Delay-Tolerant Networks For Earth Observation

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DTN-EO

OVERVIEW

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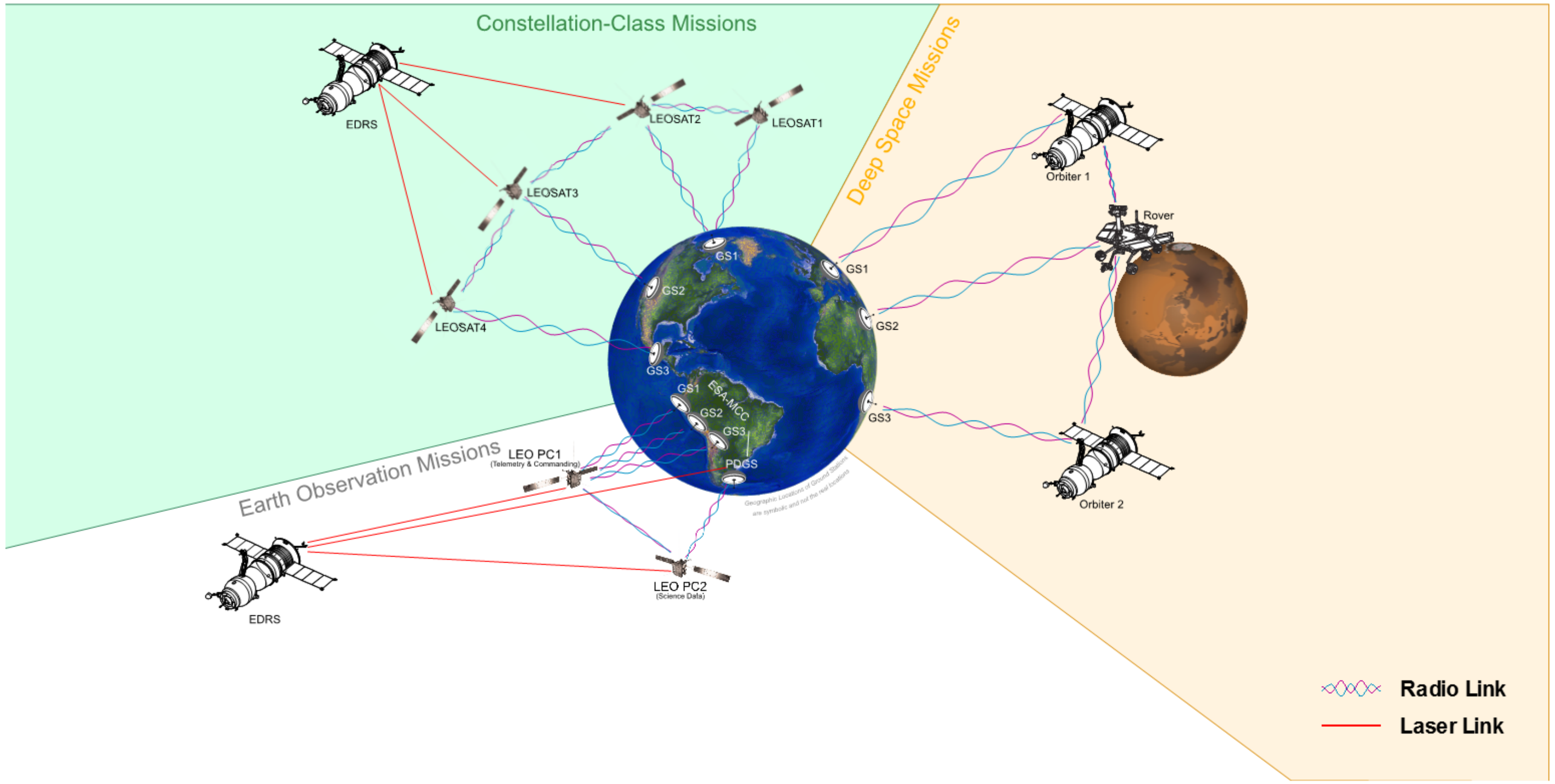
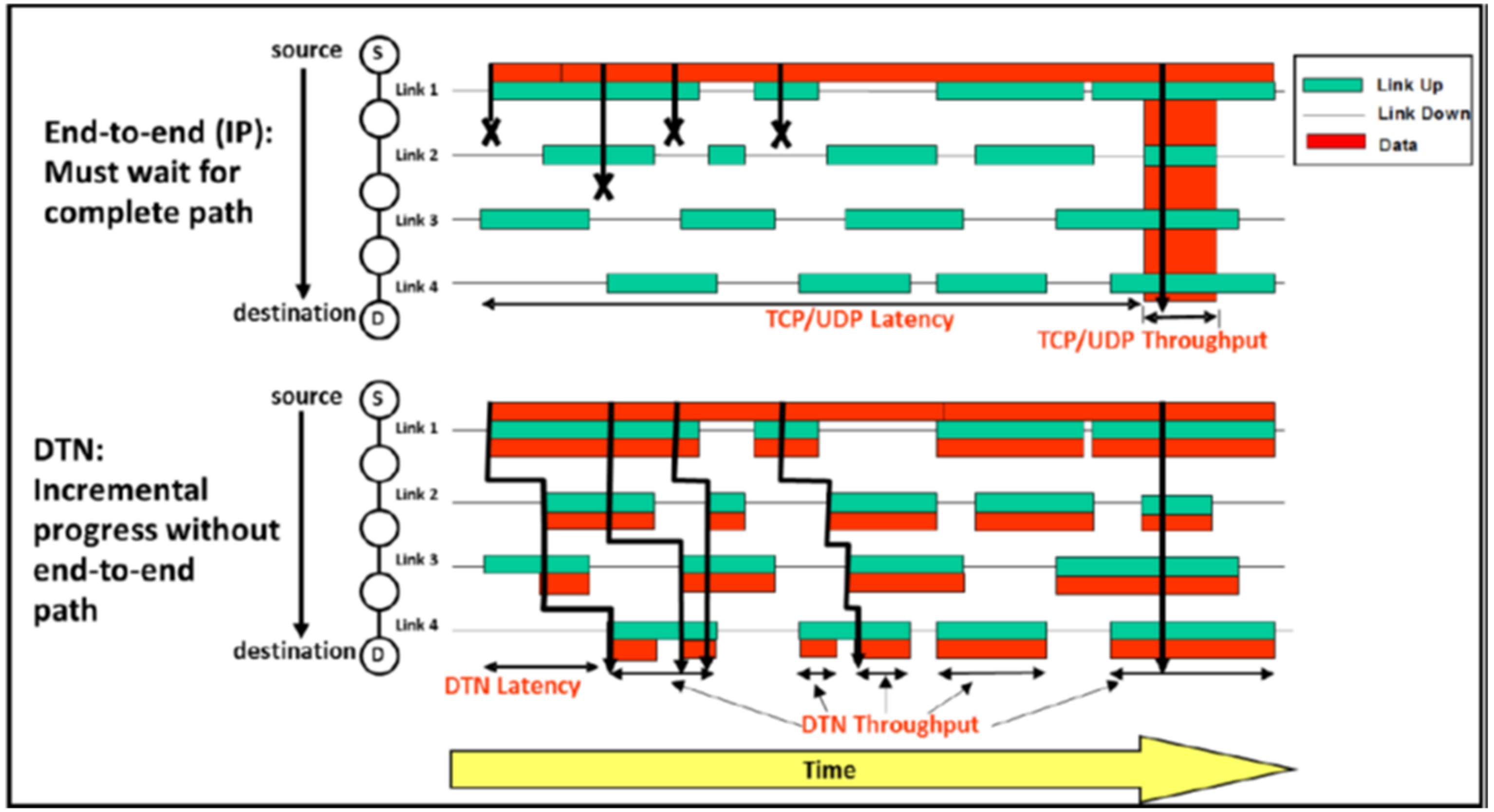
STUDY OBJECTIVES

- **How to realize the establishment of the Space Internet around Earth.**
- **Work out possible benefits of DTN.**
  - Develop implementation scenarios
    - Maximize resource utilization
    - Reduction of data delivery time using Contact Graph Routing (CGR)
    - Support emergency communication
  - Proof of concept
    - Configuration generation
    - Representative Simulations
  - Rollout strategy
    - Introduction roadmap
    - Investment break-even
  - Implementation Analysis, based upon scenario testing



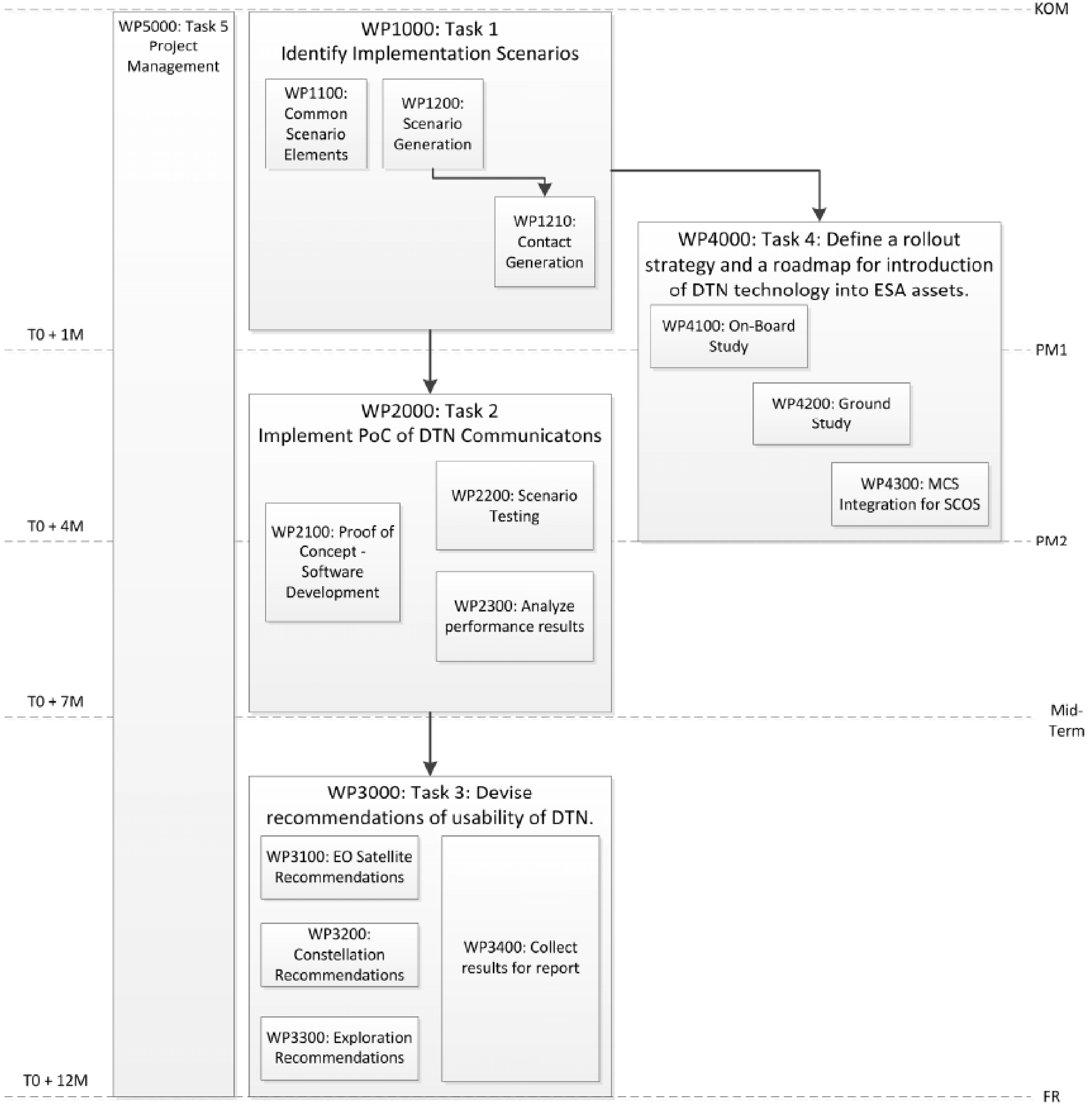
DTN – A MODERN MISSION ENABLER

- **DTN provides a robust protocol suite in order to guarantee reception of data in complex and challenging network environments**
  - Well-suited to space applications & includes a robust priority system.
  - Includes Licklider Transmission Protocol (LTP) – A reliable protocol for UDP or space links.
- **Flown Heritage:**
  - 2016 – NASA enables DTN for ISS Payloads
  - 2015 – CCSDS approves the bundle protocol specification for space applications
  - 2013 – The Lunar Laser Communications Demonstration (LLCD) experiment aboard NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) exercises DTN capabilities between earth and the moon.
  - 2012-Today – The ESA METERON project controls ground-based robots from the ISS



TASKS

- **Task 1**
  - Definition of scenarios and collection of scenario data
- **Task 2**
  - Simulator Creation and simulation of scenarios
  - Generation of contact graphs for DTN
  - Creation of contact graph generation script/tool for DTN
- **Task 3**
  - Simulator analysis report
- **Task 4**
  - High level roadmap and rollout strategy for DTN in EO satellites
- **Task 5**
  - Project Management
  - Reporting



DELIVERABLES

Title	Name
Scenario Report	**GMV-INS-DTN_EO-REP-0001 D1 - Scenario Report**
Simulator & configurations for all three scenarios implementing DTN	**GMV-INS-DTN_EO-REP-1002 S1 - Simulator Report**
Test Report – Showing Results from Scenario Emulation	**GMV-INS-DTN_EO-REP-1003 D2 - Test Report**
Report: Simulation analysis and interpretation	**GMV-INS-DTN_EO-REP-1004 D3 - Simulation Analysis and Interpretation Report**
Report: Requirements and Roadmap for DTN in EO	**GMV-INS-DTN_EO-REP-1005 D4 - Requirements and Roadmap Report**
Final Presentation	**GMV-INS-DTN_EO-PRS-1006 FP - Final Presentation**
Executive Summary Report	**GMV-INS-DTN_EO-REP-1007 ESR - Executive Summary Report**
Two Illustrations	**GMV-INS-DTN_EO-ILL-1008 IL - Illustrations**
Final Report	**GMV-INS-DTN_EO-REP-1009 FP - Final Report**

