Distributed CFDP Ground Infrastructure Implementation for High Data Rate Downlink

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Abstract

ESA's upcoming Copernicus Sentinel Expansion missions will feature very high downlink data rates of up to 7.5 Gbit/s over less reliable K-Band. To facilitate management of these high data volumes and enable automatic re-transmission of lost data, a file-based operations approach based on the CCSDS File Delivery Protocol (CFDP) will be used. However, due to limitations in available terrestrial data rate from ground stations to mission operations and payload processing centres, running a standard CFDP entity centrally and closing the protocol loop in near real-time is not feasible. To allow for such real-time protocol closure and support CFDP transactions even spanning different ground stations, the Distributed CFDP (DCFDP) concept has been developed. The distributed CFDP concept is based on a separation between near real-time protocol closure and a slower, central file re-construction. A Return CFDP PDU service based on the CCSDS Cross-Support Transfer Services framework is defined for returning 'reduced' CFDP PDU from ground stations. These 'reduced' CFDP PDU provide all necessary information for detecting data losses and successfully completing CFDP transactions. Full file re-construction makes use of files of recorded TM or AOS frames which are retrieved from ground stations at a lower rate. Three new systems are currently developed to support this concept and will be deployed in the ground segment: the Ground Station DCFDP system, the Control Centre DCFDP system and the CFDP File Re-construction system.

Keywords: CCSDS File Delivery Protocol (CFDP), Earth Observation Missions, High-Data Rate, Ground Segment Infrastructure, File-based Operations

1. Introduction and Motivation

ESA's planned Copernicus Sentinel Expansion Missions to be launched within the next 5 years will feature high data rate downlinks with up to ~7.5 Gbit/s over less reliable K-Band which is susceptible to sudden and temporary disruptions due to atmospheric and weather effects [1]. To cope with related data losses a mechanism to re-transmit lost data is needed. As all future ESA missions will use a file-based operations approach [2], the acknowledged mode of the CCSDS File Delivery Protocol (CFDP Class 2) [3] can be used to guarantee completeness of downlinked files by means of automatic re-transmission of lost file data.

CFDP Class 2 is based on negative acknowledgements which are generated by the receiving entity checking the file data that has been received. For a timely finalisation of a file transaction, it is required that these negative acknowledgments and a final acknowledgment are send quickly to the on-board CFDP entity. As the data rates on the terrestrial links are often limited to a few 100 Mbit/s to maybe 1 Gbit/s this cannot be achieved within a ground station pass if CFDP is processed centrally within the ground segment. The problem can be solved by reconstructing the file in the ground station as done for ESA's Euclid mission [4]. In this scenario, a complete CFDP entity is running in the ground station and CFDP Directive Protocol Data Units (PDU) are send via the Mission Control System to be uplinked to close the protocol loop. For Earth Observation Missions the routing of CFDP PDU for uplink via the MCS is even more important as TC authentication is frequently used and security keys shall be kept centrally at the mission control centre and not be passed to ground stations. From an operational point of view, it is also beneficial to have a single source for all commanding at the mission control centre to keep a complete overview and have clear responsibility and accountability for all spacecraft operational aspects. However, Earth Observation missions are more constraint than astronomy or planetary missions as they have much shorter (but more frequent) ground station passes which makes it desirable to be able to continue a file downlink that has been started on one station over another station. To avoid passing file transaction related information across the ground segment a central point for CFDP processing to keep the full context of each file transaction is required.

