Space Internetworking Protocols & Delay Tolerant Network Prototyping

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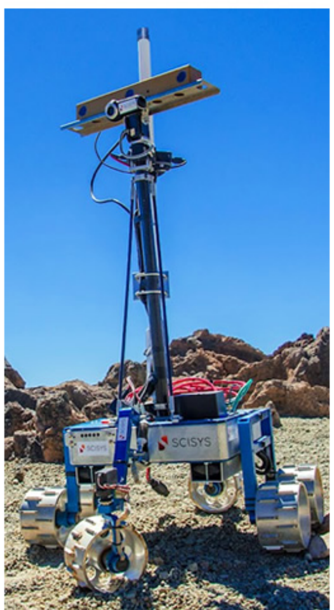
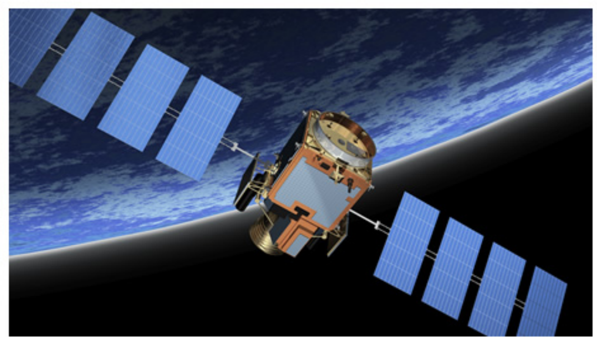
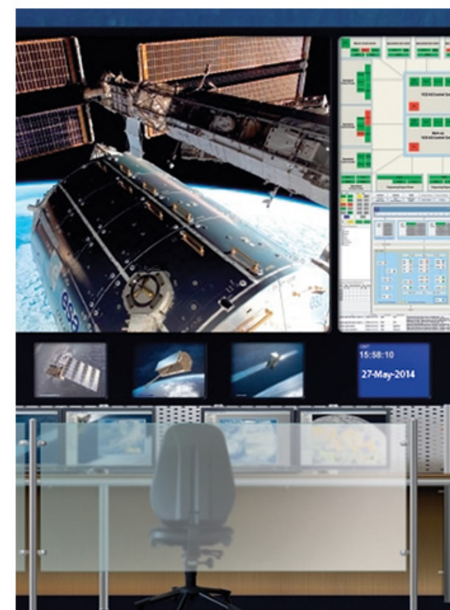
12th December 2013



Overview

- Consortium and Project Objectives
- System and Space Segment Communications Architectures
- Space Communications Simulator
- Protocols Testbed
- Roadmap to Introduction of CFDP and DTN
- Conclusions

Consortium and Project Objectives

Consortium

- SCISYS
  - » Prime, Software development
  - » Simon Wheeler, Daran Paramanantham, Martin Kelly, Stuart Fowell
- Keltik Ltd subcontractor
  - » Space Communications protocols and architecture consultancy
  - » Dai Stanton
- Tolerant Networks Limited (spin-off from Trinity College Dublin) subcontractor
  - » DTN consultancy and support for DTN2 and ION implementations
  - » Stephen Farrell

Project Objectives

- Scrutinise the use of a network based architecture using DTN based protocol suites for use in ESA and cooperative missions and to identify any shortcomings or required changes and additions.
- Determine the impact on the existing space infrastructures, including protocols and the flight data handling system
- Gain experience with operating DTN through the provision of a test-bed infrastructure suitable for cooperating in international experiments.
- Identify a deployment policy which takes account of the use and capabilities of the existing CCSDS and ECSS protocols, in particular CFDP.
- Provide a simulation capability able to evaluate complex internetworking scenarios.
- Complement on-going ground studies by focussing on flight segment aspects.
- Provide analysis and feedback to the CCSDS DTN working group.

System and Space Segment Communications Architectures

System Requirements

- Candidate Future Missions. Categorise and catalogue communication characteristics (contact periods, utilised bandwidth, comms latencies and error rates, user data sizes):
  - Observatory, e.g. L2 such as Herschel, Planck, Gaia, Darwin, Euclid, IXO/Zeux, Plato
  - Low Earth Orbit, e.g. GOCE, SMOS, ENVISAT
  - Deep Space, e.g. ExoMars TGO/EDL/Rover, MSR, Mars Express, Beagle2, Odyssey, MER, Bepi-Columbo, EJSM/TSSM, Marco-Polo NEO, Solar Orbiter
  - Others, e.g. ISS, Chandrayaan-1
- Space Internetworking Protocols
  - CFDP: Core and Extended Procedures, Store-and-Forward Overlay, Reliable and Unreliable, Proxy Operations
  - DTN: Bundle Protocol (BP) and Licklider Transmission Protocol (LTP)
  - CCSDS Space Packet, Packet TM and TC, AOS, Proximity-1
  - CCSDS Encapsulation Service
  - Space Link Extension (SLE)
  - Packet Utilisation Standard (PUS)

Reference Mission Scenarios

- Direct to LEO
  - OWLT 2.6 ms, Uplink Rate: 10k to 1M bps, Downlink Rate: 1 Gbps
  - Contact periods: 10 minutes (continuous) in every 100 minutes (from T0 to T0+10 minutes)
- Direct to L2
  - OWLT 5 seconds, Uplink Rate: 100 kbps, Downlink Rate: 10 Mbps
  - Contact periods: 10 hours per day (from T0 to T0+10 hours)
- Direct to Mars
  - OWLT 3 to 21 minutes, Uplink Rate: 4k to 16k bps, Downlink Rate: 4k to 16k bps
  - Contact periods: 3 hours per sol (from T0 to T0+3 hours)
- Relay to Lunar Surface
  - Earth to Orbiter
    - OWLT 1.3 seconds, Uplink Rate: 10k to 1M bps, Downlink Rate: 1 Gbps
    - Contact periods: continuous
  - Orbiter to Lander
    - OWLT 2.3 to 26 ms, Uplink Rate: 8k to 64k bps, Downlink Rate: 64k to 2048k bps
    - Contact periods: 8 hours per 12 hour orbit (from T0 to T0+8 hours)
- Relay to Mars Surface
  - Earth to Orbiter
    - OWLT 3 to 21 minutes, Uplink Rate: 128k to 2048k bps, Downlink Rate: 128k to 2048k bps
    - Contact periods: up to 16 hours per sol (from T0 to T0+16 hours)
  - Orbiter to Lander
    - OWLT1.3 ms (for a 400 km circular orbit), Uplink Rate: 8k to 64k bps, Downlink Rate: 64k to 2048k bps
    - Contact periods: 10 to 15 minutes, two to five times per sol

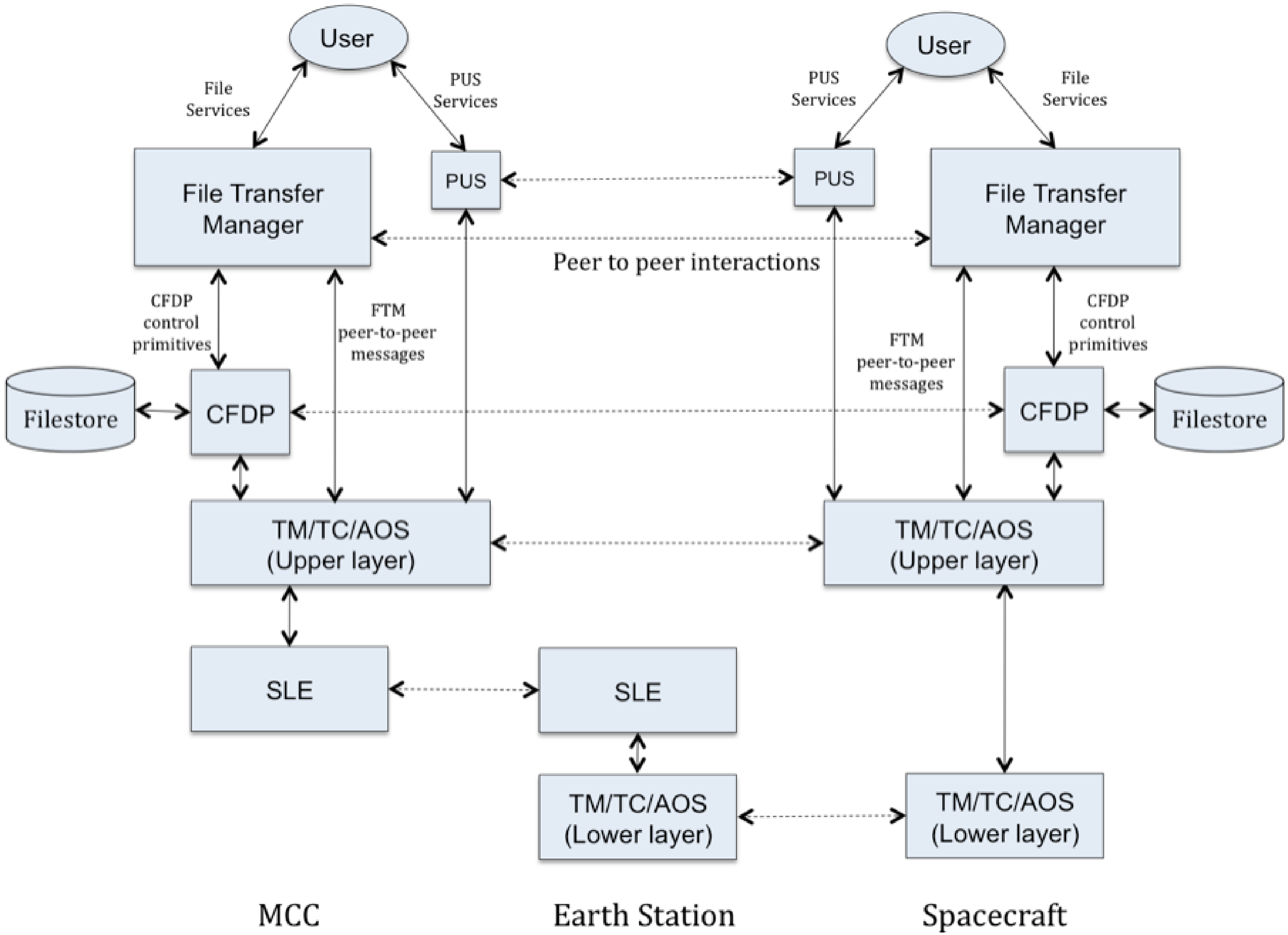
Mission Scenarios vs. Communication Architectures