DTN-EO EMULATOR

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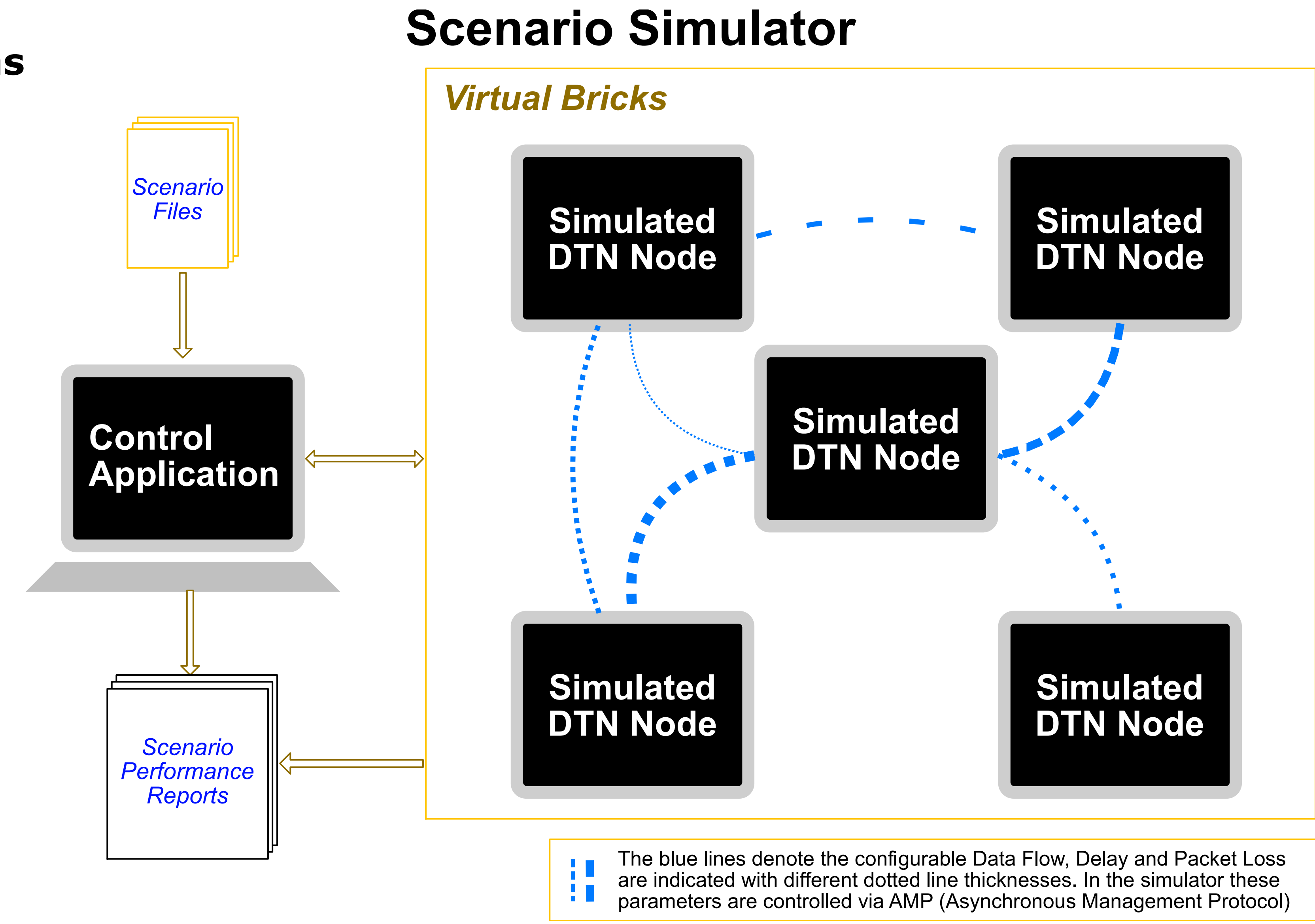
DESIGN

- **Technical Background The emulator generated as a result of WP2xxx is designed as a series of modules.**
  - Using Free and open-source software (FOSS) and consortia developments.
  - Runs on Linux.
  - Dynamic loading of the scenarios is accomplished via IETF standards (AMP).
  - Performance analysis and data generation performed via DTNPerf

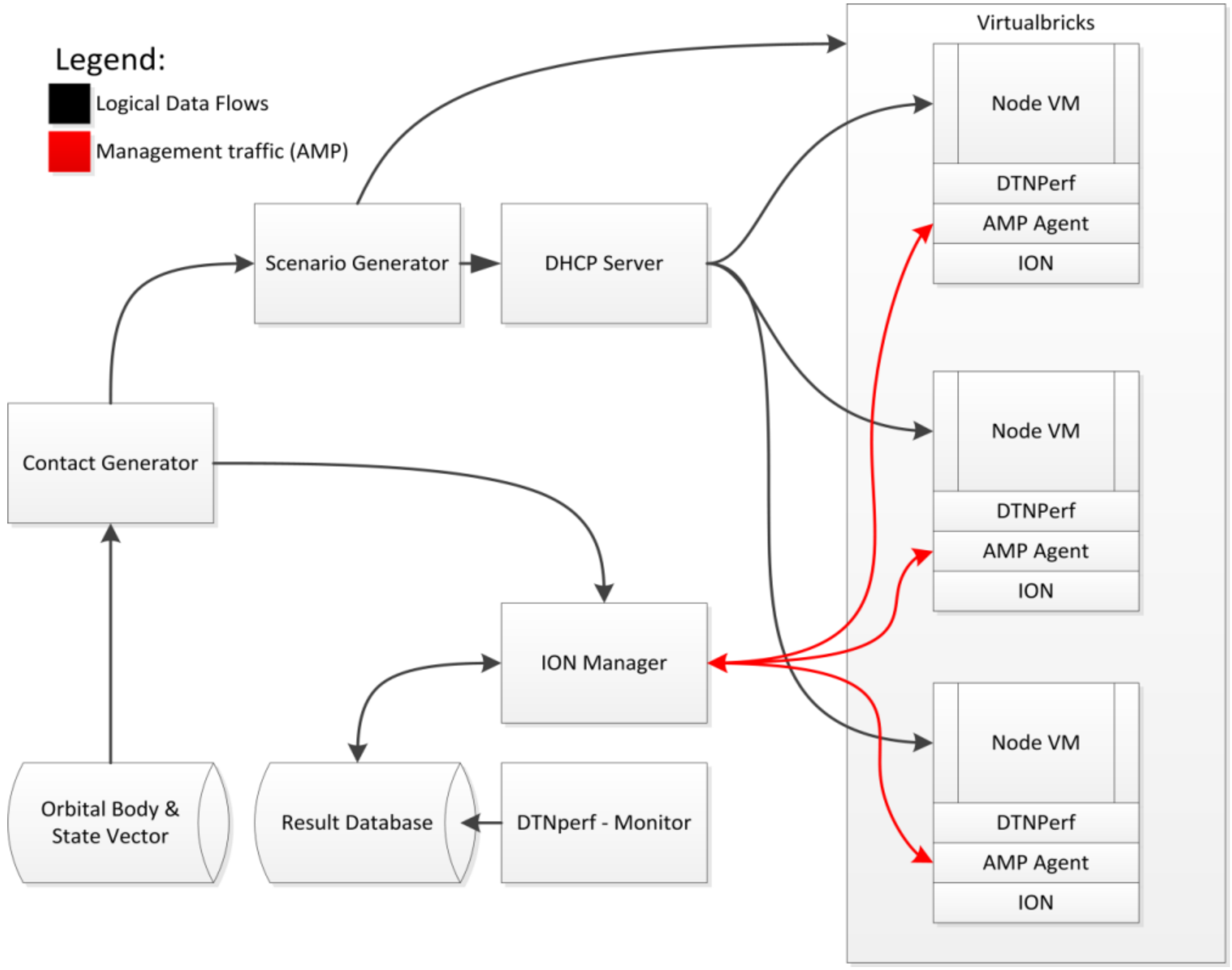


SCENARIO CREATION AND PROCESSING

- **Scenarios are provided to the emulator as a series of JSON & CSV files.**
- **These files describe the nodes, network topology, reporting, etc. for a single scenario.**
  - Bitrates and contact times may be scaled.
- **Assets can be configured with DTN & system settings:**
  - Base VM images, IP addresses, DTN specific settings.
  - ION Settings are provided with a template file.
- **associated with orbital parameters:**
  - Body (Earth, Mars, etc.)
  - Antenna visibility cone & rotation
  - And one of the following additional descriptors:
    - ground station (Latitude, longitude, and elevation)
    - Orbital entity, using MEE2000: (sma, ecc, inc, RAAN, perigee and true anomaly)
- **Upon startup, an initial list of contacts are generated for the user.**
  - The user can use these files to refine the potential contacts, before the next step.
  - All contacts are generated as CSV files, in order to allow simple editing.
- **After user editing, the emulator is provided with the pre-built scenario inputs, all configuration files are generated.**
  - The scenario may be run or shared.
  - Includes ION configuration as well as a VirtualBricks project.
    - Includes a capability to push files into the Virtualbricks VM images, in order to quickly generate customized virtual machines.

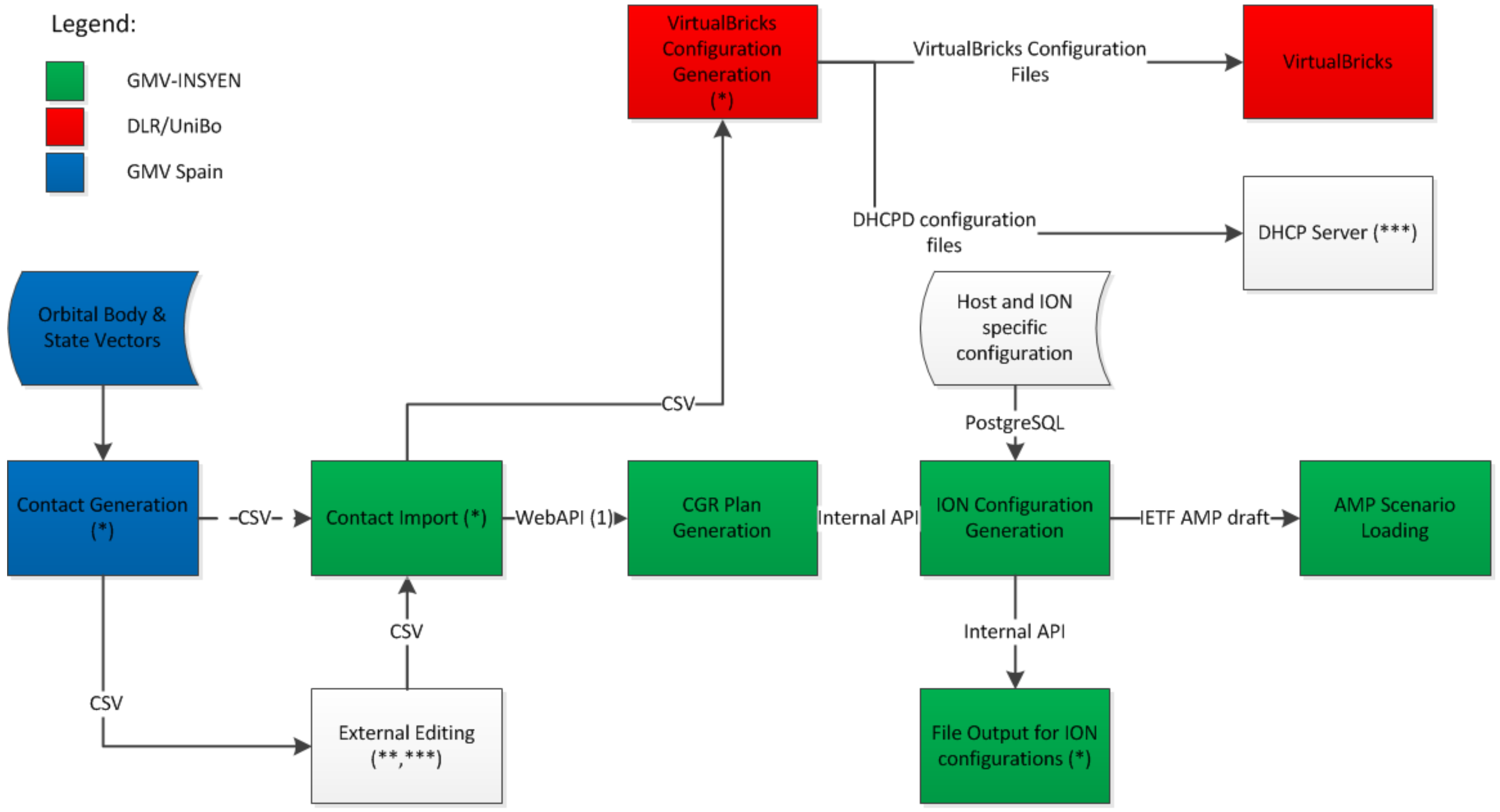
EMULATOR

- **Technical Background The emulator generated as a result of WP2xxx is designed as a series of modules.**
  - Using Free and open-source software (FOSS) and consortia developments.
  - Runs on Linux.
- **Individual elements are developed by individual consortia members, based upon their strengths.**



DESIGN

- **As the emulator is being developed by different members, well-defined interfaces are critical.**
- **Many of the individual components use well-defined interfaces.**
  - E.g. the ION Configuration generation, etc. is based on internal APIs and a well-defined webAPI.
  - ION configuration file formats are well-known and stable.
  - Dynamic loading of the scenarios is accomplished via IETF standards (AMP).
- **The largest interface description will be the CSV file containing the contacts.**
  - Used by GMV-ES, GMV-I, and UniBo.