2. Distributed CFDP Concept

The Distributed CFDP Concept has been developed to cover the needs of Earth Observation missions with high-rate downlinks[1]. It is based on the idea of a single ground CFDP entity with specific functionalities distributed across ground stations, mission control centre and file reconstruction (see Fig. 1). From the spacecraft point of view, the ground CFDP entity behaves exactly like a standard CFDP entity and no changes to on-board implementations or the CCSDS standard itself are required. On ground, the concept relies on the separation of real time protocol information for transaction closure (red arrows in Fig. 1) and a slower, offline part for the actual file data retrieval and file reconstruction (blue arrows in Fig. 1). The ground station receives CFDP PDU encapsulated in CCSDS packets and frames from the spacecraft. These CFDP PDU are processed in a dedicated Ground Station DCFDP system which removes the actual file data (i.e., the content of the original file) from CFDP File Data PDU as described in 2.1 below. These 'reduced' CFDP File Data PDU and all CFDP File Directive PDU (Metadata, End-of-File, acknowledgments) are provided via a standardised Return CFDP PDU Cross-Support Transfer Service (see 2.2 below) to the Flight Operations Segment (FOS) in real-time. There the Control Centre DCFDP system receives and processes this protocol information using a slightly modified CFDP Entity able to accept 'reduced' CFDP File Data PDU. This allows to close the CFDP protocol loop and to generate the required Negative Acknowledgment (ie, request re-transmission of lost data), Acknowledgment and Finished PDU and to provide those to a mission control system for multiplexing into the uplink TC stream.

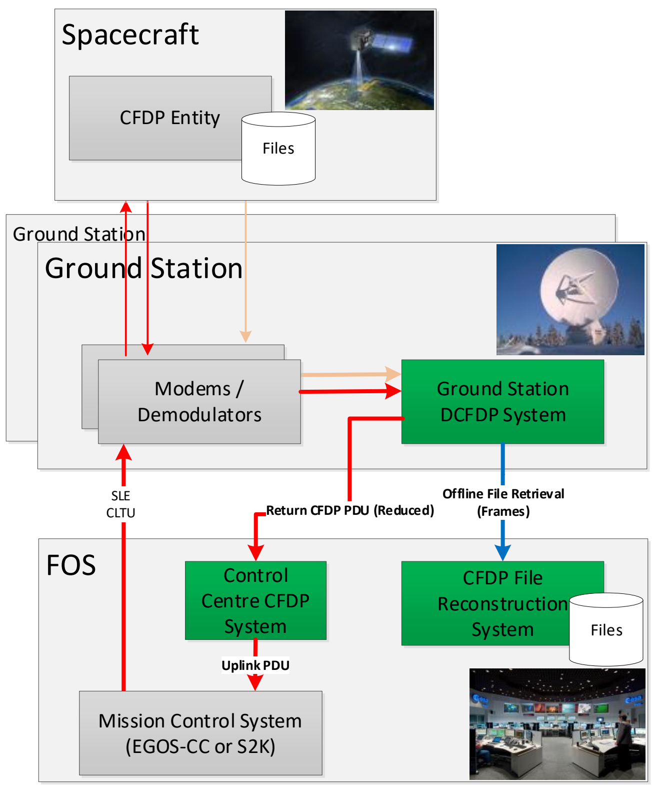

Fig. 1. Distributed CFDP – Ground Architecture. Red arrows show the real-time part while blue indicates offline retrieval. Multiple modems and demodulators may provide input to the GS-DCFDP system.

[1] Alternative concepts based on CCSDS Bundle Protocol (BP) and CCSDS Licklider Transport Protocol (LTP) have also been considered but have been dismissed for the short-term due to missing in-flight experience. It is expected that these concepts will play a role in the longer term and that future missions might use CFDP Class 1 over LTP (for reliability) and BP (for multi-hop delivery).

All downlinked frames including the file data are stored in frame files and forwarded at a lower rate to the central CFDP File Reconstruction systems to reconstruct the files as they have been sent by the CFDP on-board entity. As data which has been lost on the space link will be detected by the Control Centre DCFDP system and re-transmission will be requested, these frame files will contain the full file content (although in maybe a different order and received at different ground stations) which allows re-construction of the complete files. Transaction failures will be already detected at the CC-DCFDP system and will also be flagged by the file reconstruction system. The architecture and system implementation supports warm and hot redundancy concepts with running several Ground Station DCFDP systems, Control Centre CFDP systems and Mission Control Systems in parallel.

2.1 Reducing CFDP File Data PDU

File Data CFDP PDU consist of the fixed-format CFDP PDU Header and the PDU Data Field containing the file segment offset, optional metadata, and a file segment. For reducing the File Data PDU, the file segment in the PDU data field is replaced by the size of the original file data (calculated using the PDU Data Field Length information from the header) and the partial modular file checksum[2] calculated over the file data in the original File Data PDU. In addition, the 'PDU Data Length Field' in the CFDP PDU Header is adjusted to the new length of the PDU data field. This allows to reduce a File Data PDU (up to 64 kilobyte) to around 20 bytes (depending on the lengths of entity IDs and the transaction sequence number in the header and assuming no per segment metadata).