Mission Topology	CFDP Class 1 or 2 (using SFO for relaying)	CFDP and Messaging over DTN (BP/LTP)	CFDP and Messaging over LTP-only
LEO	Currently well understood and implemented	No obvious advantage	Interesting as an alternative to evolution CFDP
Lunar	Suitable for dark and light side operations and dark side relay	Applicable for dark side relay. Interesting for rover surface communications	Light side operations only
L2	Direct or indirect communications	Direct or indirect communications.	Direct communications only
Interplanetary	Direct or indirect communications	Direct or indirect communications.	Direct communications only

Detailed issues to consider include:

- Communication Environment, e.g. latency, predictable & unpredictable disruption, channel characteristics
- Communication Services; file and messages
- Quality-of-Service, Security, Routing,
- Prioritisation of Command Transfers, File Transfer Monitoring & Control, In-Transit Data Management
- Onboard Resource Management
- Operational Requirements: Ground-to-Ground, Space-to-Space, Forward and Return Space Link
- Application Use Cases, e.g. Configuration Data uplink, Data Product downlink
- Packet Encapsulation within files

Recommended CFDP Direct Architecture



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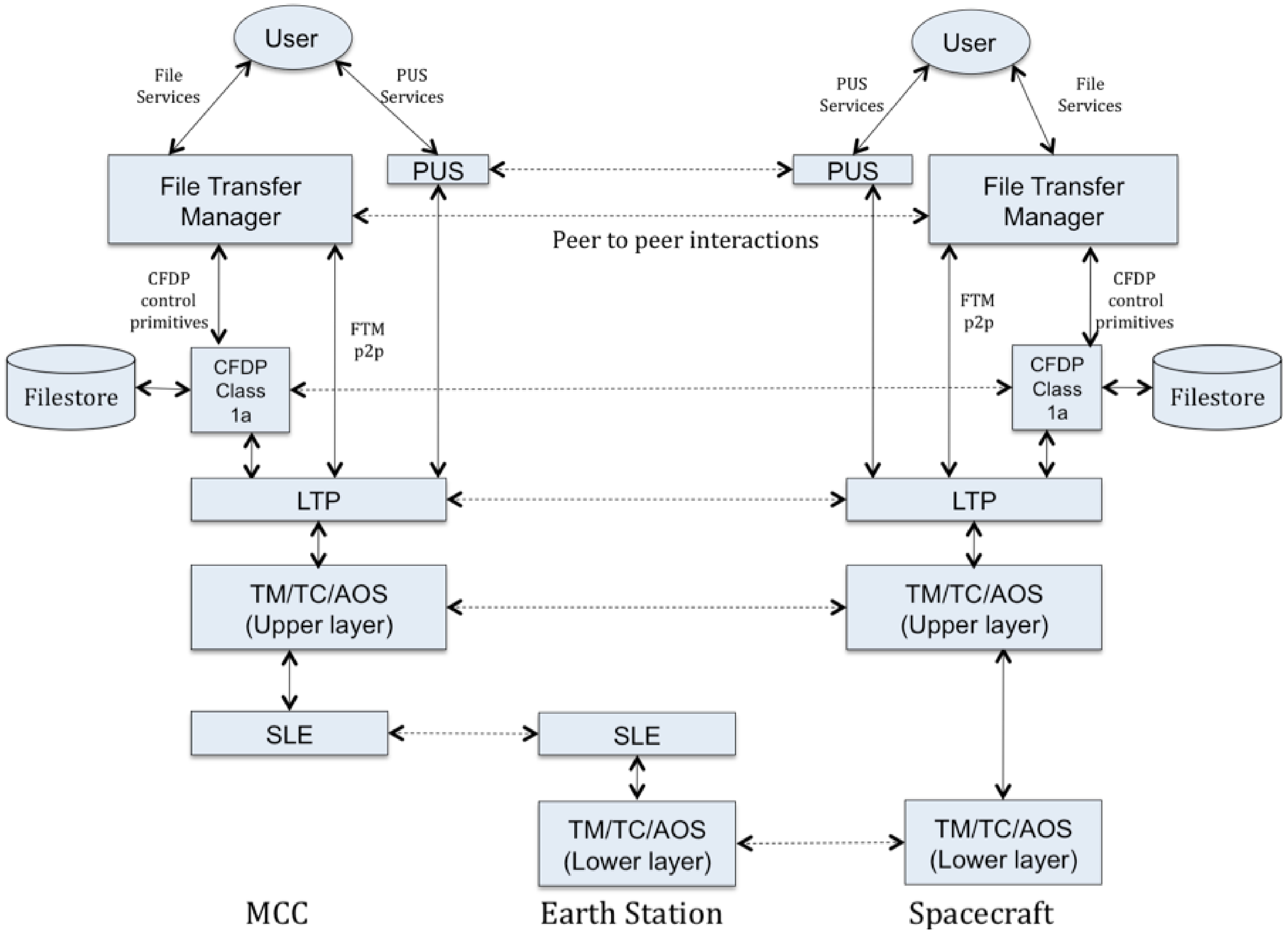
Recommended CFDP over LTP Direct Architecture



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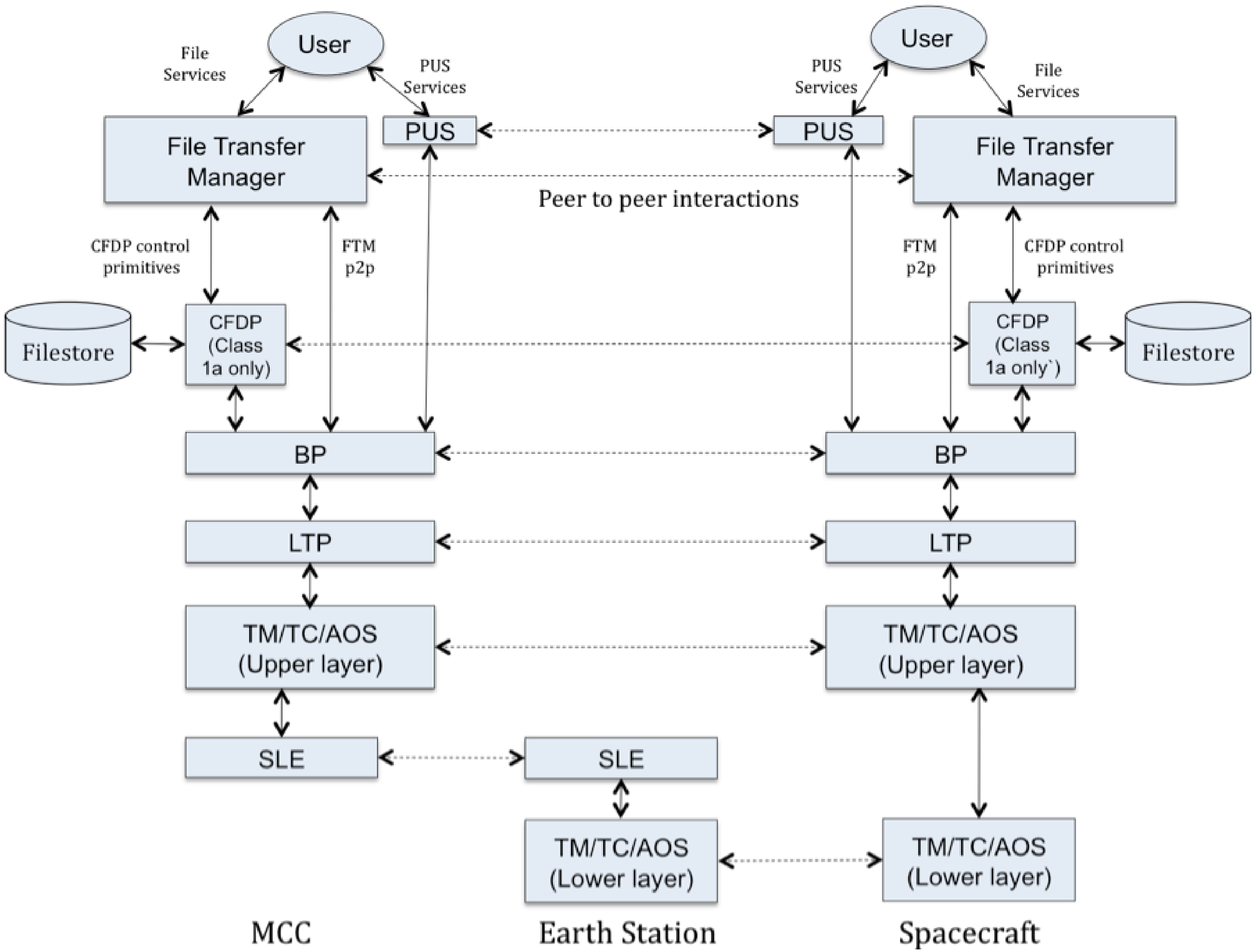
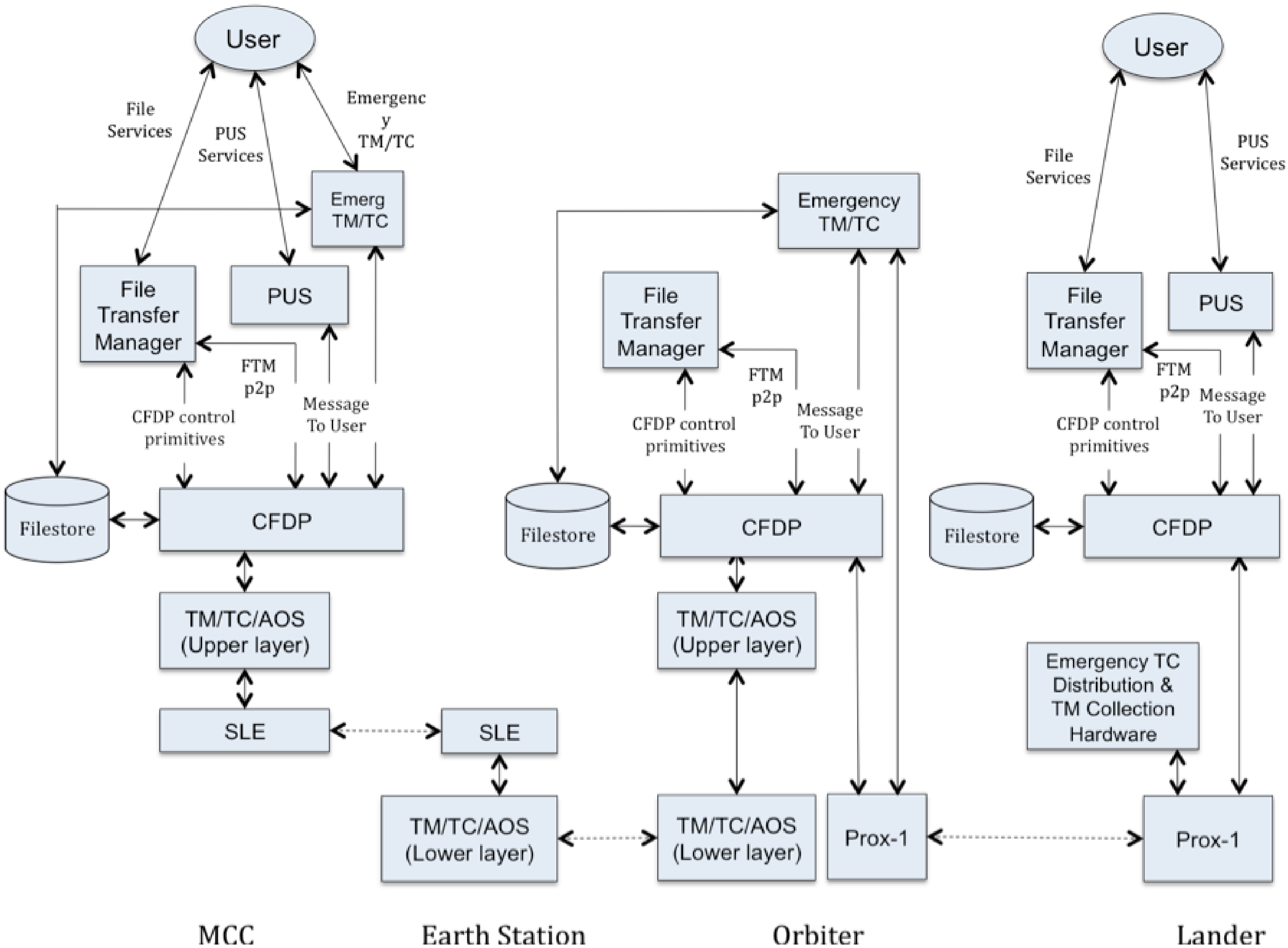
Recommended CFDP over DTN Direct Architecture