References:
- *CSV file format will be defined in WP1100, but may be based on https://cwe.ccsds.org/sis/docs/Forms/AllItems.aspx?RootFolder=%2Fsis%2Fdocs%2FSIS-DTN%2FDraft%20Documents%2FSchedule-Aware%20Bundle%20Routing%20(SABR)*
- *(1) . https://github.com/INSYEN/Sphere_Middleware/wiki/Web-Services---API-Description*

Notes:
** indicates new development and/or a modification on existing software*
*** Selection of the external editing tool (Excel, Open/LibreOffice, etc) may be determined by indvidual users & consortium members.*
**** Open-source tool.*

Scenario Inputs

- **Scenarios are provided to the emulator as a series of JSON & CSV files.**
- **These files describe the nodes, network topology, reporting, etc for a single scenario.**
  - Bitrates and contact times may be scaled.
- **Assets can be configured with DTN & system settings:**
  - Base VM images, IP addresses, DTN specific settings.
  - ION Settings are provided with a template file.
- **associated with orbital parameters:**
  - Body (Earth, Mars, etc)
  - Antenna visibility cone & rotation
  - And one of the following additional descriptors:
    - ground station (Latitude, longitude, and elevation)
    - Orbital entity, using MEE2000: (sma, ecc, inc, RAAN, perigee and true anomaly)

Scenario/

- General.json
- Assets.json
- Links.csv
- Reports.csv
- Dataflows.csv
- Configurations/
  - ScenarioC.rc

Scenario Operation – Build Mode

- **Provided with the scenario inputs, an initial list of contacts are generated for the user.**
  - The user can use these files to refine the potential contacts, before the next step.
  - All contacts are generated as CSV files, in order to allow simple editing.

Scenario/

- General.json
- Assets.json
- Links.csv
- Reports.csv
- Dataflows.csv
- Configurations/
  - ScenarioC.rc
- *Contacts/*
  - *EDRS-A.csv*
  - *ESA-MCC.csv*
  - *Martian Lander.csv*

Scenario Operation – Create Mode

- **Provided with the pre-built scenario inputs, all configuration files are generated.**
  - The scenario may be run or shared.
  - Includes ION configuration as well as a VirtualBricks project.

Scenario/

- General.json
- Assets.json
- Links.csv
- Reports.csv
- Dataflows.csv
- Configurations/
  - ScenarioC.rc
- Contacts/
  - EDRS-A.csv
  - ESA-MCC.csv
  - Martian Lander.csv
- *outputConfigurations/*
  - *105_EDRS-A/*
    - *ScenarioC.rc*
  - *231_ESA-MCC/*
    - *ScenarioC.rc*
  - *143_Martian Lander/*
    - *ScenarioC.rc*
  - *ScenarioC.vbp*

DTN-EO

SCENARIOS & RESULTS

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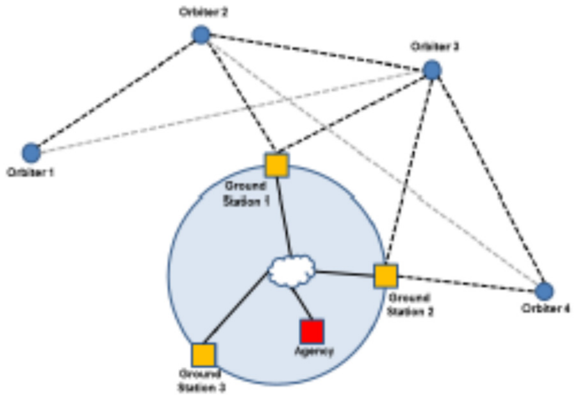
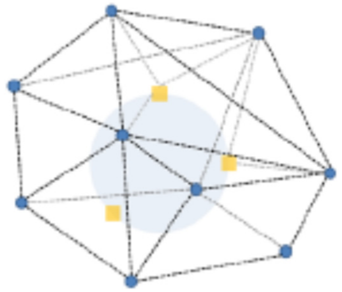
SCENARIOS

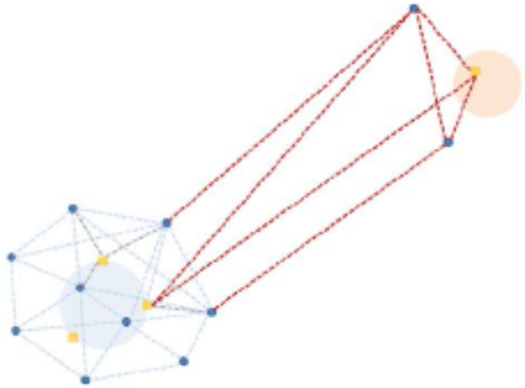
- **3 Scenarios**
  - Scenario-A (Observation)
    - One EO satellite
    - Relay satellites via DTN
    - Realistic ground station Network
  - Scenario-B (Constellation)
    - theoretical globe-spanning fleet of DTN satellites
    - one relay satellite with optical inter-satellite communication
    - Sat-to-sat communication
    - X-Band up and downlink
  - Scenario-C (Exploration)
    - expansion of Scenario-B to deep space DTN communication (planetary, moon, deep space)



Scenario-A



Scenario-B



Scenario-C

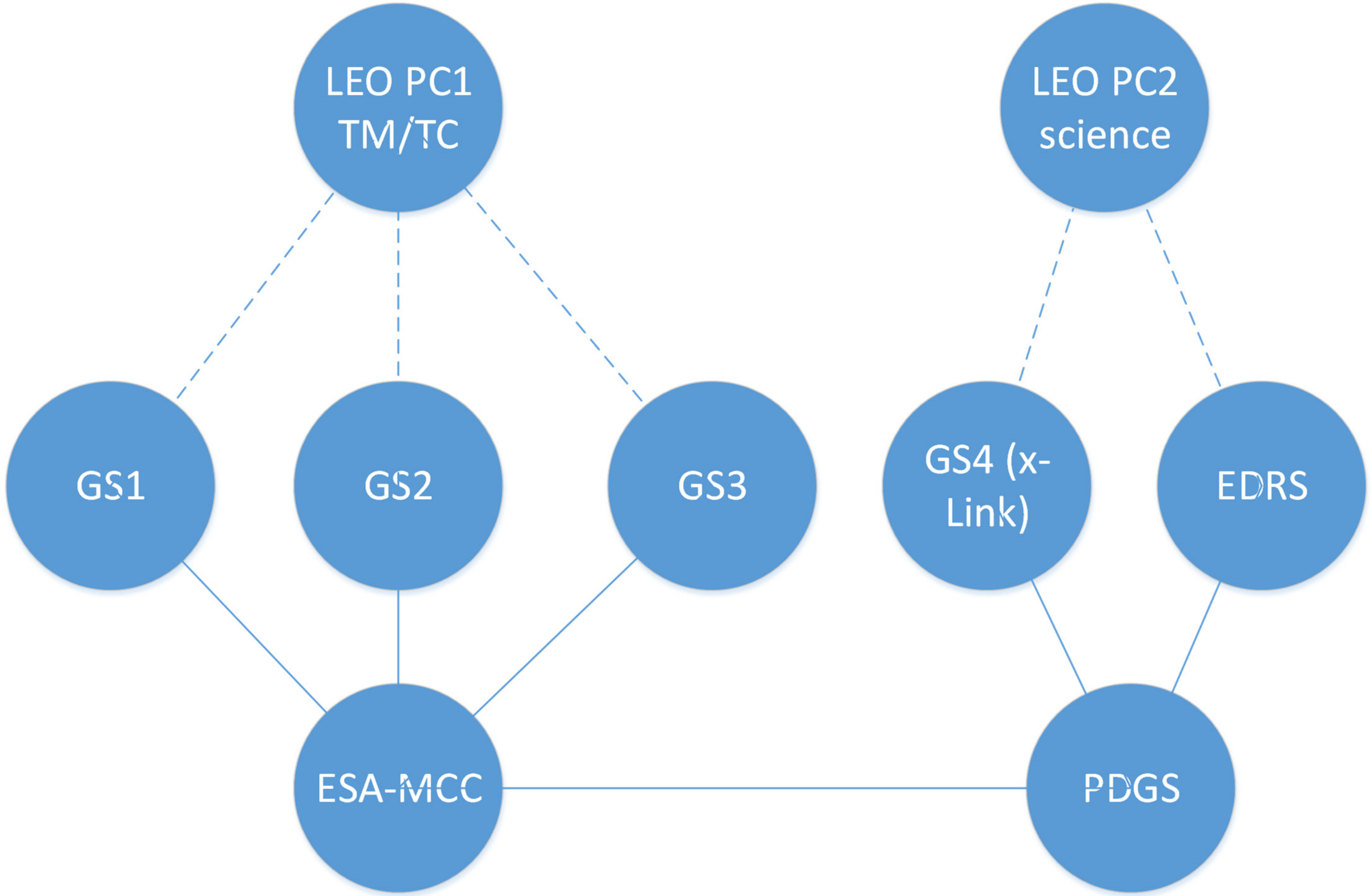
ASSUMPTIONS

- **Basic Assumptions**
  - Emulations as realistic as possible
  - Whenever possible, rooted in CCSDS best practices for DTN networks in space applications
  - All scenarios based on CCSDS variant of the Bundle Protocol (RFC 5050)
- **Link Protocol Assumptions**
  - TCP for Ground interconnections
  - (Red) LTP for bidirectional Space
  - (Green) LTP or UDP for unidirectional Space
  - Links constant or with duty cycle (e.g. contacts)
- Fixed size packets (segments or bundles)
- **Telemetry Assumptions**
  - No division into R/T and Dump TM
  - All generated data directly bundled, buffered and transmitted by the on-board DTN implementation
- **Link Loss Assumptions**
  - Using AWGN (Additive White Gaussian Noise) model
  - Reliability characterized in Packet Error Rates (PER), derived from reasonable bit error rates experienced in the corresponding scenarios.
  - Ground interconnections ideal (TCP)
- **Data Flow Assumptions**
  - Different packet types (TM/TC, TC Ack, science data)
  - Different data rates, bundle sizes, and priorities for each

Link	Packet Error Rate
S-Band	0.001
X-band	negligible
EDRS downlink to Earth	negligible
Inter-Satellite Links	negligible

SCENARIO A

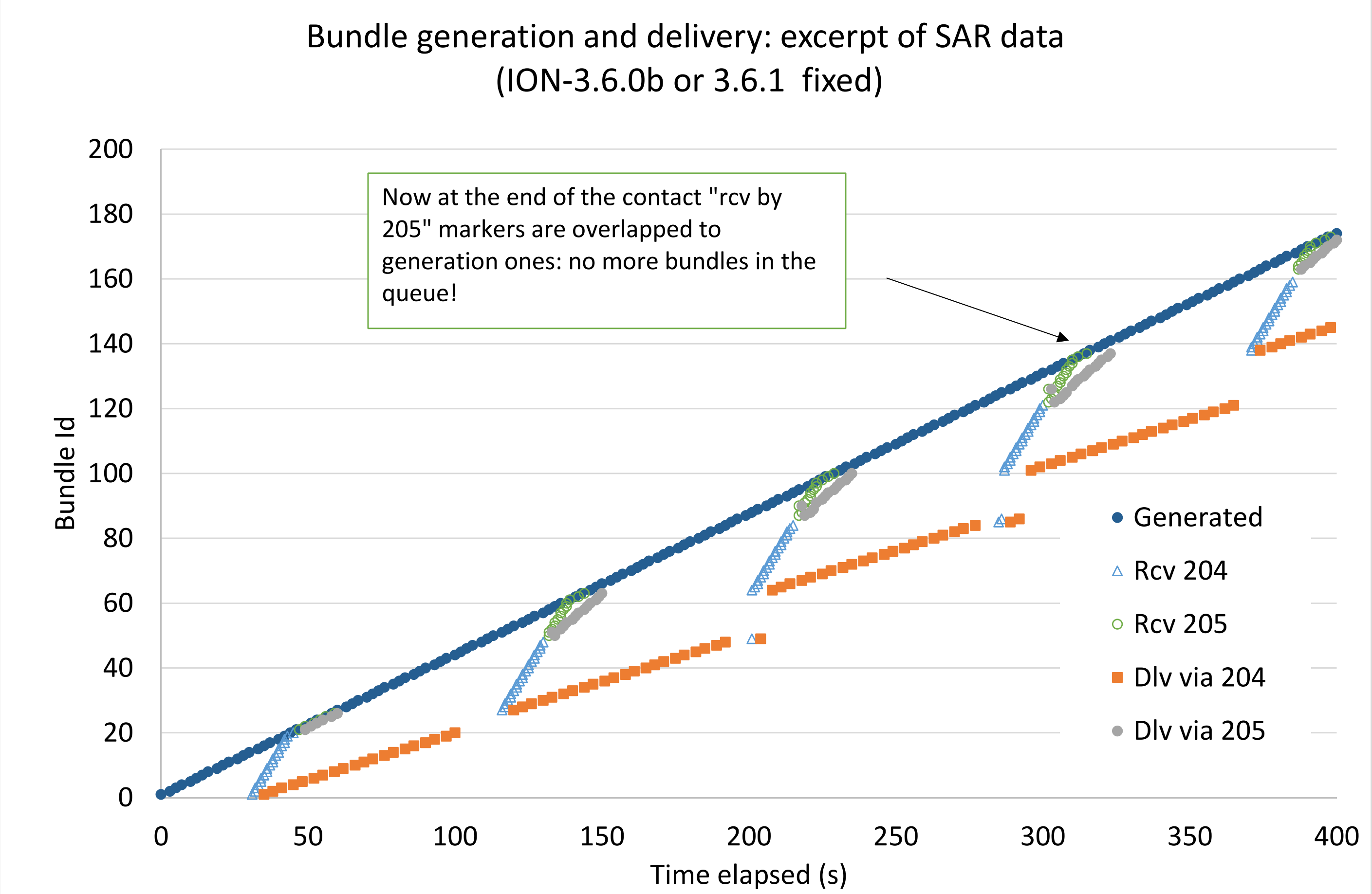
- **Scenario A (Observation)**
  - Two on-board computers: LEO PC1 & 2:
  - X-Band and EDRS links unidirectional (science)
  - S-Band bidirectional (TM/TC)
  - EDRS-A link:
    - Modelled as single hop (no storage), but
    - Presence and constraints influence CGR
    - Uni-directional optical links assumed
  - Delays below the DTN granularity of 1s
- **Objective is to acquire knowledge about**
    - Throughput increase and
    - Delivery time reduction when using DTN
    - Verification of BP store-and-forward mechanism
    - Test CGR effectiveness with regards to multiple paths