The original file segment length together with the offset information is used by the receiving entity to detect gaps in the transmitted file data. The partial modular checksum allows to calculate the modular file checksum and compare it with the checksum transmitted by the sending CFDP entity in the EOF PDU. However, this is possible if the segmentation of a file is not changed during the transaction even for re-transmitted file data (duplicated or out-of-order file data does not cause problems with the checksum calculation). This is automatically guaranteed if files are always segmented in the same way, e.g., use of the maximum file segment size for all CFDP File Data PDU except for the last file segment (which would just contain the remaining part of the file). This is the "natural" implementation of the standard although it is not explicitly required.

2.2 Return CFDP PDU Cross-Support Transfer Service

To allow use of external ground stations, the forwarding of CFDP PDU in reduced or full mode is defined as an explicit Return CFDP PDU Cross-Support Transfer Services [5] based on the CCSDS Cross-Support Transfer Service Specification Framework [6]. The service is conceptually very similar to the well-known SLE services and offers an explicit management of the connections and buffering. This provides increased reliability and an explicit monitoring and control of the connections towards the ground stations in parallel with any additional SLE connections. The service allows to aggregate several CFDP PDU in a single Transfer Data invocation to further reduce the required bandwidth. For typical mission parameters a reduction in required data rate with a factor of 1000 can be assumed[3], i.e., for a 7.5 Gbit/s downlink rate on the space link, around 7.5 Mbit/s are required on the link from the ground station to the Mission Operations Centre. The definition and implementation of this service based on the CSTS Framework is relatively straight forward. The publication of the service specification as experimental recommendation under CCSDS is on-going and commercial ground station providers are expected to implement this service to support the Copernicus Sentinel Expansion Missions. The recommendation also offers a mode to transfer full CFDP PDU to allow CFDP deployments with file reconstruction in the ground station (in which case CFDP PDU for uplink can be transferred to a Mission Operations Centre) and for cases where sufficient bandwidth is available.

3. DCFDP Implementation in ESA's Ground Segment Infrastructure

ESA is maintaining a common ground segment infrastructure which is used across missions and mission families. This ground segment infrastructure is currently being updated to support the Distributed CFDP concept by implementing a library for the Return CFDP PDU Cross-Support Transfer Service, the Ground Station, and the Control Centre CFDP systems, and the CFDP File Reconstruction System. The primary focus for Distributed CFDP are Earth Observation missions although the same concept might be applied to other mission families in the future as well.

All systems are implemented in JAVA as OSGi applications making use of already existing infrastructure software such as ESA's CFDP implementation, the library for implementation of ESA's ground station monitoring and control protocol, the SLE API and the Cross-Support Transfer Service Framework implementation.

[2] The partial checksum can be omitted if the NULL checksum is used. Other checksum types are currently not supported.

[3] Assuming a frame length of 2048 bytes, 16 384 bytes packet size and aggregation of 100 CFDP PDUs in a single R-CFDP Transfer Data message.

3.1 Return CFDP PDU Cross-Support Transfer Service Library

The Return CFDP PDU Cross-Support Transfer Service API Library (R-CFDP CSTS API) is based on the CCSDS Cross-Support Transfer Service implementation and allows embedding applications to create R-CFDP Users and R-CFDP Providers. It includes the logic for reducing CFDP File Data PDU and encapsulates all communication aspects between service user and provider including the buffering of transfer data operations in case of network backpressure.

3.2 Ground Station DCFDP System (GS-DCFDP System)

The Ground Station DCFDP System (GS-DCFDP System) ingests the AOS or TM frames from the configured ground station modems and demodulators. TCP/IP and UDP/IP interfaces are supported and vendor-specific information in headers or trailers can be stripped of to support different modem interfaces. The CFDP PDU are extracted from space packets reconstructed from the frames received at these interfaces. Extracted CFDP PDUs are provided to an R-CFDP Service Provider instance, which creates the reduced CFDP PDUs and performs the transfer to the CC-DCFDP system. An interface session concept is supported, where each Session represents a connection to a Ground Station modem (e.g., one for reception of housekeeping TM frames via S-Band and one for receiving payload AOS frames via K-Band). Received frames are also stored in files for retrieval and reconstruction by the CFDP File Reconstruction System.