Recommended CFDP Relay Architecture



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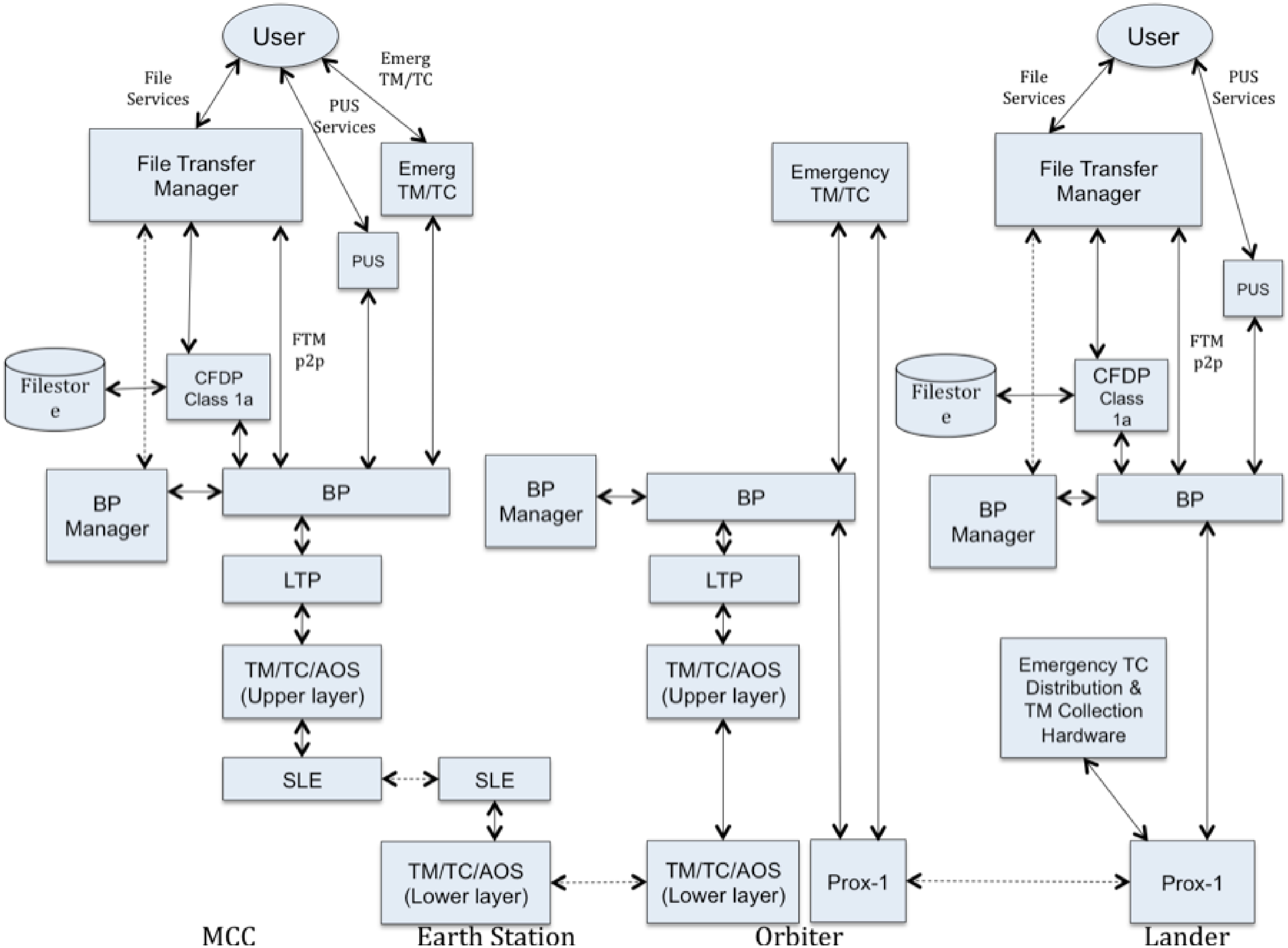
Recommended CFDP over DTN Relay Architecture



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Recommended Spacecraft Communications Architecture

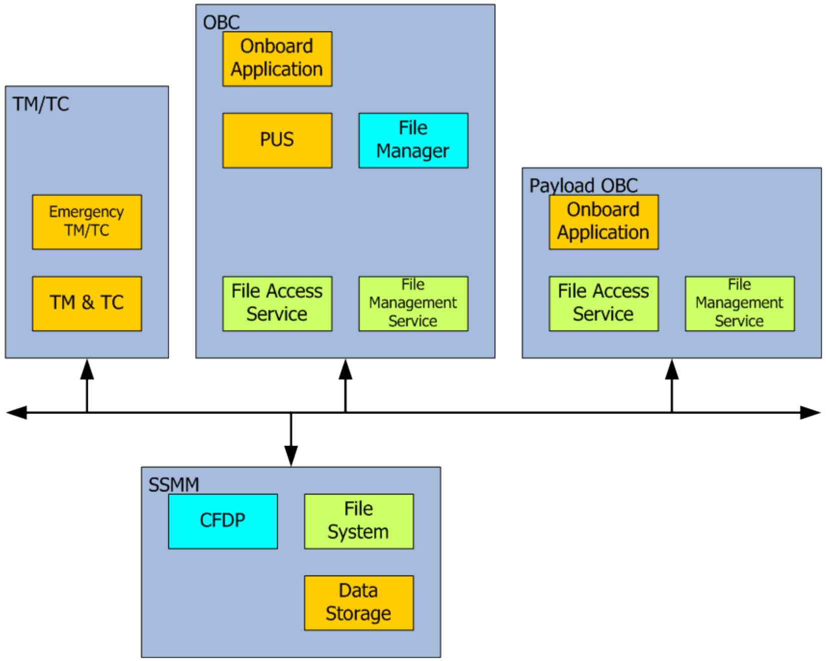
- Analysis of deployment of recommended space comms architectures upon spacecraft
  - Space-based comms waypoints (e.g. Orbiters) and endpoints (e.g. Landers and rovers)

- Spacecraft are resource constrained
- Use of more complex communications protocol stacks requires additional computing resources, i.e. processing and memory
  - Some comms processing handled by separate TM and TC equipment
  - but need to determine where CFDP/DTN protocols will run e.g. on processor in OBC or the various SSMMs
  - => additional processing load upon OBC/SSMM
  - => additional comms load upon spacecraft busses, e.g. the avionics bus.
- At same time, spacecraft comms architecture is also evolving
  - Move from MIL-STD-1553B and serial links to CANbus and SpaceWire networks
  - Introduction of the SOIS comms protocols and services to avionics and instrument applications.
- Deployment of the space comms architecture onboard spacecraft must take these factors into account.