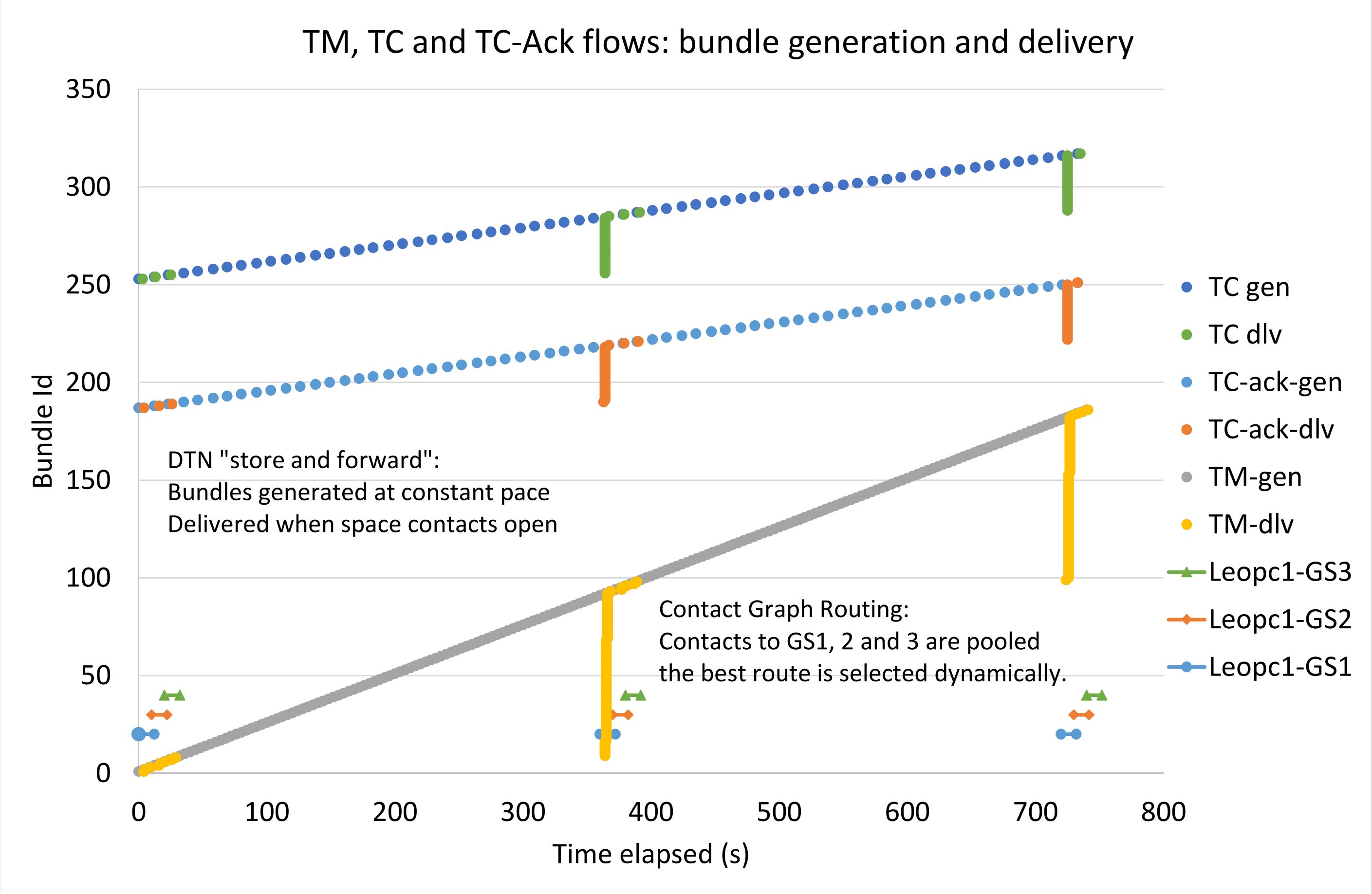
Flow Name	Bitrate (Max)	Bundle Size (bytes)	Priority	Duty cycle (active time/total time)
TM	8 KBit/s	4096	1 (normal)	Constant
Replay TM	8 KBit/s	4096	2 (normal)	Constant
TC	64 kbit/s	1024	2 (expedited)	1min/90min
TC acks	64 KBit/s	1024	2 (expedited)	1min/90min
SAR	512 Mbit/s	1,024,000	0 (bulk)	25min/90min

SCENARIO A - RESULTS

- **Analysis of SAR Flow**



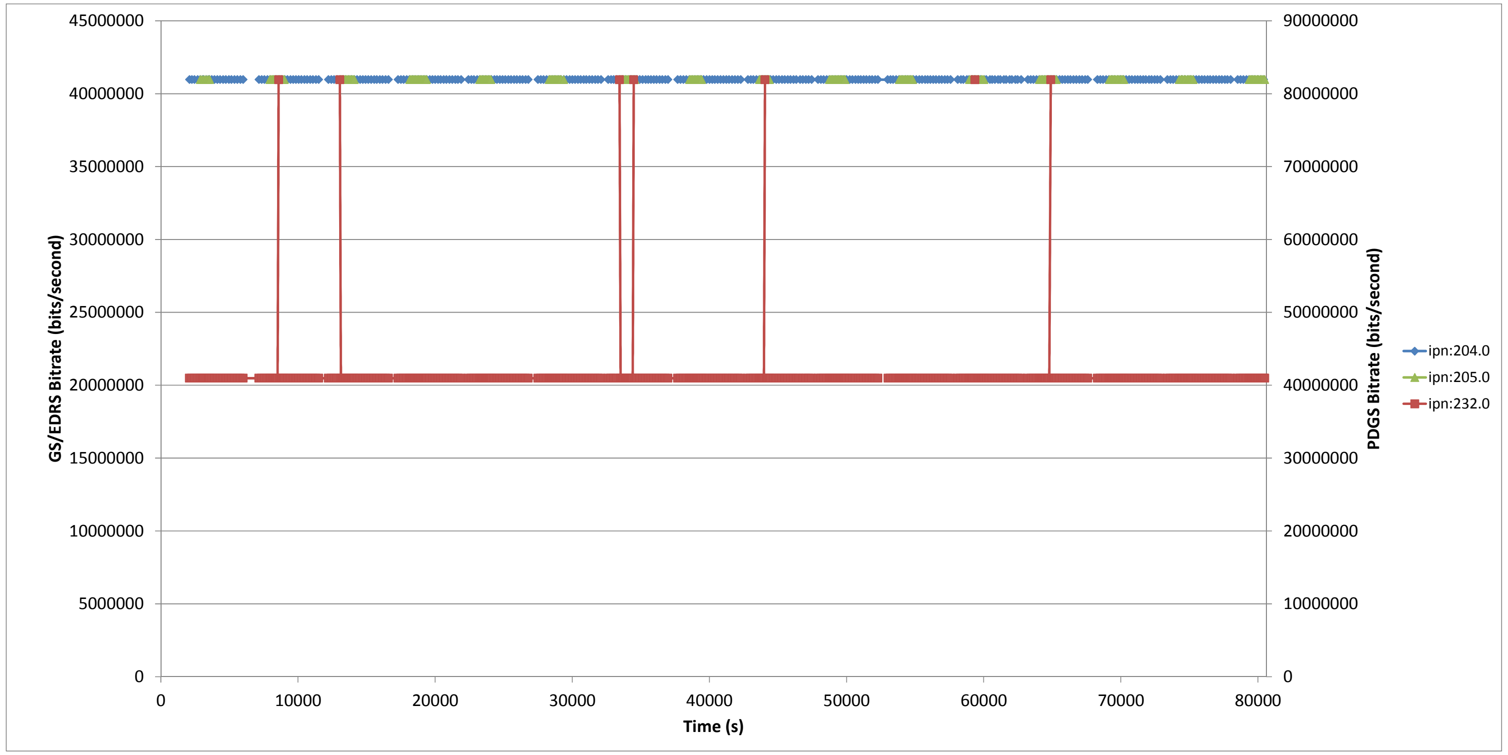
- **Analysis of TM/TC Flows**



SCENARIO A – RESULTS

- **A comparative analysis of throughputs was performed**
- **It was found that DTN efficiently utilized the entire contact duration for scientific data & TM/TC**
  - DTN-based transmission used *94%* of the maximum possible contact duration, equaling 53,400MB per day of additional data.

Analysis of High-Rate Throughput

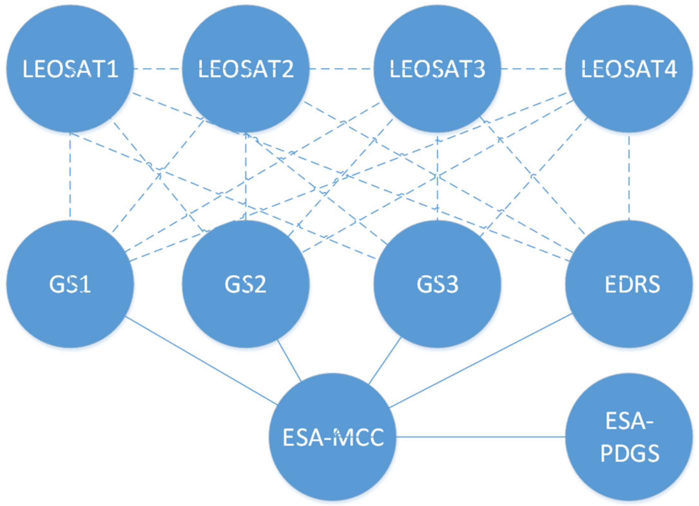


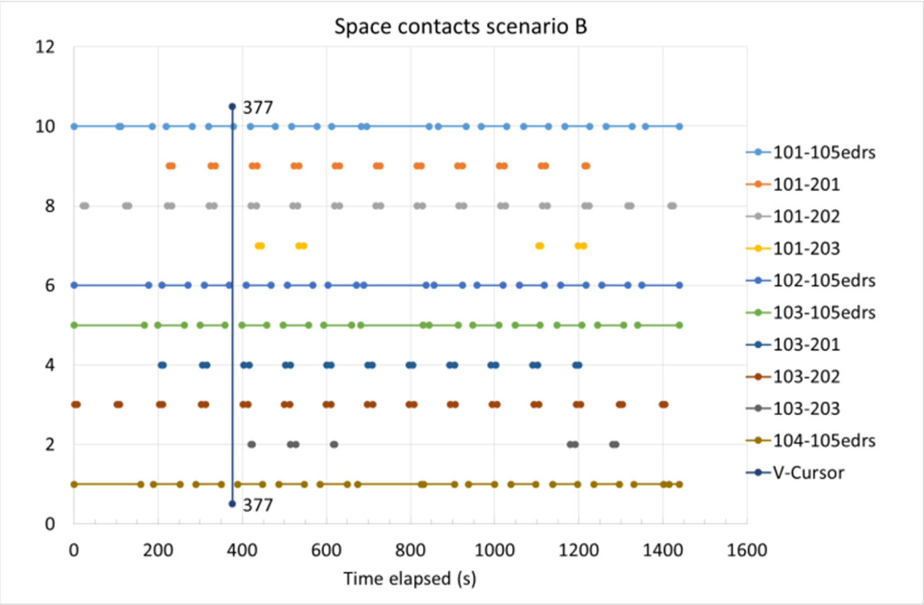
Downlink	Theoretical Max (MB)	Safe Max. (MB)	DTN Max. (MB)	Delta data volume (between safe and DTN) (MB)
EDRS	552,960	475,520	497,512.5	21,992.5
X-Band	868,352	817,152	848,559.375	31,407.375
Total	1,421,312	1,292,672	1,346,072	53,400

SCENARIO B

- **Scenario B (Constellation)**

  Same as Scenario A (data rates, contact plans…), but:
  - Theoretical convoy of DTN LEO satellites
  - Two kinds of science instruments (1&3, 2&4)
  - Geometrical simulation (orbital data)
  - Exclusive use of DTN Bundle Protocol
  - X-Band links bi-directional, no S-Band
  - Bi-directional Inter-Satellite Links (ISL)
- **Objective is to investigate:**
  - Effects on data delivery time using data balancing between satellites
  - Virtual extension of Space-to-Ground connections
  - Link capacity gain with increasing number of assets
  - Optimal path selection with CGR