A web based MMI is provided for the monitoring and control of the system parameters and actions. The available actions include the management of the active Sessions, allowing starting and stopping them. Furthermore, the system supports the ESA M&C protocol for ground stations which allows integration with ESA's ground station management systems supporting remote monitoring and control and full automation. For ESA stations, the system would be operated by the Network Operations Centre as part of ground station operations.

3.3 Control Centre DCFDP System (CC-DCFDP System)

The Control Centre DCFDP System (CC-DCFDP System) uses a R-CFDP Service User instance for the reception of CFDP PDUs in reduced mode from the GS-DCFDP system and provides them to the corresponding CFDP Entity to generate the CFDP File Directive PDU required for the protocol loop closure. The generated CFDP PDUs are wrapped in Space Packets and TM frames for providing them to a mission control system via a standard SLE RCF service; finally, the MCS will send these CFDP PDUs to the CFDP entity on-board of the spacecraft. A CFDP entity session concept is supported, where each session represents a ground CFDP Entity and an SLE connection towards the mission control system and can receive CFDP PDU from different R-CFDP service providers. This allows to support different CFDP entities for payload or housekeeping telemetry or even to support different missions in parallel.

A web based MMI allows the monitoring and control of the system parameters and actions. The available actions include session management, control of R-CFDP Service User instances and even control of individual CFDP transactions. The system will be operated by the Flight Control Teams. A scripting interface provides automation capabilities for mission control systems e.g., to initiate the required connections to Ground Station DCFDP systems at a specific ground station before the start of a pass.

3.4 CFDP File Reconstruction System (CFRS)

The CFDP File Reconstruction System (CFRS) retrieves files containing AOS or TM frames recorded at the ground stations and extracts the underlying CFDP PDU, wrapped in CCSDS Space Packets. The CFDP PDUs are then processed to re-construct the files as sent by the on-board CFDP entity. A database is used to track the status of each transaction and an MMI is provided for monitoring purposes.

3.5 Test and Validation Framework

In addition, test tools and an extensive test framework is required to ensure that the demanding data rates can be met on commodity PC hardware in time for the first missions to use this infrastructure from 2025 on. The implementation and integration of the systems is supported by a multi-faceted testing methodology to ensure that the final and fully integrated DCFDP system meets all its requirements, specifically with regards to performance and stability. During the development, unit tests are written by the development team which are executed via automated GitLab Continuous Integration (CI) jobs to verify correct behaviour of individual software components.

In parallel, a dedicated validation and verification team is developing test tools to facilitate component, integration, system, and end-to-end testing of all DCFDP components. Central part of the test tool development is the 'DCFDP-E2E Test Tool' which uses the ESA CFDP implementation to simulate the on-board CFDP entity enabling CFDP Class 1 and Class 2 file transactions (see Fig. 2).). Interfaces to all DCFDP components are implemented in the E2E Test Tool to support testing in isolation and end-to-end scenarios.