- For each of the recommended space comms architectures, information flows between different comms functions onboard were analysed with particular focus upon the load upon the avionics bus

- NOTE: The analysis performed took no account of the following:
  - Available “spare” CPU and avionics bus load
  - CPU load imposed upon the various processors in the spacecraft
  - Data link protocols across the avionics buses and space links
    - E.g. segmentation of user data, QoS, retransmissions due to error rates(typically low on avionics bus)

Example: CFDP Direct



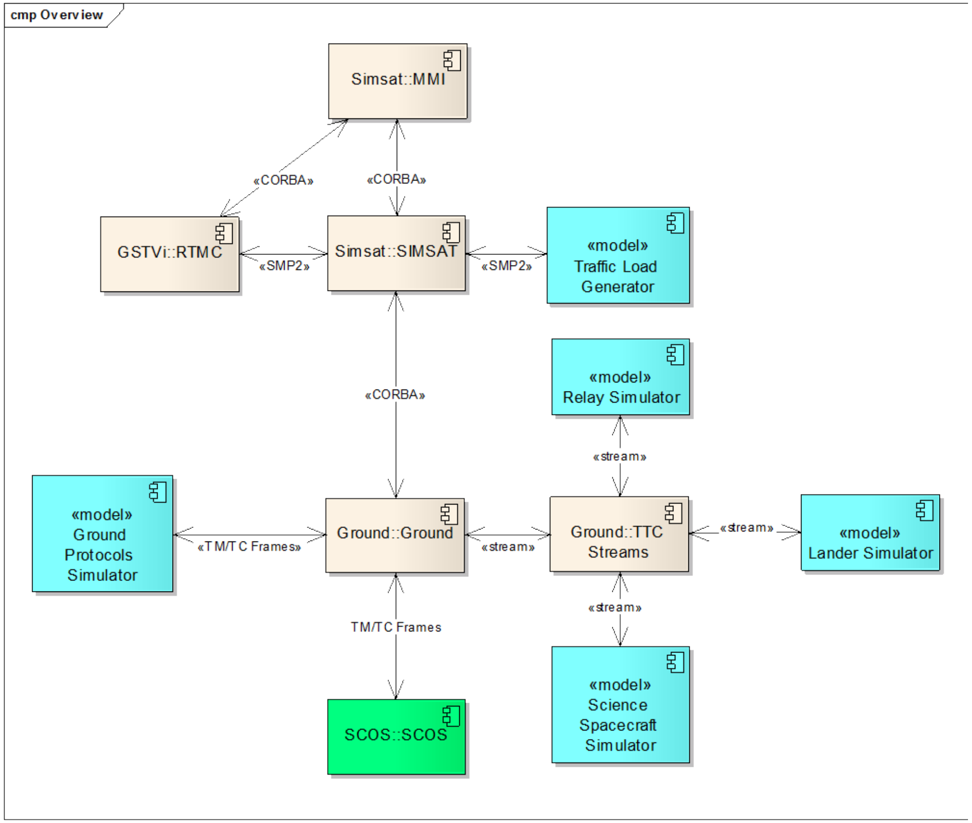
- Spacecraft must accommodate PUS File Transfer Manager and CFDP Protocol Engine (PE)
- File Transfer Manager is assumed to be collocated with rest of Data Handling implementing PUS and therefore always deployed upon the OBC PM
- Deployment of CFDP PE was considered in TM/TC radios, OBC PM, and in SSMMs
- As CFDP only used for file transfers, optimal deployment is CFDP PE in TM/TC radios or SSMMs
- NOTE: More recent work has identified the probability of multiple CFDP PEs for different SSMMs and associated TM/TC radios
  - E.g. CFDP PE in OBC SSMM and separately in Payload SSMM with shared S-/X-band uplink and separate S-/X- and Ka-band downlink

Recommended Spacecraft Communications Architecture

Space Comms. Architecture	Spacecraft	Recommended Spacecraft Comms. Arch.	Comments
CFDP Direct	Spacecraft	CFDP -> TM/TC radio or SSMM	Alternatives have equal number of avionic bus transfers
CFDP over LTP Direct	Spacecraft	LTP -> TM/TC Radio BP -> TM/TC Radio CFDP -> TM/TC Radio or SSMM	
CFDP over DTN Direct	Spacecraft	LTP -> TM/TC Radio BP -> TM/TC Radio CFDP -> TM/TC Radio or SSMM	
CFDP Relay	Orbiter	CFDP -> SSMM	
	Lander	CFDP -> Proximity-1 Radio or SSMM	CFDP on SSMM preferred for commonality
DTN Relay	Orbiter	LTP -> TM/TC Radio BP -> TM/TC Radio CFDP -> SSSMM	
	Lander	BP -> Proximity-1 Radio CFDP -> Proximity-1 Radio or SSMM	CFDP on SSMM preferred for commonality
Overall		**LTP -> downlink radio (Prox-1 or TM/TC)** **BP -> downlink radio (Prox-1 or TM/TC)** **CFDP -> SSMM**	

Space Communications Simulator

Space Communications Simulator Design

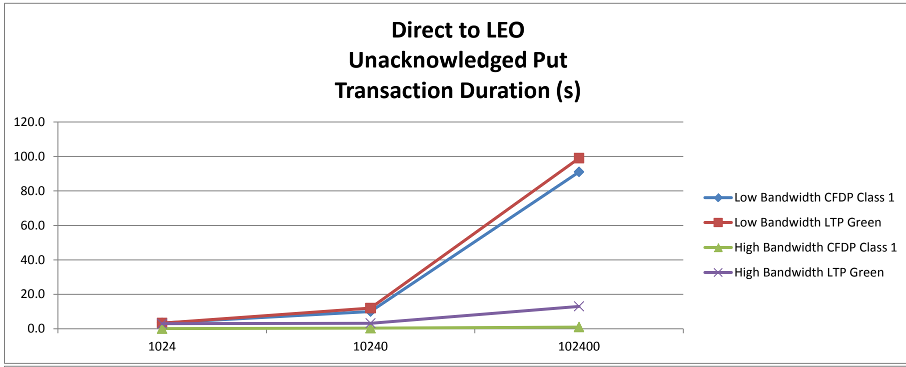


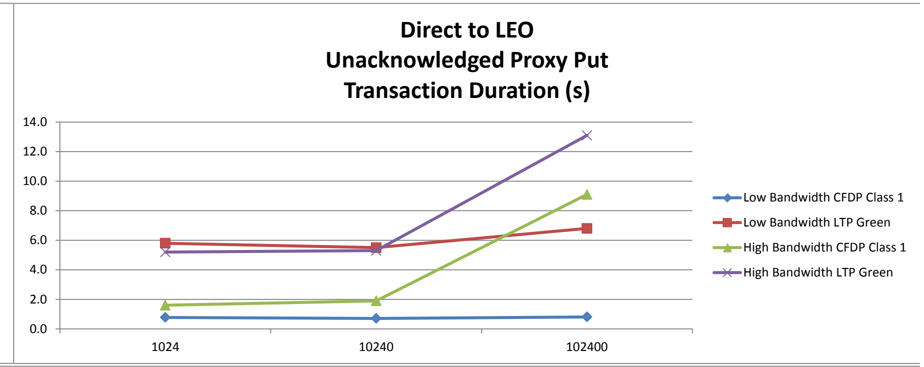
- To evaluate the suitability and performance of the Space Communications Architecture in performing the operational concepts for the different mission scenarios, a flexible Simulator was developed
  - » Running on Ubuntu Linux laptop
  - » Campaign of simulations for reference mission scenarios
- Built on SIMSAT and GSTVi, using CFDP Java and DTN2 reference implementations over TM/TC and Proximity-1 models

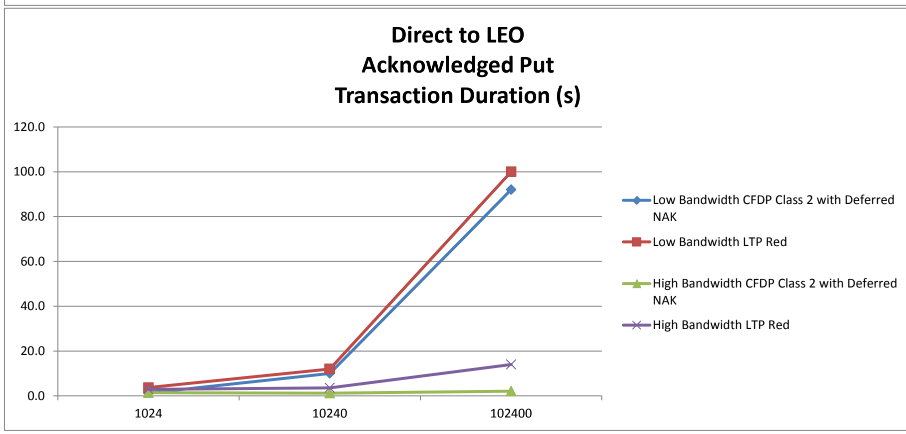
Simulation Tests

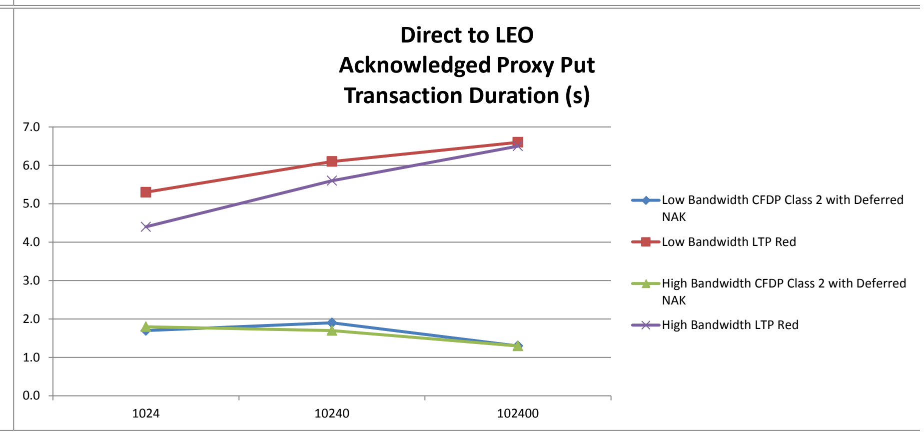
- Direct communication scenarios
  - » File transfer at LEO using CFDP vs CFDP over DTN
    - › CFDP Class 1 (unreliable), Class 2 (reliable)
    - › LTP Green mode (unreliable), Red mode (reliable)
  - » File transfer at L2 using CFDP vs CFDP over LTP
  - » File transfer at Mars using CFDP vs CFDP over DTN
- Relay communication scenarios
  - » File transfer at Lunar using CFDP vs CFDP over DTN
    - › CFDP Class 3 (unreliable), Class 4 (reliable), Store-and-Forward Overlay
    - › LTP Green mode (unreliable), Red mode (reliable)
  - » File transfer at Mars using CFDP vs CFDP over DTN
- Measure Transaction Durations and Memory Utilisations
  - » Uplink and Downlink
  - » 1K, 10K and 100K files
  - » No packet loss, with packet loss