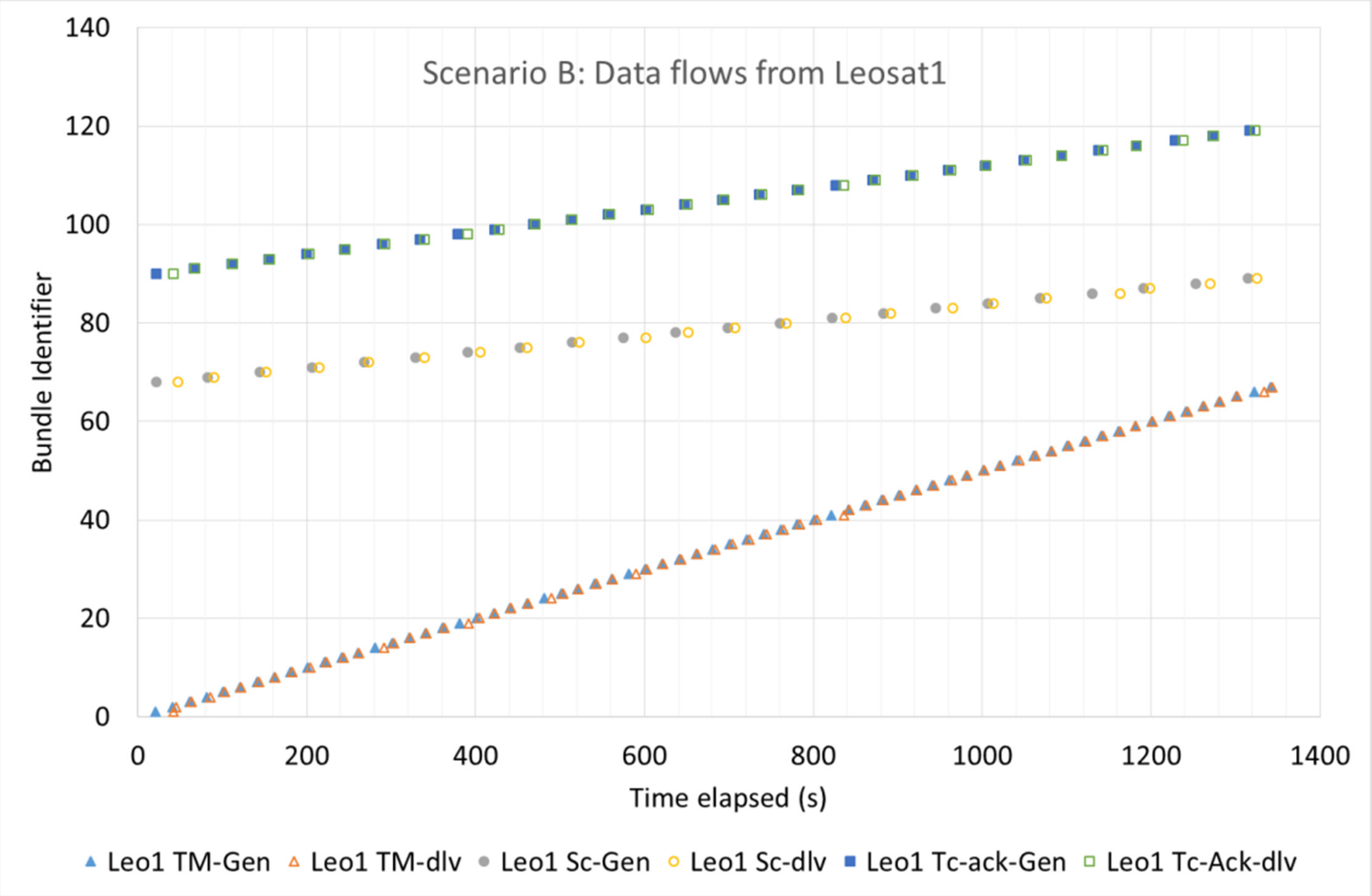




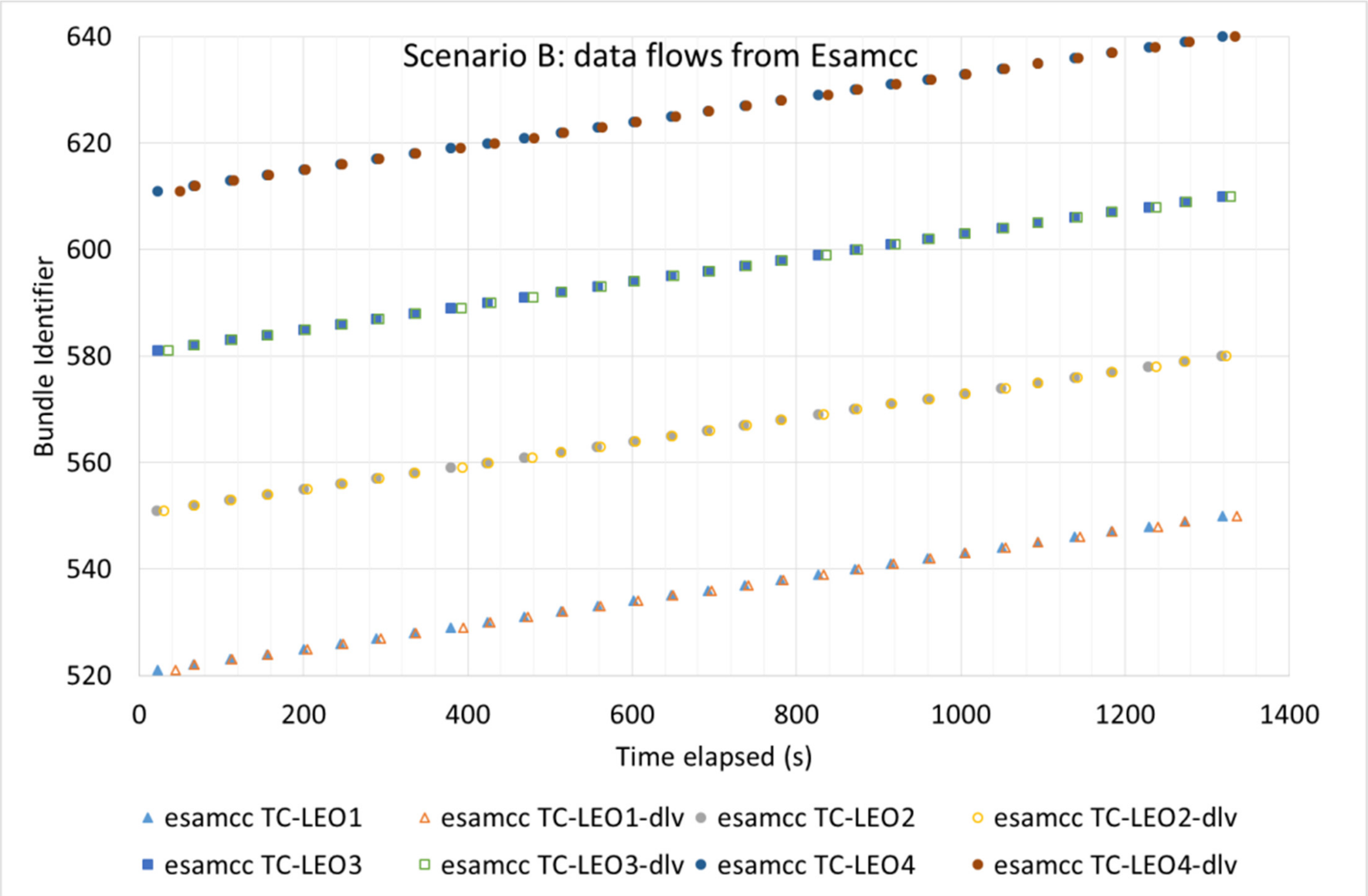
Flow Name	Bitrate (Max)	Bundle Size (bytes)	Priority	Duty cycle (active time/total time)
TM	64Kbit/s	4096	1 (normal)	Constant
TC	64 kbit/s	1024	2 (expedited)	1min/90min
TC acks	64 kbit/s	1024	2 (expedited)	1min/90min
Science 1	32 Mbit/s	1,024,000	0 (bulk)	15min/90min
Science 2	32 Mbit/s	512,000	0 (bulk)	15min/90min

SCENARIO B - RESULTS

- **Downlink Flows (LeoSAT1)**



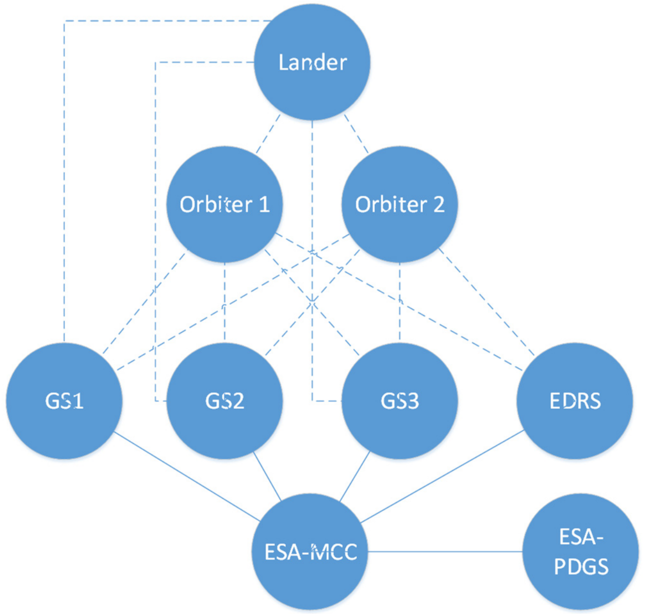
- **Uplink Flows**

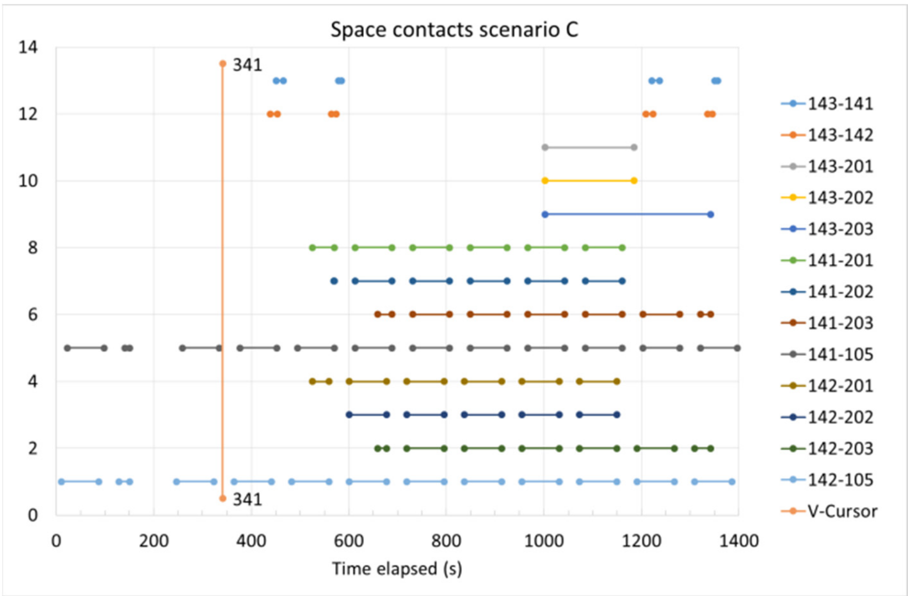


SCENARIO C

- **Scenario C (Exploration)**

  Same assumptions as Scenario B (data rates, contact plans…), but:
  - Mars Lander/Orbiter combo replaces convoy of LEOs
  - Lander-Earth connection dependent on Earth/Mars positions and position of Lander on Mars
  - Lander-Orbiter connection
    - Visibility ~8min/sol with a cycle time of ~8h
  - Orbiter-Earth connection
    - Visibility ~16h/day
  - Very high delays between 3 and 22 min
- **Objective is to study:**
  - Influence of long delays
  - Very limited connection opportunities
  - DTN’s Multipath behavior
  - Different planetary bodies

