable implementation of the DTN architecture. ION proved also light on resource usage (memory and CPU) for the Smallsat DTN use-case.

One thing that its value became obvious is the combination of Linux + ION on space hardware. Practically in this project ION provided BP, LTP and CFDP and Linux provided its invaluable ecosystem.

What also became apparent, is the parallel use of BP based and SPP based remote operations. Since DTN implementations, are still in development software bugs and crashes may appear. Having an alternate way, not based on BP, for remotely recovering the DTN stack in case of malfunctions, is an invaluable tool.

One very important outcome of this demonstrator, is that Smallsat DTN experiment, operated the Flight Demonstrator LEO DTN network, continuously for the duration of three days, handling the unexpected events of real operations (without restarting any of its software components in space or ground segment) and successfully completed the project's demonstration scenarios.

6. Future Work

As a next step following this demonstrator, Smallsat DTN team aims to investigate the issues of CFDP and bundle priorities in ION, encountered during ground testing and flight demo.

There is also, an ongoing common experiment on OPS-SAT, with ESA DTN team. For this joint OPS-SAT experiment, there will be an upcoming flight demonstrator, where HAI will provide the ION DTN Node on OPS-SAT and ESA DTN Team the DTN Node on ground, using ESA's brand-new DTN implementation called DTNA. The goal of this demonstrator will be to showcase besides DTN concepts, interoperability between the used BP implementations and the benefits of common DTN standards in future multi-entities missions

Smallsat DTN team will also work on implementing 'service point' DTN applications like MQTT bridges for ION DTN.

7. Reference Documents

Ref.	Document Title
[RD-1]	F. Warthman. Delay-Tolerant Networks (DTNs): A tutorial, 2003.
[RD-2]	CCSCD BUNDLE PROTOCOL SPECIFICATION, RECOMMENDED STANDARD CCSDS 734.2-B-1
[RD-3]	LICKLIDER TRANSMISSION PROTOCOL (LTP) FOR CCSDS. RECOMMENDED STANDARD CCSDS 734.1-B-1
[RD-4]	https://sourceforge.net/projects/ion-dtn/
[RD-5]	CCSFS FILE DELIVERY PROTOCOL (LTP). RECOMMENDED STANDARD CCSDS 727.0-B-5
[RD-6]	Smallsat DTN Final Report
[RD-7]	CDF STUDY REPORT OPS-SAT-2 Assessment of CubeSat In-Orbit Demonstration experiment CDF-221(A) November 2021

8. Abbreviated Terms

Acronyms	Description
AOS	Acquisition of Signal
BP	Bundle Protocol
CFDP	CCSDS File Delivery Protocol
DTE	Data Terminal Equipment
DTN	Delay Tolerant Networking
LEO	Low Earth Orbit
LOS	Loss of Signal
LTP	Licklider Transmission Protocol
SPP	Space Packet Protocol
TC	Telecommand
TM	Telemetry