Simulation Results – Direct to LEO









- Similar figures when introducing dropped packets on downlink triggering retransmissions
- Largely similar performance by CFDP and CFDP over DTN
- Memory utilisation is largely determined by CFDP file segment size but DTN adds overheads due to additional buffering

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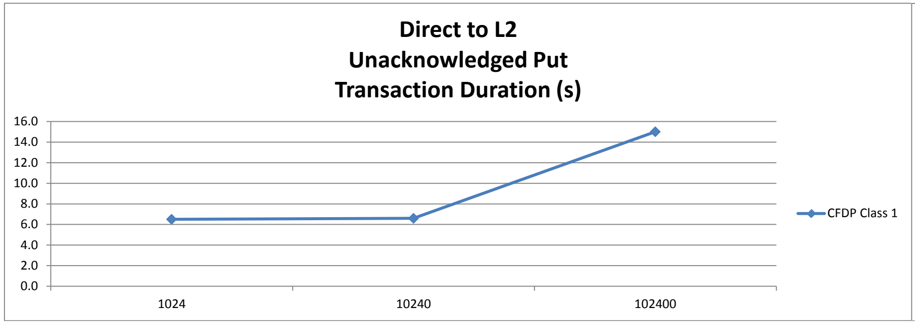
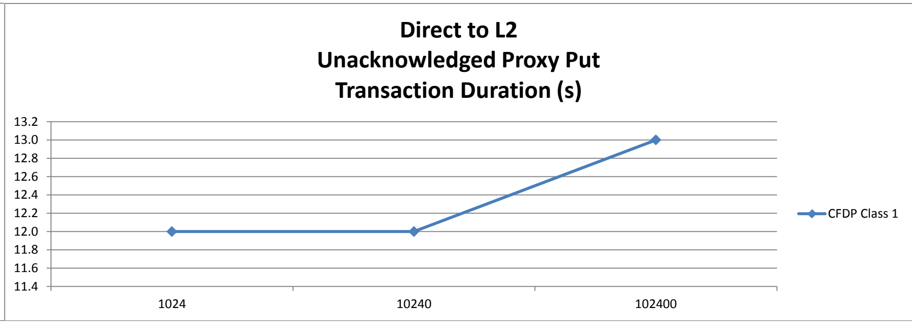
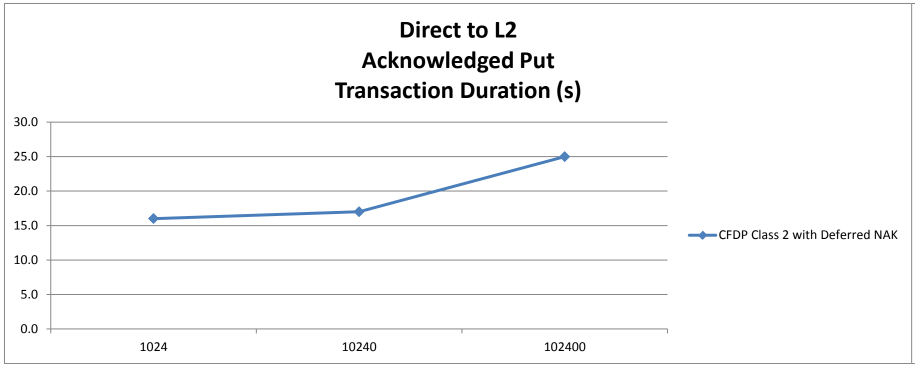
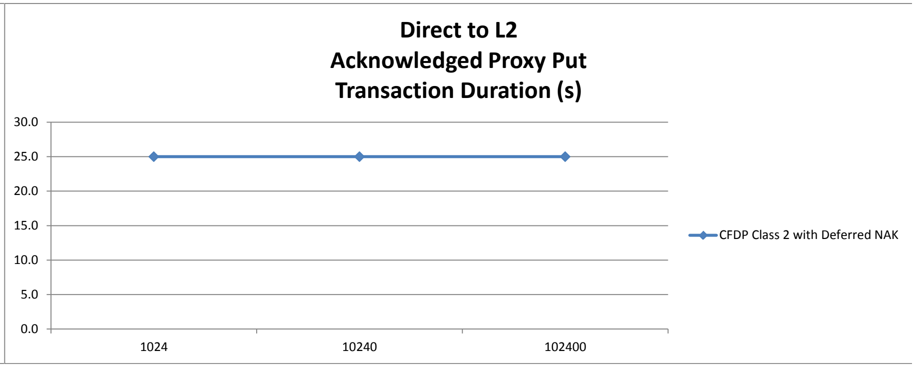
Simulation Results – Direct to L2



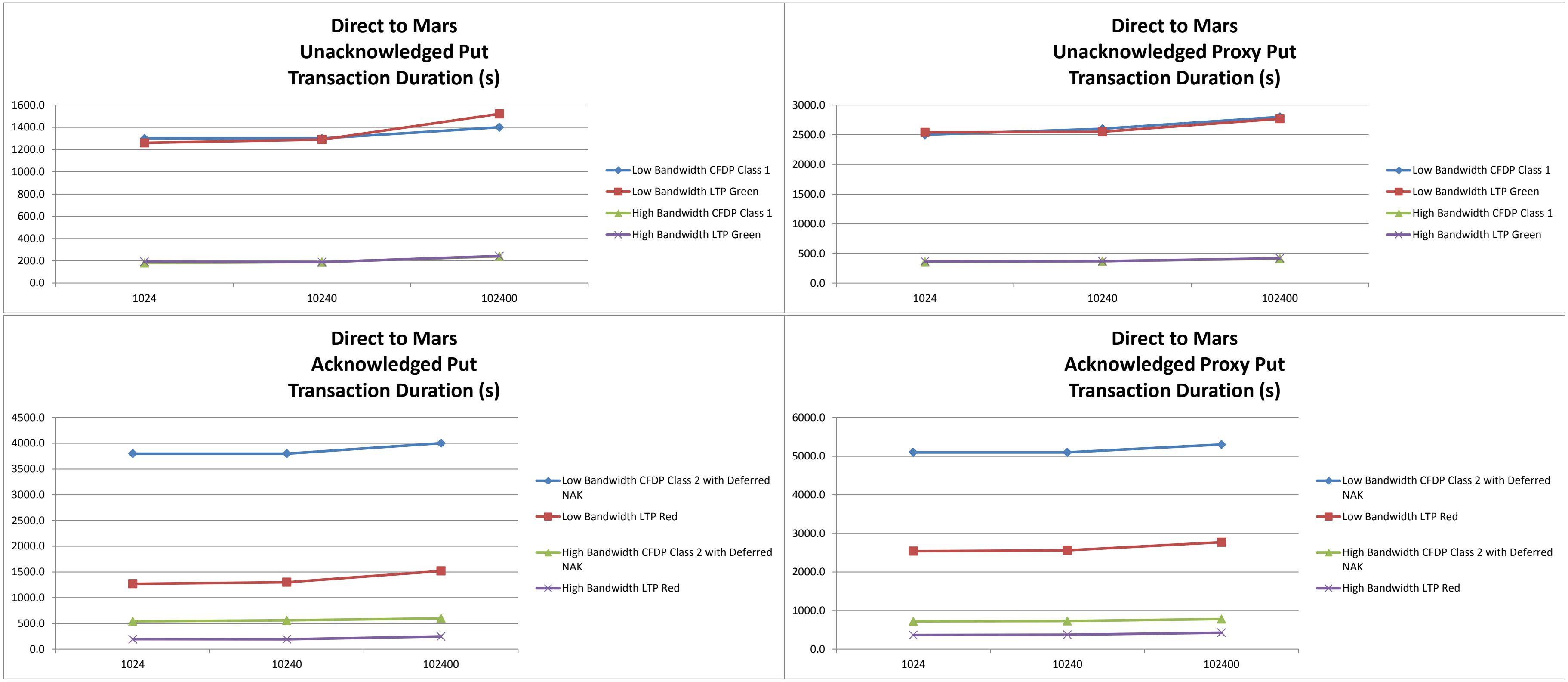






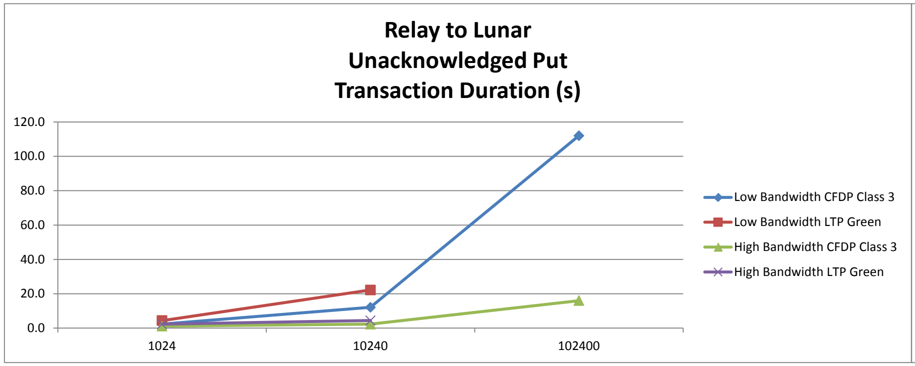
- Architectural issue with LTP implementation meant CFDP over LTP could not be simulated
- Similar figures when introducing dropped packets on downlink triggering retransmissions
- Memory utilisation is largely determined by CFDP file segment size