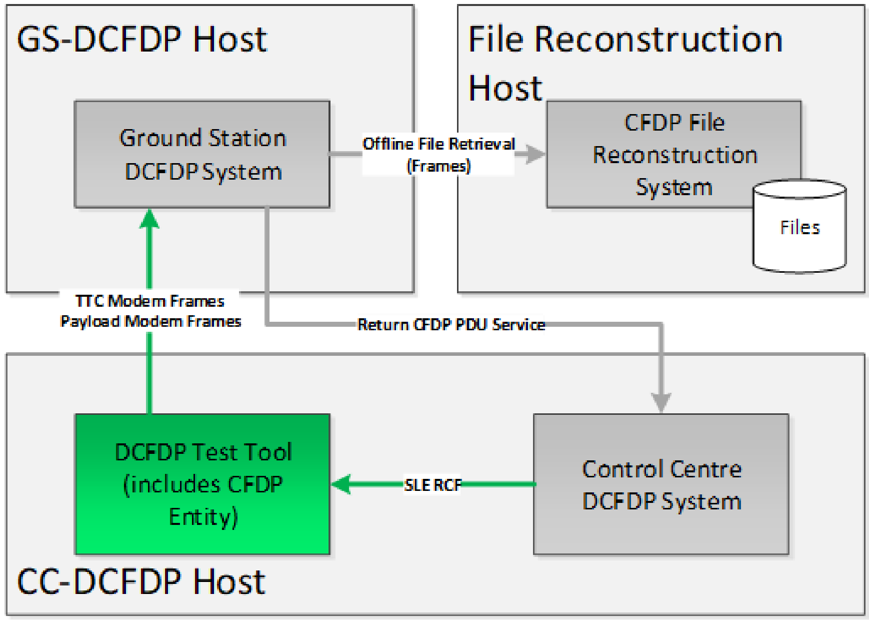

Fig. 2. Distributed CFDP – End-to-End Test Tool. The test tool supports additional interfaces to for testing of the individual systems in isolation.

Whenever possible, component, and higher-level tests are automated. CI pipelines are used to build and deploy the required test software as well as the components to be tested as containers. The actual test execution is automated using BDD (Behavior-Driven Development) scripts executed via the YAKS framework [7]. This relatively new testing methodology allows to define tests as a set of pre-conditions, the steps which must be taken, and the desired (or undesired) outcomes using a human-readable nomenclature. These BDD scripts are directly attached to test cases managed in Jira using the Zephyr Scale Plugin. From there the scripts are fetched by the CI jobs to run the test steps via Kubernetes pods on dedicated hardware servers.

4. Prototyping, Implementation and Deployment

The concept has been successfully prototyped based on the existing CFDP Assembly [4] and initial performance testing and optimisation has confirmed that processing speeds of up to 7.4 Gbit/s can be achieved for typical mission configurations with Java an implementation on commodity hardware for the Ground Station DCFDP System. The performance of the CC-DCFDP system is less critical as the system does not have to reconstruct CCSDS packets from frames but gets CFDP PDU directly as input via the R-CFDP service and checksum calculation is limited to the partial checksums provided in the reduced CFDP PDU. Performance testing on commodity hardware confirmed that the system would be able to process data equivalent to a downlink rate on the space link of 55 Gbit/s.

The full operational implementation has been kicked-off early 2022 and a first release of the R-CFDP Service API has already been provided. Implementation of the GS-DCFDP and CC-DCFDP systems has started, and mock-ups of the operational MMI have been reviewed with the operational users. First releases are expected within 2023 and implementation of the CFDP File Reconstruction system will start.

The GS-DCFDP system will be deployed in the ESTRACK Kiruna ground station by 2024. The first user of the distributed CFDP concept will be the CO2M mission and joint test and validation activities involving the operational simulator and the mission control system will start soon. In addition, parts of the software will be used within the EGSE to test and verify on-board CFDP implementation.

5. Conclusions

ESA is fully embarking on a file-based operations approach for its upcoming missions. In particular, the use of less reliable communication bands makes the use of CFDP Class 2 with automatic re-transmission of lost data very useful and files offer a good way to manage the enormous amount of data produced by upcoming Earth Observation missions. However, due to limitations in available terrestrial bandwidth from the ground station to mission control centres (in the Mbit/s range) compared to envisioned downlink rates on the space link (Gbit/s range), CFDP cannot centrally be deployed and operate in near-real time. Therefore, a novel, distributed CFDP concept is being implemented as part of the ground infrastructure which supports a fast, near-real-time closure of the protocol which allows the spacecraft to free up resources quickly. The concept does not require any adoption of standard compliant CFDP on-board implementations but requires the development of three new ground segment infrastructure systems. The GS-DCFDP system in the ground station provides reduced CFDP File Data PDUs to the CC-DCFDP system in the Mission Control Centre. This CC-DCFDP system runs one or several CFDP entities and makes use of the mission control system to uplink CFDP PDU back to the spacecraft. Finally, the CFDP File Reconstruction System receives frame files from ground stations and re-constructs the files as they have been on-board. These systems will be used by the upcoming Copernicus Sentinel Expansion Missions starting with the CO2M mission in 2025.

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