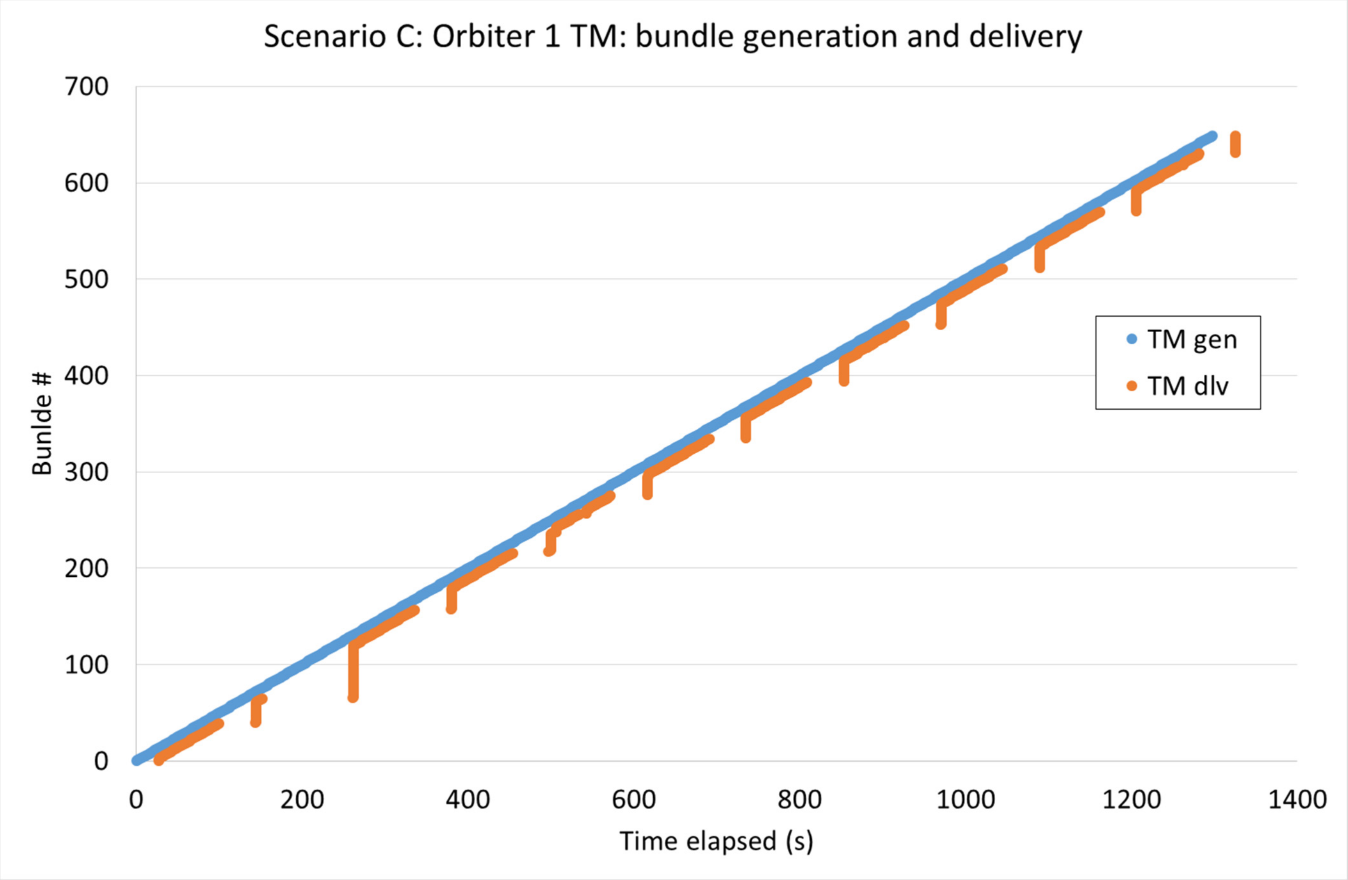




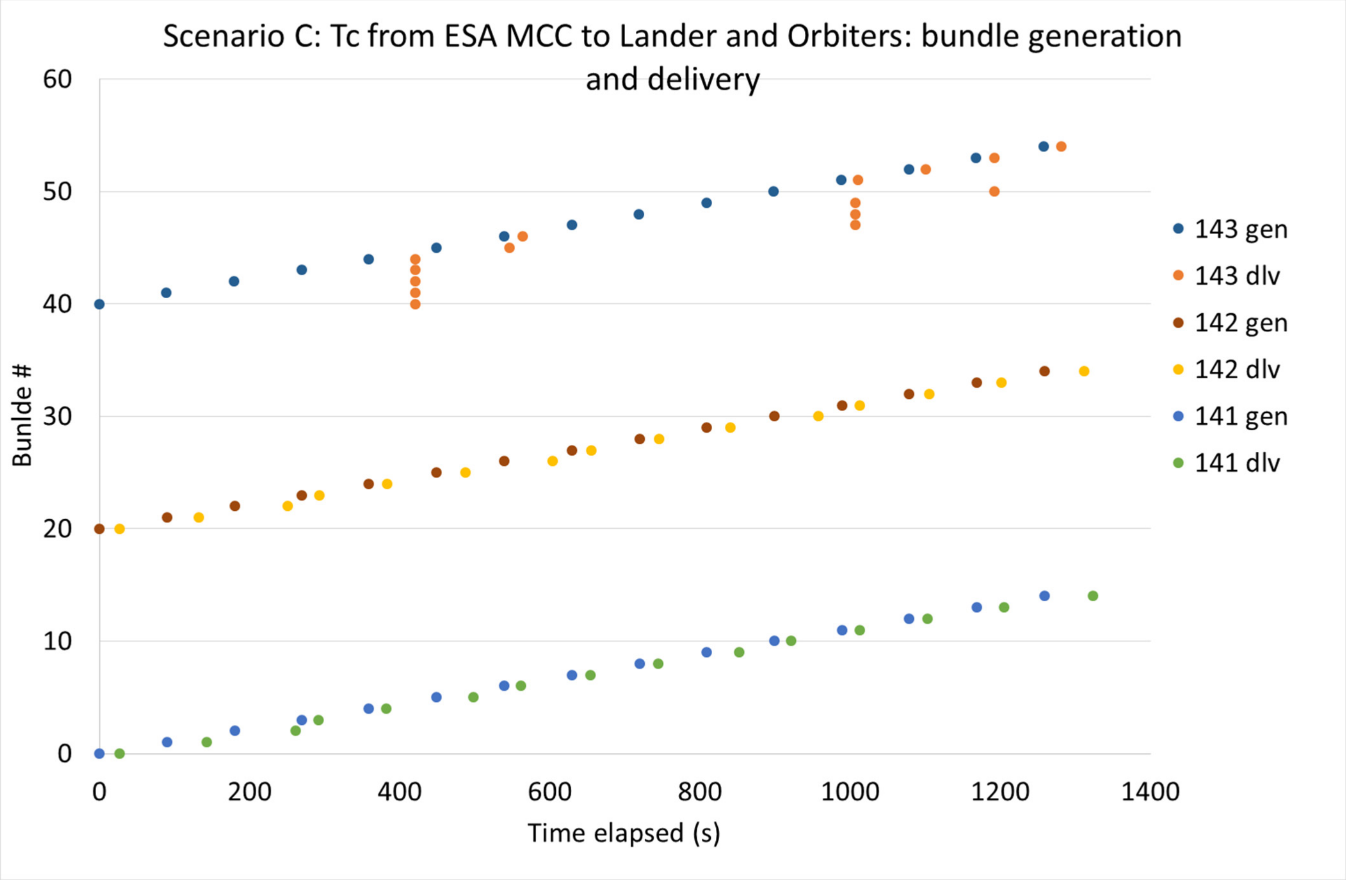
Flow Name	Bitrate	Bundle Size (bytes)	Priority	Duty cycle (active time/total time)
TM	16Kbit/s	4096	1 (normal)	Constant
TC	8 kbit/s	1024	2 (expedited)	1min/90min
TC-ACK	8 kbit/s	1024	2 (expedited)	1min/90min
Science 1	16Kbit/s	256,000	0	25min/90min
Science 2	32Kbit/s	512,000	0	15min/90min
Science 3 - DEM	128Kbit/s	512,000	0	10min/90min
Science 4 - Video	2Mbit/s	64,0000	0	10min/90min

SCENARIO C - RESULTS - ORBITERS

- **TM: from Orbiter to MCC**

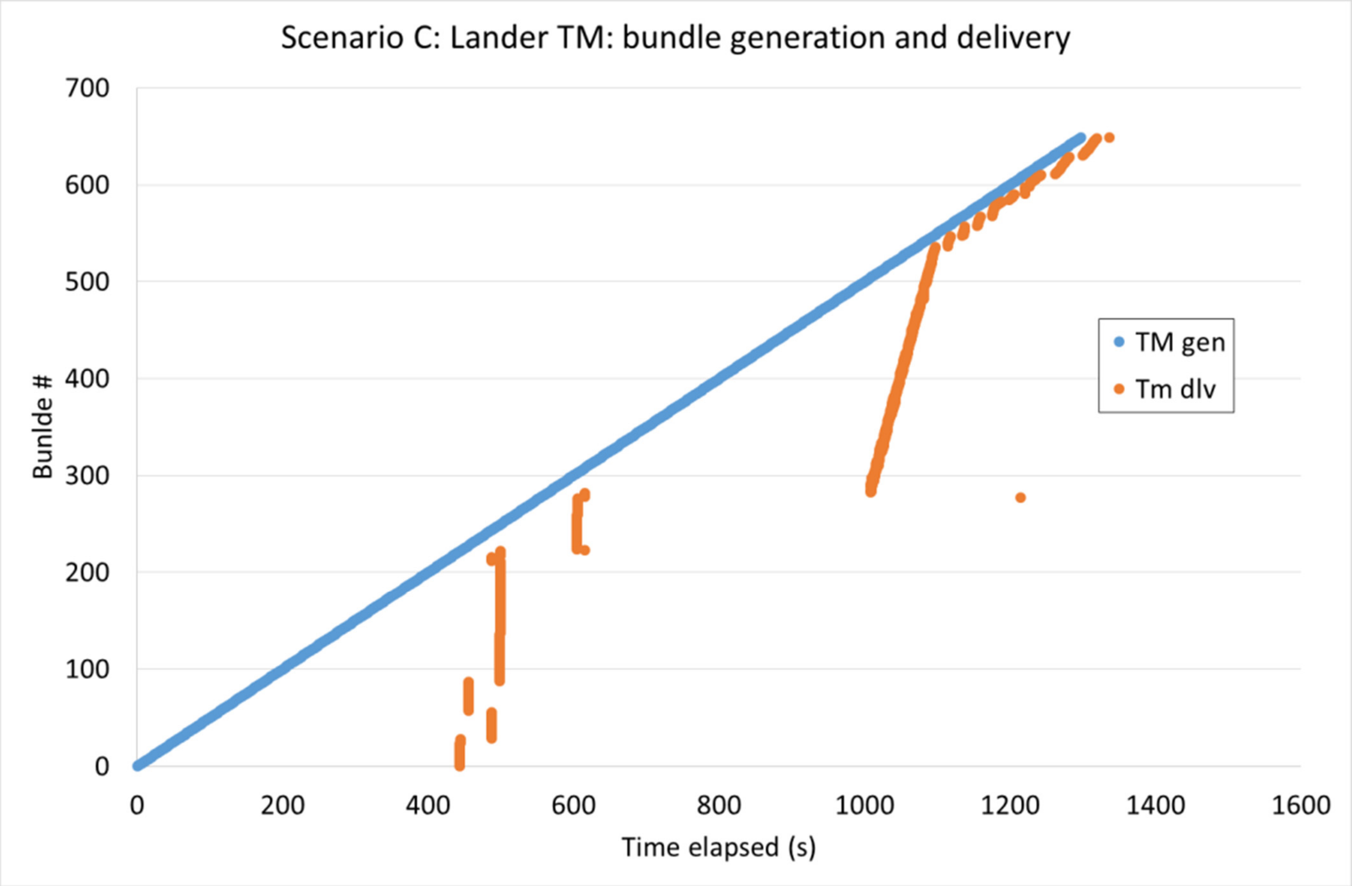


- **Uplink: Telecommand to Orbiters**

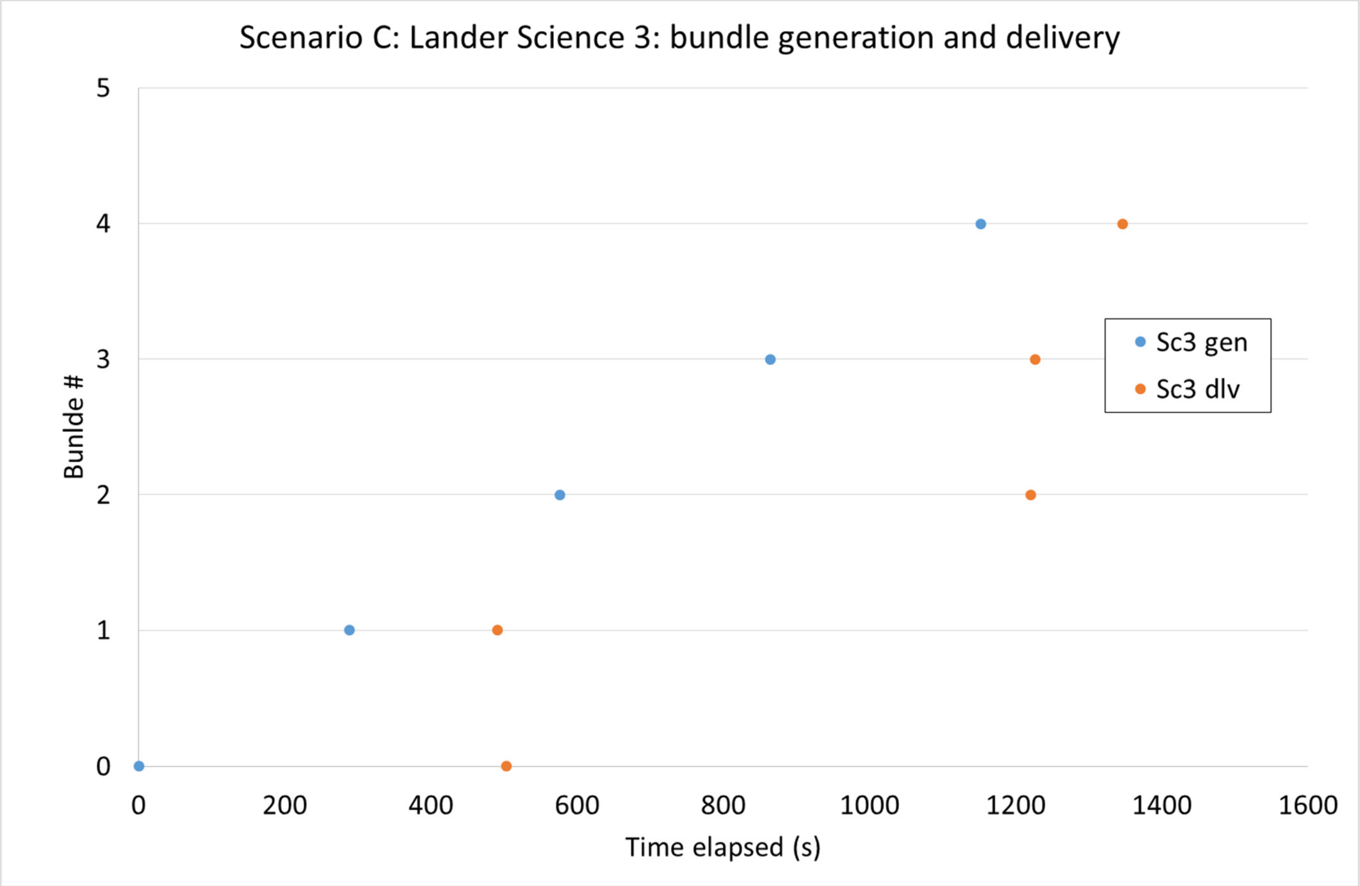


SCENARIO C – RESULTS - LANDER

- **TM: from Lander to MCC**



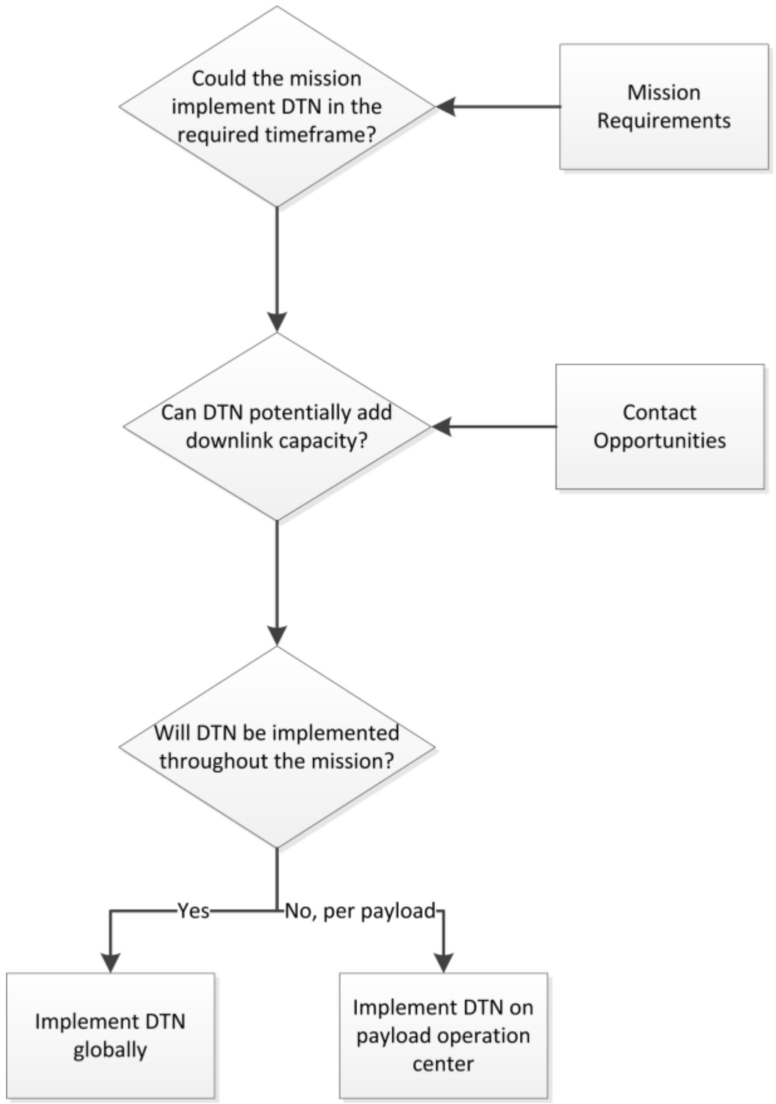
- **Science Data – 512kb bundles, to Earth**