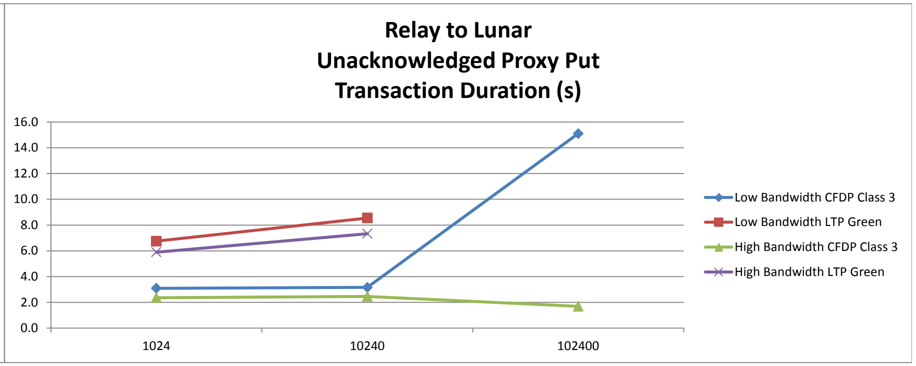
Simulation Results – Direct to Mars

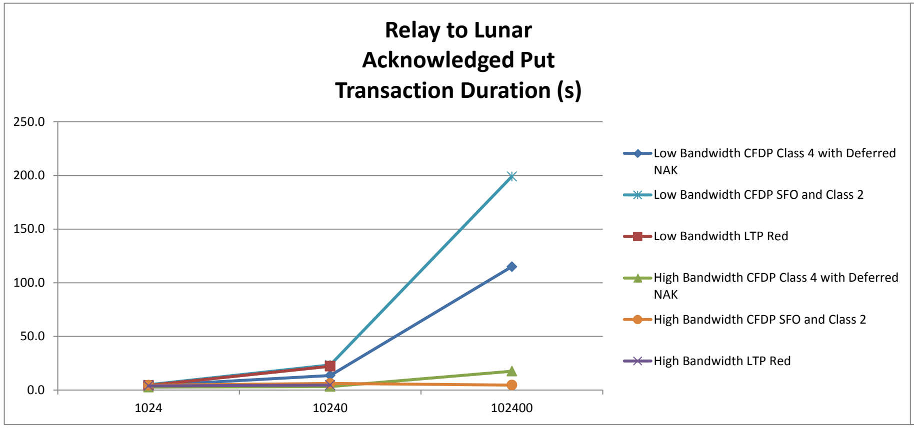


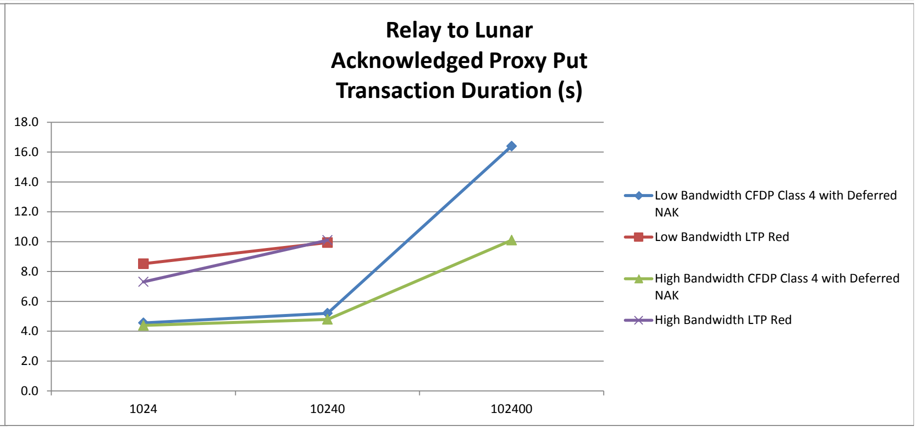
- Similar figures when introducing dropped packets on downlink triggering retransmissions
- Largely similar performance by CFDP and CFDP over DTN for unreliable transfers
- DTN is quicker than CFDP for both low and high bandwidth links for reliable transfers
  - » CFDP Class 2 includes protocol traffic to ack completed delivery of file, whereas DTN pass data up to CFDP then ack
- Recommendation introduction CFDP Class 1a with positive ack that the file was transferred
  - » CFDP Class 1a over BP/LTP in Red mode will then have similar characteristics to CFDP Class 2
- Memory utilisation is largely determined by CFDP file segment size but DTN adds overheads due to additional buffering

Simulation Results – Relay to Lunar









- CFDP SFO doesn’t support Proxy Put so unable to compare with CFDP Class 3, 4 and DTN
- CFDP Class 3 performs better than DTN
- CFDP Class 4 and DTN both perform better than CFDP SFO due to immediate forwarding of file segments with continuous connectivity
- Memory utilisation is largely determined by CFDP file segment size but DTN adds overheads due to additional buffering

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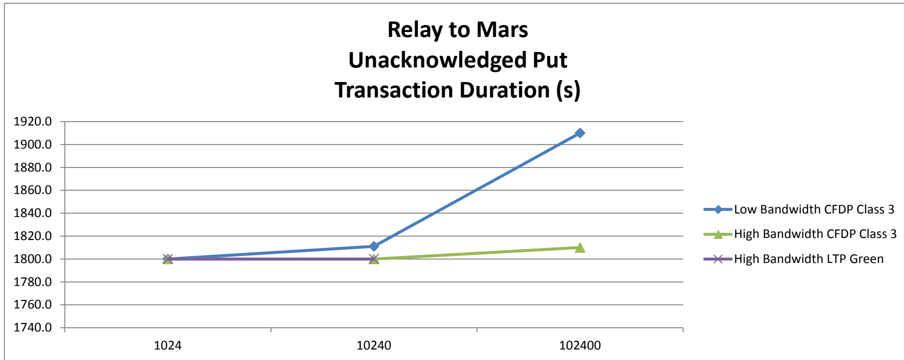
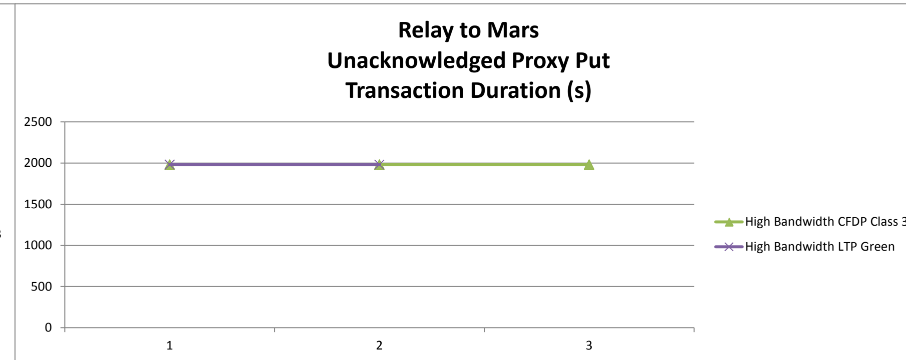
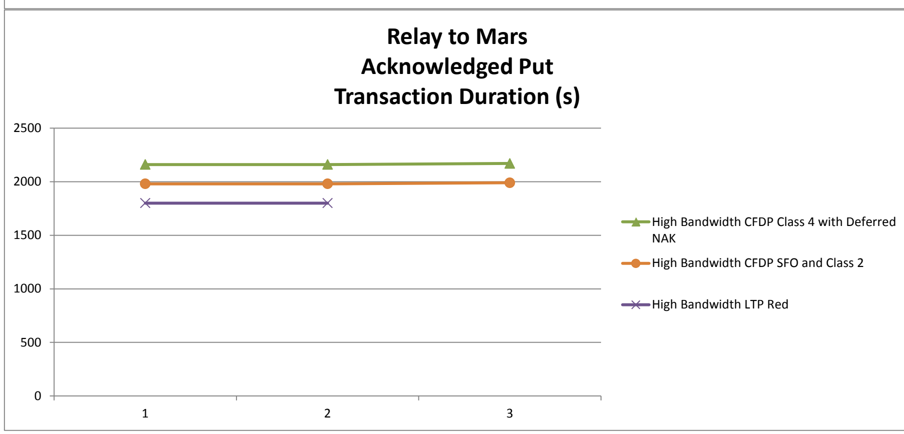
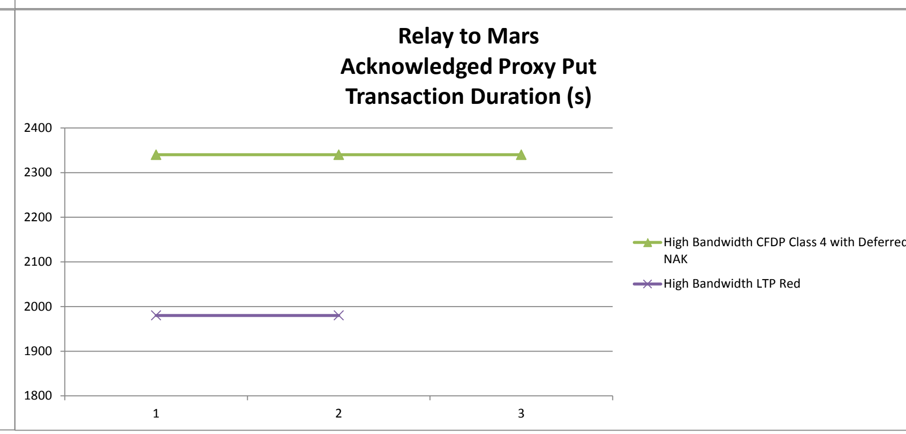
Simulation Results – Relay to Mars