DTN-EO
ROLL-OUT

Roll-Out Analysis - General

- **Question: What would be involved in the introduction of DTN into a mission?**
- **Factors which were considered:**
  - Cost & Cost Savings
  - Staffing Requirements
  - Additional hardware/software
  - Ease of installation



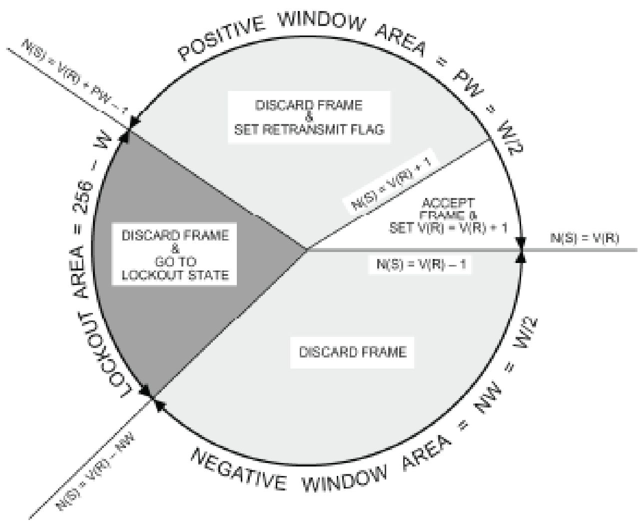
Roll-Out Analysis - Avionics

- **Metrics used for this portion of the study:**
  - Communication Windows & Contact Durations
  - Utilization of legacy equipment
- A set of requirements for DTN systems was developed:
  - Focused on high data-rate systems
  - Designed to be implemented on avionics systems, in one or more of the following areas:
    - CD&H system
    - Payload Processing
    - RF/Optical Communications Systems
  - Analyzes security, performance, etc.
- Incompatibilities were found between standard commanding (COP-1) and DTN-based systems:
  - May be mitigated by commanding via file (CFDP)

ID	Requirement
DTN-OB-REQ-1	High-speed, high bandwidth high-rate link. Aerial and ground nodes capable of handling data at rates in the gigabit range.
DTN-OB-REQ -2	Vast mass memory allocation and fast access to data
DTN-OB-REQ -3	The avionics shall include low-level stack communication functions, physically implemented in HW, or module IPcore, for TCP-UDP-LTP
DTN-OB-REQ -4	The avionics shall include processing unit running SW driver for management and high-level stack communication functions
DTN-OB-REQ -10	The avionics DTN implementation shall allow Out-of-band key reception mechanism. Key management as a subset of network management.
DTN-OB-REQ -12	The DTN shall implement communication built upon CCSDS standard. Hence, the avionics shall include CCSDS TM/TC modules or implement the ip-cores in programmable logic.
DTN-OB-REQ -15	Other mitigation- scrubbing, mitigation.

Roll-Out Analysis – COP-1 and DTN

- **The COP-1 FARM has a built-in retransmission mechanism for out-of-order frames.**
  - Prevents the simple encapsulation of TC transfer frames in DTN bundles
    - *DTN arrivals may be out-of-order, by default (unless Delay Tolerant Payload Conditioning is used)*
  - Therefore, encapsulating TC transfer frames into DTN bundles may cause unexpected results (excessive retransmits, etc.)
- Inserting TC into CFDP “files” solves these problems:
  - CFDP has built-in verification, etc.



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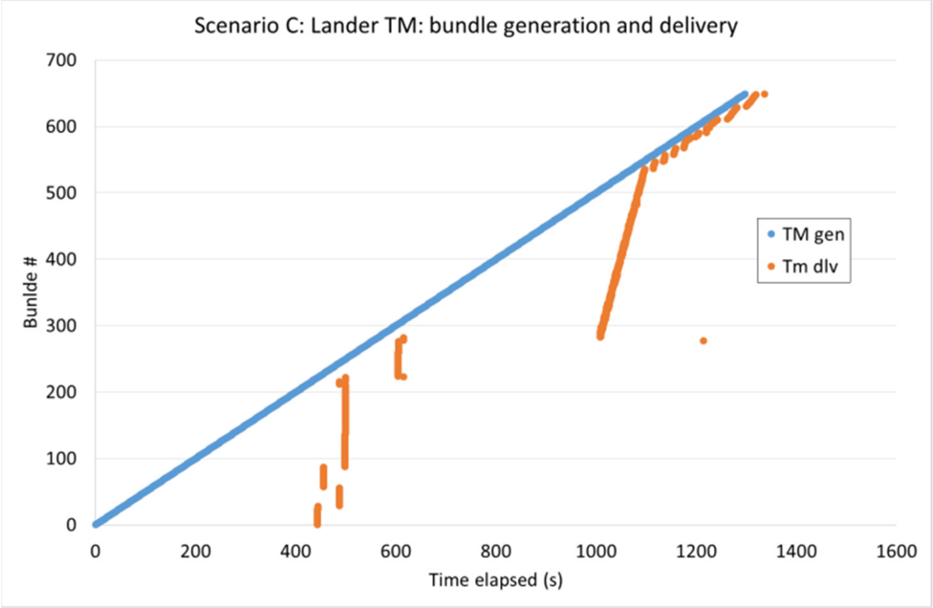
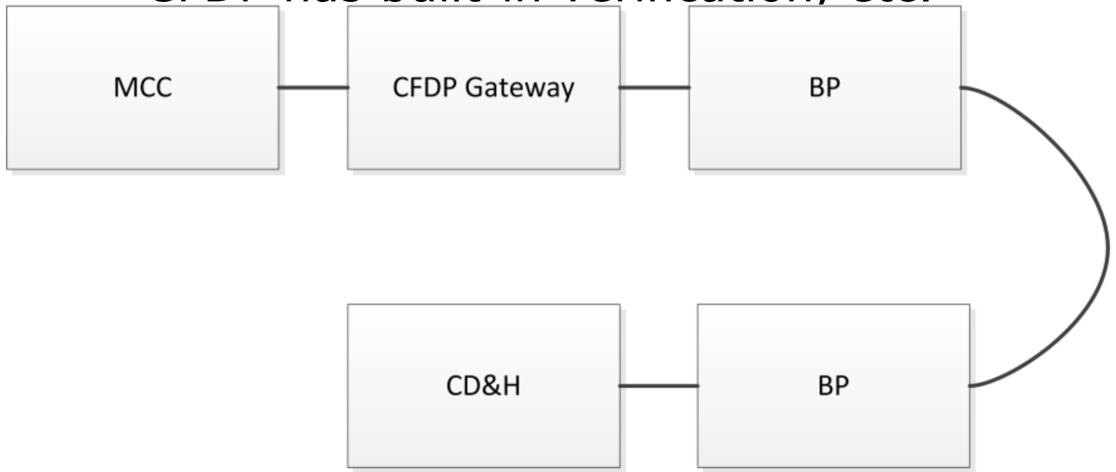


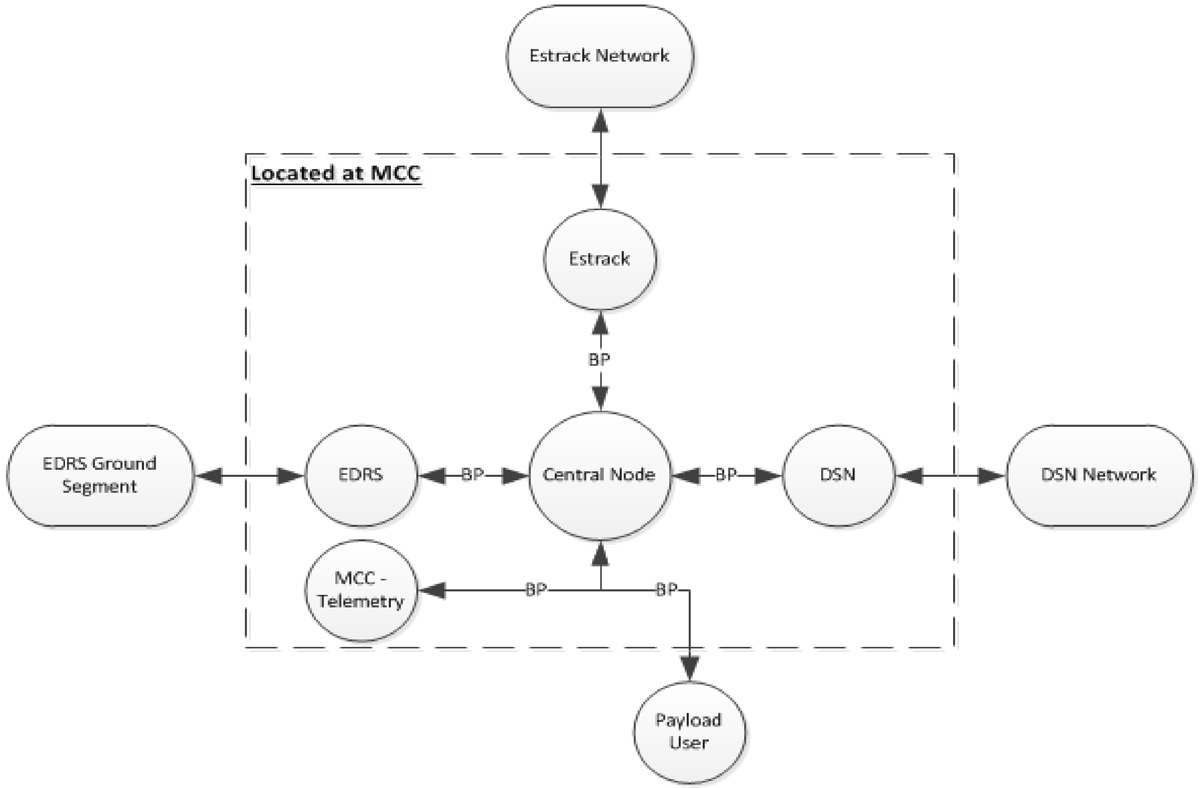


Roll-Out Analysis - Ground Segment

- **Metrics used for this portion of the study:**
  - International Collaboration – use of foreign assets (DSN, etc.)
  - Integration into MCS systems
  - Cost
- Several potential DTN Network Topologies have been evaluated, each with unique benefits and shortcomings…

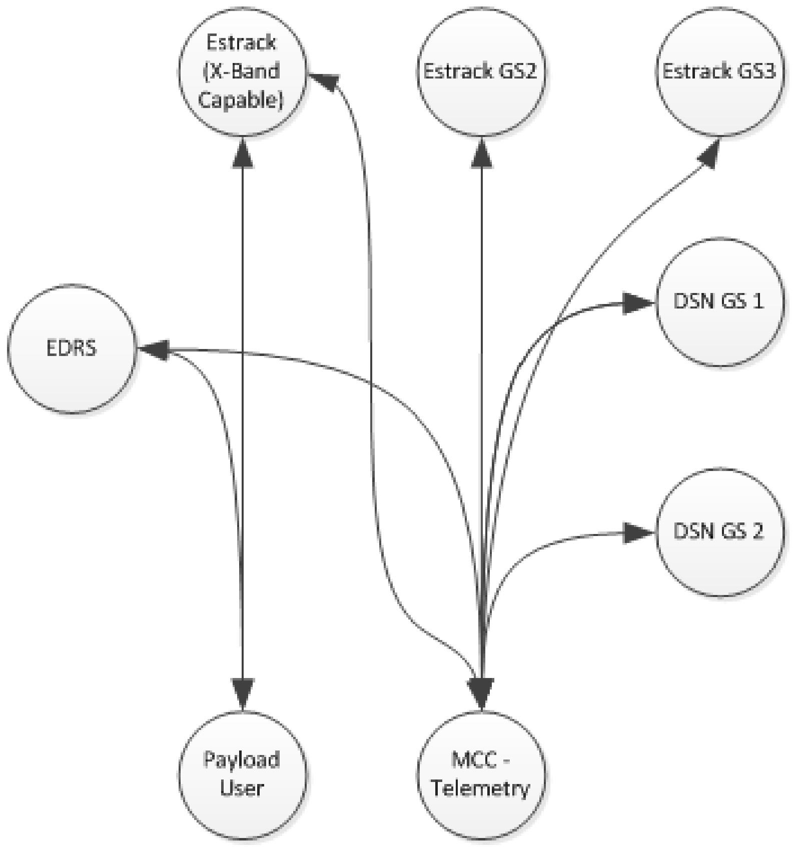
Roll-Out Analysis - Centralized

- **Pros:**
  - Easy to implement.
  - Can be reused across missions.
  - Minimal additional hardware (1 ESx server, 4 virtual machines)
- **Cons:**
  - Subject to MCC availability.
    - No remote buffering possible, connection between ground stations and MCC must be highly available.
  - Must stay in a trusted environment, with connections to all networks.
- **Optimal For:**
  - Multiple Missions utilizing the same MCC.
  - Missions with many space-to-ground connections.