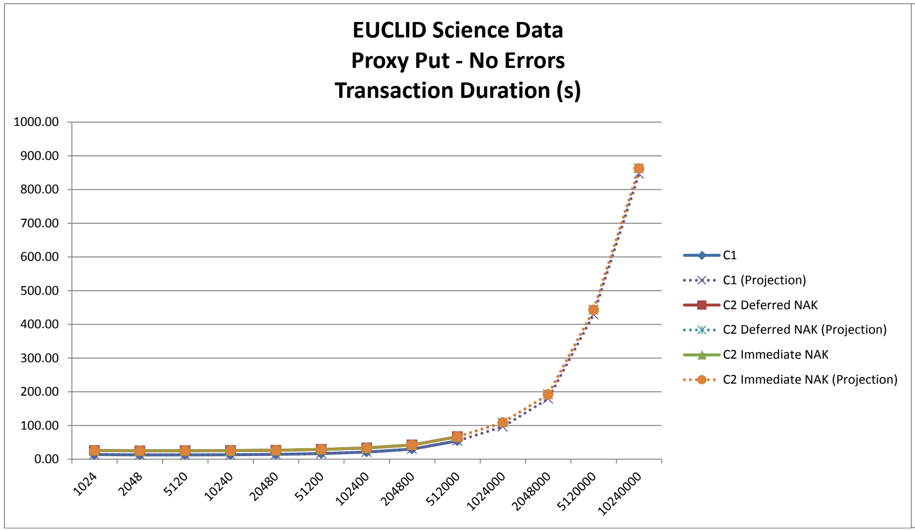


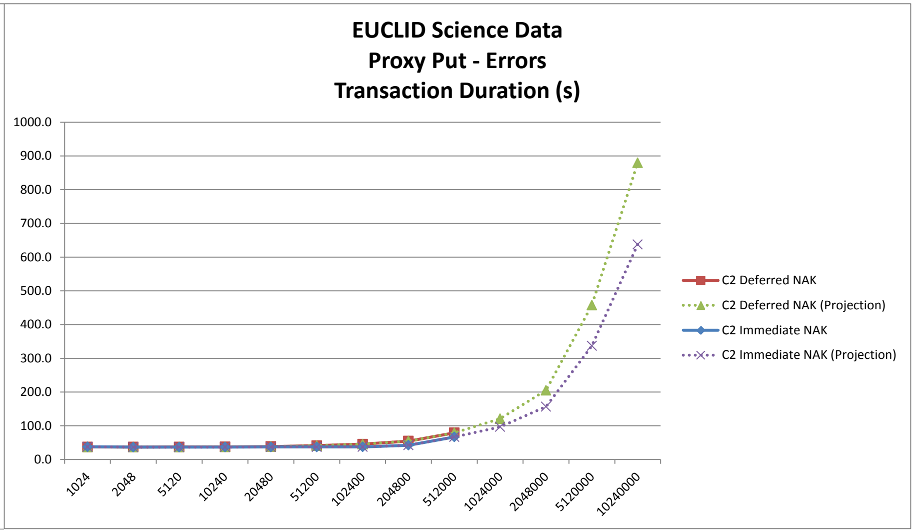




- CFDP SFO does not support Proxy Put so unable to compare with CFDP Class 3, 4 and DTN
- CFDP SFO performs better than CFDP Class 4 due to completed transfer of file prior to forwarding rather than single end-to-end transfer because of connectivity model
- DTN performs better than CFDP due to same reasons as for Direct to Mars scenario
  - » CFDP Class 1a will correct this
- Memory utilisation is largely determined by CFDP file segment size but DTN adds overheads due to additional buffering

Simulation Results – EUCLID Science Data Downlink





- Space Communications Simulator used to simulate return of Science Data from Euclid Mission using CFDP classes 1 and 2.
- Limitations in various aspects of the Simulator meant that:
  - » Spacecraft-initiated downlink of files not possible; instead ground-initiated downlinks were performed and so additional downlink protocol traffic has to be taken into account.
  - » Maximum file size transferred was 500 Kbytes, file segments 220 bytes for uplink and 1024 bytes for downlink;
  - » Simulation of specific error characteristics of Ka-band downlink not possible; instead effect of dropping a single packet was simulated
- CFDP performed as expected with, as file sizes increased, time to transmit becomes dominant, the difference between Class 1 and Class 2 negligible
- Where packets were dropped, immediate NAKs found to reduce recovery time over deferred NAKs
- Downlink bandwidth effectively completely used at peak (69.6-73.6 Mbps out of 75 Mbps)
- Maximum memory utilisation was effectively a single packet.

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Space Communications Simulator Conclusions

- CFDP and DTN are comparable in short latency direct and relay scenarios
  - Only detected differences being the memory utilisation
  - Determined by the configured CFDP file segment and BP bundle sizes
- CFDP Class 1 over DTN is faster than CFDP Class 4 for long latency relay scenarios
  - Due to the manner in which CFDP class 1 operates over DTN
  - However not truly achieving reliable transfers as there is no final ACK that the file has been successfully received, only that its segments have bee received
  - Recommended that a CFDP Class 1a be introduced, that uses a reliable unitdata transfer (UT) layer and ACK a successfully completion of a transaction.
- CFDP Class 4 performed better that CFDP SFO in the Lunar relay scenario
  - Due to the immediate forwarding of file segments where there was continuous connectivity
  - even in the error test case where the retransmission is only between Earth and the Orbiter for SFO as opposed to end-to-end for Class 4
  - However, this is unlikely in expected relay scenarios.
- CFDP SFO performed better than CFDP Class 4 in the Mars relay scenario
  - Due to the file being completely transferred from Earth to Orbiter before the Orbiter to Lander link session becoming available; i.e. non-continuous connectivity
  - without the need for end-to-end acknowledgements required by Class 4
- No major different conclusions were reached over those from CFDP Bundle study
  - Despite higher fidelity Proximity-1 simulation and refined link connectivity models in the relay scenarios

Protocols Testbed

Protocols Testbed Design

- Protocols Testbed developed to evaluate the use of the space communications architectures in a realistic environment, i.e. ESA's existing RASTA Test Facility
  - » LEON3 in FPGA @40MHz or LEON2 as AT697F @ 80MHz
  - » SOIS-compliant File system running on LEON2/3 accessing RAM-based Mass Memory over SpaceWire

- Investigate feasibility of various aspects of the architectures, in particular:
  - » Performance of file transfer management on realistic flight processor
  - » Implementation of emergency TM/TC in a relay scenario
  - » Integration with SOIS recommendations

- CFDP and DTN implementations used
  - » Different CFDP and DTN implementations used to test interoperability
  - » CFDP C and ION ported to RTEMS on the LEON2/3 processor on RASTA, integrated with File System in Mass Memory and TM/TC
  - » CFDP Java and DTN2 on Linux PCs for Ground segment

- Used to execute use cases similar to those simulated and allow comparison of results, as well as gather actual resource loading

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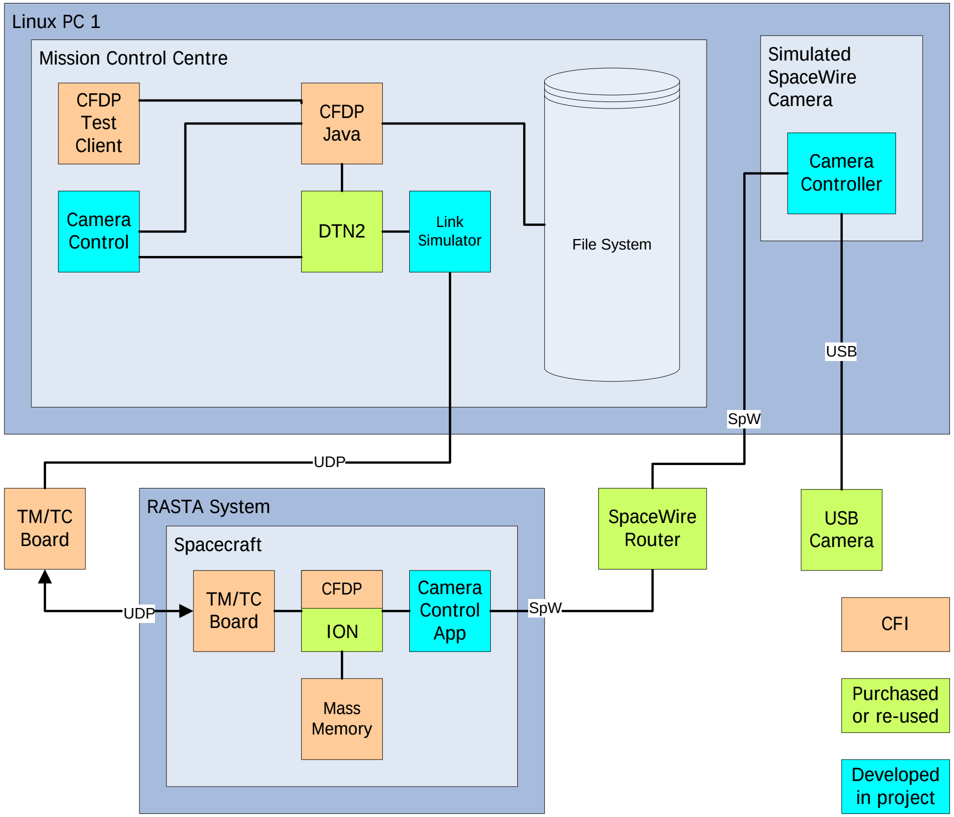
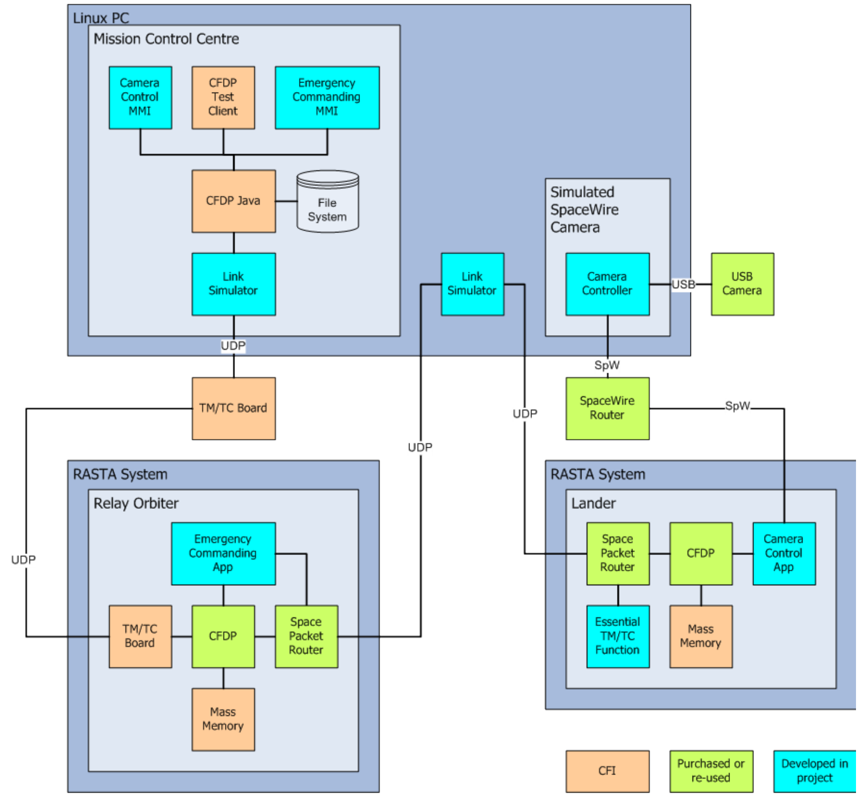
Protocols Testbed Design – Direct Scenarios



- Ground system send and receive files, and camera TCs to spacecraft.
- Spacecraft and MCC can optionally use CFDP or CFDP over DTN.
- Link Simulators represent error rate, latency and bandwidth from MCC to spacecraft at each link
- MCC communicates with the Spacecraft via the TM/TC module.
- Spacecraft runs Camera Control application that utilises the simulated SpaceWire Camera via SpaceWire Router.
- Simulated SpaceWire Camera runs on Linux PC and translates commands sent over SpaceWire into function calls in the camera software library
  - Camera itself is connected via USB to the Linux PC.

Protocols Testbed Design – Relay Scenarios



- Ground system send/receive files, send emergency TCs encoded within files and camera TCs via side-band messages to a Lander via an Orbiter acting as a communications relay.
- Orbiter and Lander only use CFDP (DTN not done due to project schedule constraints)
- Same Camera Control application using CFDP but different CFDP classes
- Same Link Simulators as with Direct Scenarios but include links Orbiter and Lander
- MCC communicates with Orbiter via the TM/TC modules
- Orbiter communicates with Lander via a UDP link (standing in for a Proximity-1 link).
- Lander runs Camera Control application and Simulated SpaceWire Camera as with Direct Scenario

Protocols Testbed Tests

- Protocols Testbed was used to demonstrate following operations in space comms architectures:
  - » Uplink and downlink of files of size 1K, 10K and 100Kbytes
    - › Unreliable, in the presence of no errors in the space links;
    - › Reliable, in the presence of no errors in the space links;
    - › Reliable, in the presence of errors in the space links.
  - » Camera control operations.
  - » Onboard filestore management operations.
  - » Emergency commanding operations (relay scenarios only).
- Following simulation results, following subset of mission scenarios selected for demonstration and comparison:
  - » Direct to LEO using CFDP against DTN
  - » Direct to L2 using CFDP (LTP not possible due to project schedule constraints)
  - » Direct to Mars using CFDP against DTN
  - » Relay to Lunar using CFDP (DTN not done due to schedule constraints)
  - » Relay to Mars using CFDP (DTN not done due to schedule constraints)

Comparison of Simulator and Protocols Testbed Results

- CFDP Direct to LEO
  - Unreliable uplinks: for the high uplink bandwidth, Protocols Testbed 5-20 x Simulator
    - Likely due to performance of CFDP C on RASTA LEON processor
  - Unreliable & reliable downlinks with no errors: for the high uplink bandwidth, Protocols Testbed = the Simulator
  - Reliable downlinks with errors, Protocols Testbed 2.5-4 x Simulator
    - Likely due to performance of CFDP C on RASTA LEON processor
- DTN [
- CFDP
  - sizes
- CFDP
- DTN [
  - WLT
- CFDP
- CFDP
  - Different connectivity used so no meaningful comparison

Summary is Protocols Testbed test results makes clear that:

- For missions with short OWLT, CPU processing on spacecraft drives transaction duration
  - Linux PC -> RASTA LEON3 @ 40MHz in FPGA = 5 – 20x increase
- For missions with long OWLT, CPU processing on spacecraft has little effect upon transaction duration
- Higher protocol overhead in packets with CFDP over DTN compared to CFDP due to additional levels of encapsulation
  - Proportion compared to user data depends upon file segment sizes and DTN bundle sizes
- Higher memory utilisation with CFDP over DTN compared to CFDP due to buffering at additional layers
  - Depends upon file segment sizes and DTN bundle sizes

Roadmap to Introduction of CFDP and DTN

Roadmap to Introduction of CFDP and DTN (1/3)

- DTN (BP and LTP) not baselined or currently foreseen for any ESA mission or infrastructure
  - CCSDS Standards for BP considered too immature and add no obvious benefit at this point in time
- CCSDS road map for CFDP recommendation refresh in 2013/4 include:
  - Deletion of Class 3 and 4 whilst retaining Store and Forward Overlay (SFO)
  - Addition of optional Finished PDU for Rx to notify Tx of transfer completion in Class 1 transfers (Class 1a)
  - Increase maximum file size from 4 Gbytes
  - Increase maximum segment size
- Therefore CFDP profiles likely to be of use are:
  - Class 1 CFDP (point to point, unreliable)
  - Class 2 CFDP (point to point, reliable)
  - Class 1 CFDP with SFO (relay, unreliable)
  - Class 2 CFDP with SFO (relay, reliable)

Roadmap to Introduction of CFDP and DTN (2/3)

- Near Earth Missions
  - » CFDP is establishing itself as de facto standard method for file transfer.
    - › Automated file transfer capability key enabler for FBO and CFDP is most credible provider
    - › CFDP also enables operation of the data downlink with reliable quality of service
    - › For reliable downlink transfer, CFDP's NACK ARQ makes it suitable for typical asymmetric links encountered in TT&C links
  - » Recommended that all near Earth missions adopt CFDP as baseline for file transfer
    - › CFDP Class 2 and possibly Class 1 for ephemeral or highly redundant data sets
  - » No planned or envisaged near Earth missions that would drive a move to DTN
- Deep Space Missions
  - » CFDP NACK ARQ specifically designed with long delay return paths in mind
  - » CFDP to support FBO particularly critical due to long delays & interactive comms particularly difficult
  - » DTN has no significant advantages over CFDP in these deep space scenarios.
- Planetary Orbiter/Lander Communications
  - » Use of CFDP Class 1 and 2 with SFO is recommended
    - › Since the contact periods in Earth/Orbiter and Orbiter/Lander links are well defined and predictable
  - » Files can be segmented at application layer to optimise data throughput and timeliness
  - » Intermediate storage of data at file level allows remote mgmt of file queues from MCC
    - › Not possible with DTN's BP.
  - » Use of DTN not recommended until no. of contact opportunities difficult to manage

Roadmap to Introduction of CFDP and DTN (3/3)

- Data Relay Satellites
  - CFDP decouples usage and management of feeder and ISLs
  - Allows capacity of links to be better utilised where limited throughput data rate alternated between feeder and inter-satellite links
    - At expense of spacecraft complexity (though simplifying link management) and subject to the limitations of storage capacity
  - Opportunity to manage intermediate file storage allowing e.g. prioritisation of data or deletion of ephemeral or duplicate data sets.
  - No obvious reason to introduce DTN. However, DTN in future large communicating via ISL constellations could provide data return with optimised throughput and timeliness
- Earth Stations
  - LEO mission may have short passes which generate large amounts of data
  - CFDP SFO with inherent rate buffering capability significantly reduce terrestrial tx bandwidth
  - Storing data in CFDP accessible file store at earth station allows for re-ordering or deletion of files by the MCC to increase mission flexibility and, in some cases, reduce space link traffic.
  - CFDP Class 2 at earth station could also increase contact period utilisation at beginning/ end of contact period by operating through periods of high BER.
  - DTN could be introduced to complement ISL satellite constellation but not planned
- Mission and Payload Control Centres
  - MCCs have CFDP as obverse of corresponding space segment CFDP implementation
  - For PCC access to CFDP capable payloads via transparent MCC, CFDP in PCC
  - MCC provide measures to ensure that PCC can’t interact with spacecraft bus functions via CFDP
  - These measures difficult to implement using DTN

Conclusions

Conclusions

- Recommended CFDP and CFDP over DTN space communication architectures defined for reference mission scenarios
- Recommended updates to CFDP standard
  - » CFDP Class 1a be introduced, with this, CFDP performance = CFDP over DTN for reliable comms
  - » CFDP SFO is recommended over Classes 3 and 4 should proxy operations be required, add Proxy Put to SFO
- Recommended spacecraft communication architecture to deploy CFDP and DTN upon spacecraft
  - » CFDP in Mass Memory implementing File System
- Space Communications Simulator developed
  - » Simulations performed comparing the different recommended spacecraft comms architectures
  - » EUCLID science data downlink scenario has been simulated and performances projected
- RASTA-based Protocols Testbed developed
  - » Selected space communication architectures demonstrated and compared against Simulator results
  - » Memory utilisations measured and deemed to be a factor of 1) buffering at each layer & 2) CFDP file segment and DTN bundle sizes
- Roadmap for the introduction of CFDP for file transfers in ESA missions defined
  - » DTN is considered too immature and adds no obvious benefits at this point in time
- Next steps: File-Based Operations project: refine file-based operational concepts and define PUS and CFDP usage to achieve these

Thank you

Any questions?