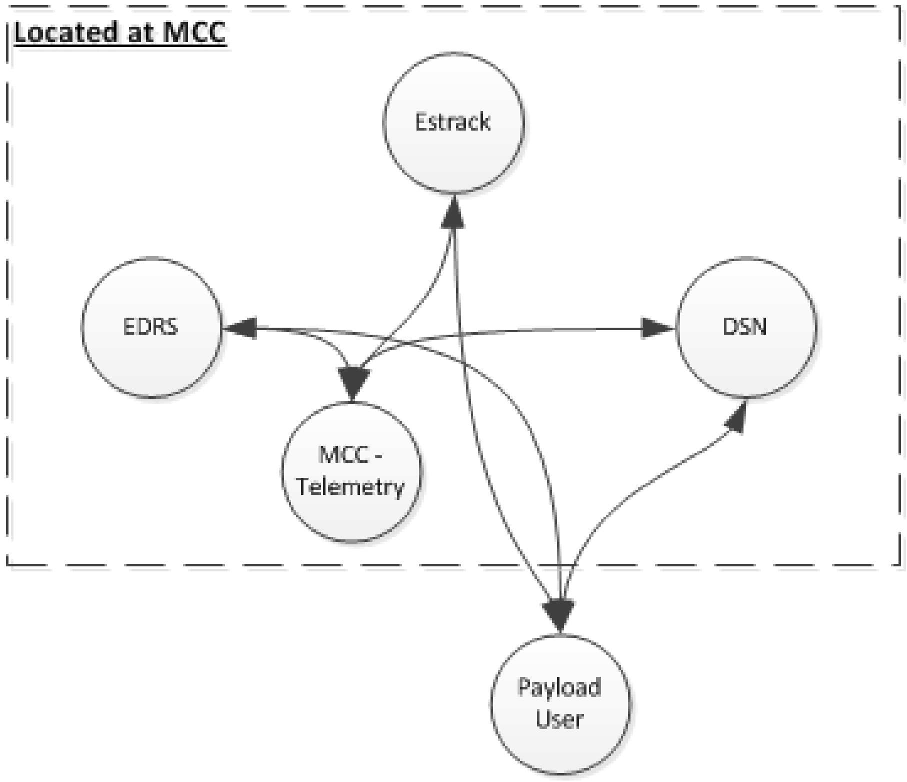
Roll-Out Analysis - Distributed

- **Pros:**
  - Extremely robust
    - As nodes are distributed across the ground segment, no individual point of failure.
  - May be distributed across multiple locations (ground segments, etc.)
  - Rapid to spin up.
- **Cons:**
  - Difficult to manage
  - Does not scale across missions
- **Optimal For:**
  - Research Demonstrator Missions
  - Missions with many space-to-ground connections.



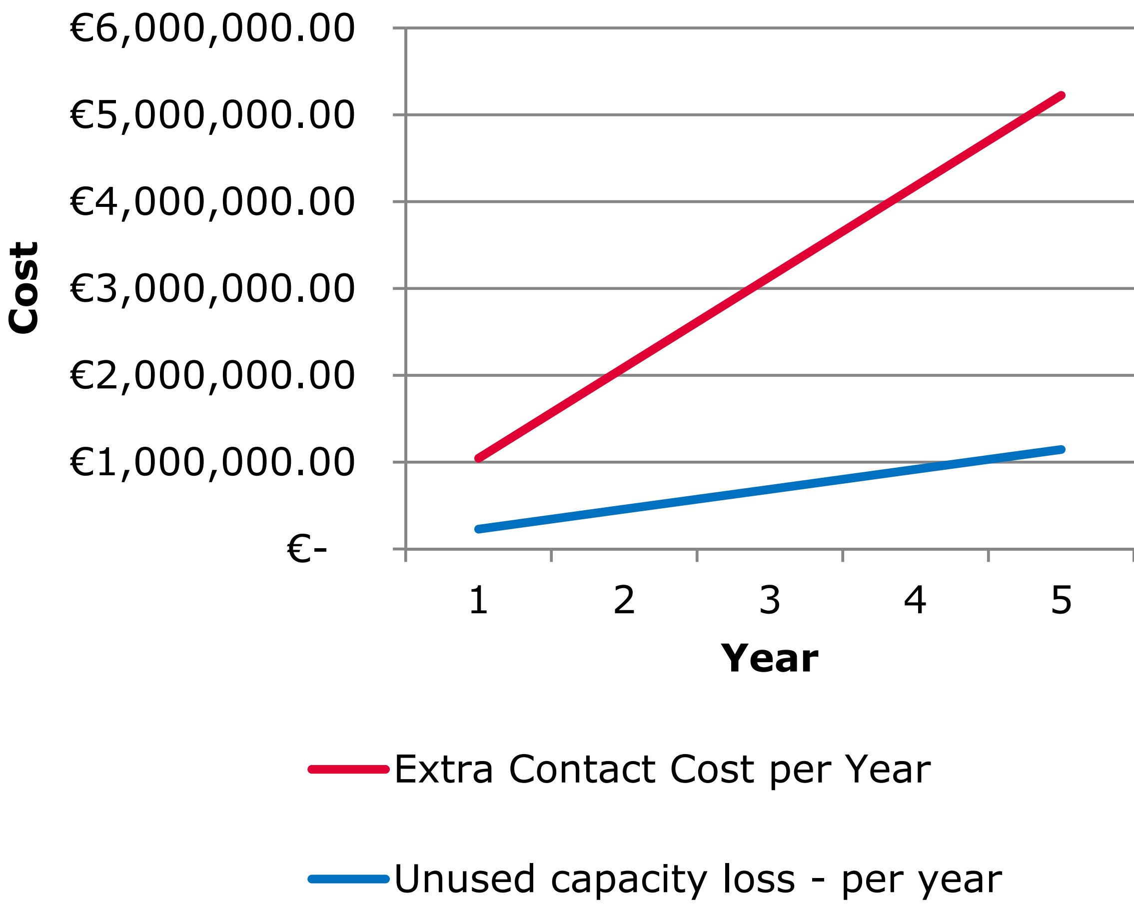
Roll-Out Analysis – Semi-Distributed

- **Pros:**
  - Easy to implement
  - Can be reused across missions
  - Robust
- **Cons:**
  - More difficult to manage
- **Optimal For:**
  - Multiple Missions utilizing the same MCC.
  - Missions with many space-to-ground connections.



Roll-Out Analysis – Cost Savings

- **Metrics used for this portion of the study:**
  - International Collaboration – use of foreign assets (DSN, etc.)
  - Contact Opportunities
  - Cost
- It was found that DTN provides a significant potential increase in total data throughput
- Additionally, our calculations revealed significant manpower reductions



Row Labels	Percentage of data lost	Extra Contacts per Week
EDRS	5.32	3.73
S-Band	21.96	4.61
X-Band	5.90	2.06
Grand Total	**33.18**	**10.40**

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NEXT STEPS

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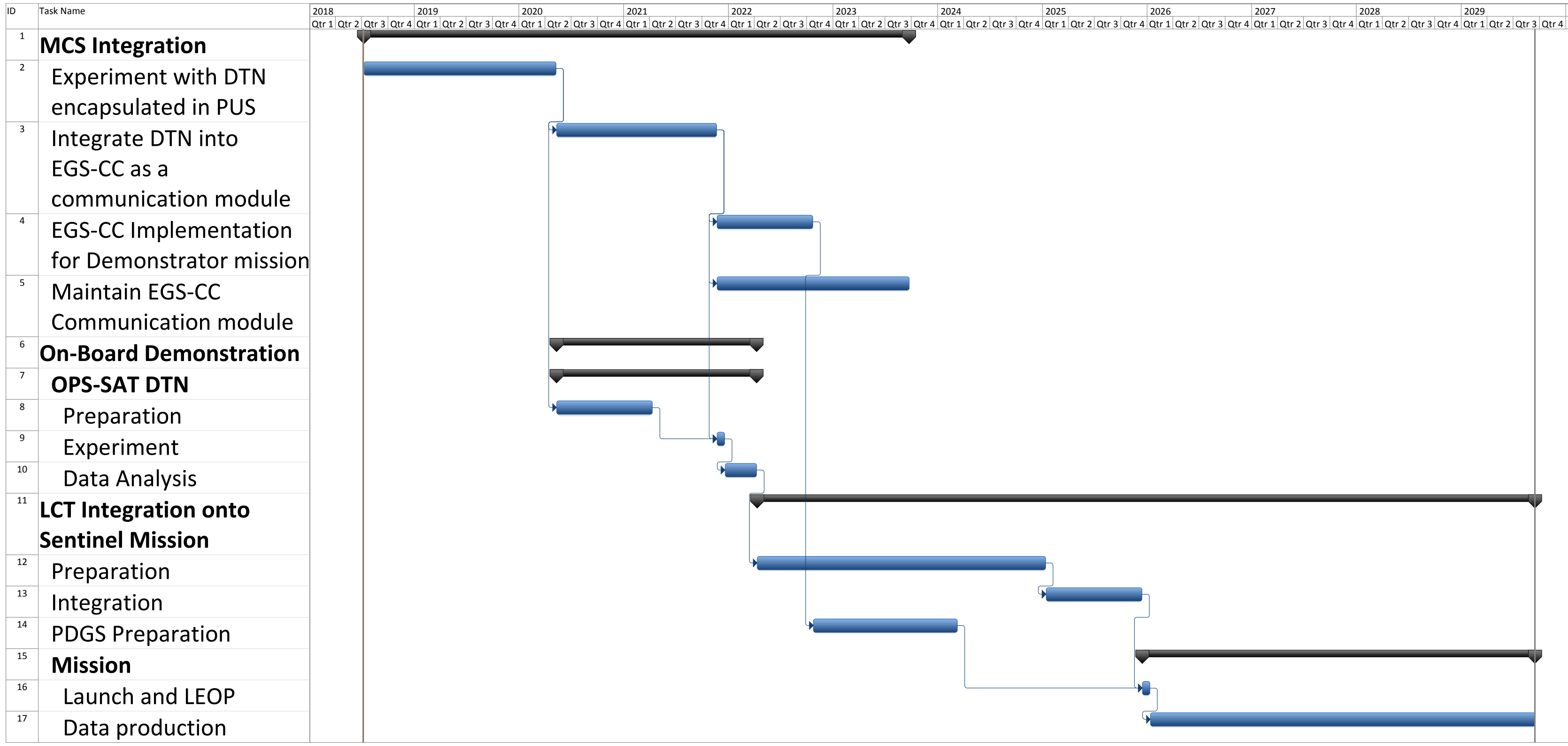
Roll-Out Analysis – Next Steps

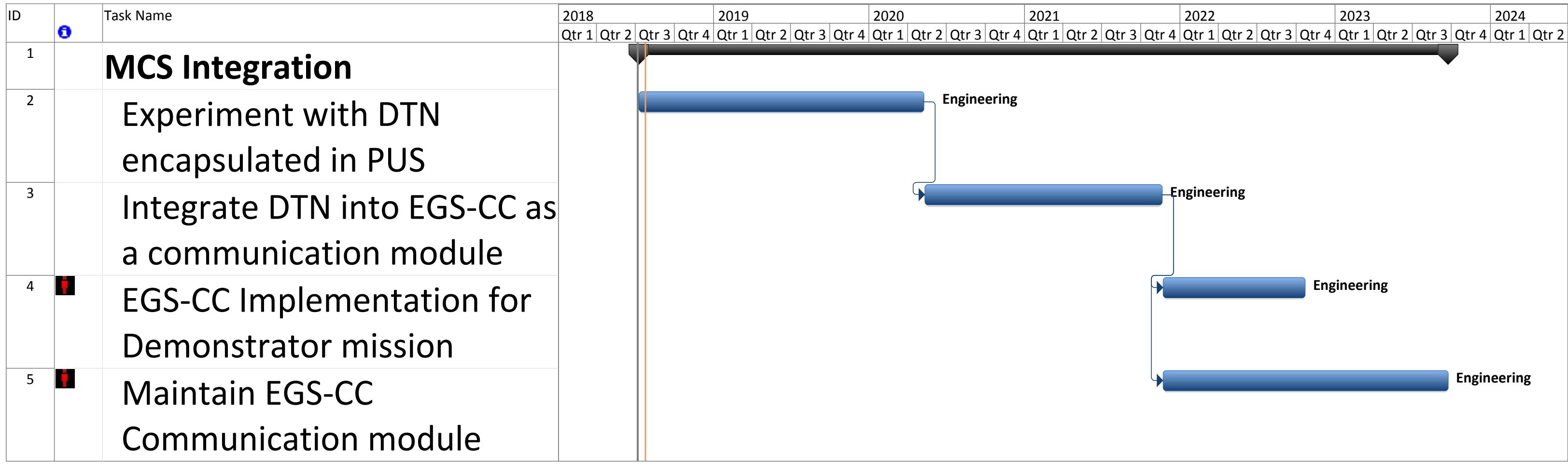
- As part of the roll-out, potential next steps for DTN within ESA were analyzed…
  - MCS Integration
  - On-Board Demonstrations
  - *Real Missions and more…*



NEXT STEPS

MCS Integration

- In order to support widespread adoption of DTN on missions, integration into a current or next-generation MCS is required.
  - Not straightforward, questions exist:
    - EGS-CC or SCOS?
    - Commanding format/mechanism?
    - Co-existence with non-DTN missions
    - Mission reuse – DTN/MCS as a basic service?

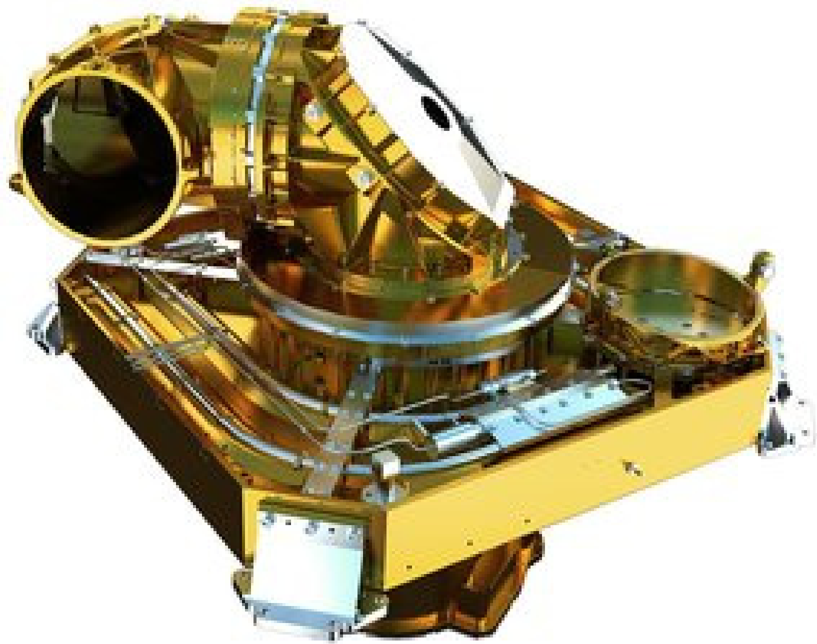


Task Name	Duration	FTE
MCS Integration	1360 days	
Experiment with DTN encapsulated in PUS	24 mons	1
Integrate DTN into EGS-CC as a communication module	20 mons	2
EGS-CC Implementation for Demonstrator mission	12 mons	1
Maintain EGS-CC Communication module	24 mons	0.5 (variable)

Demonstration Missions

OPS-SAT

(Photo: ESA)



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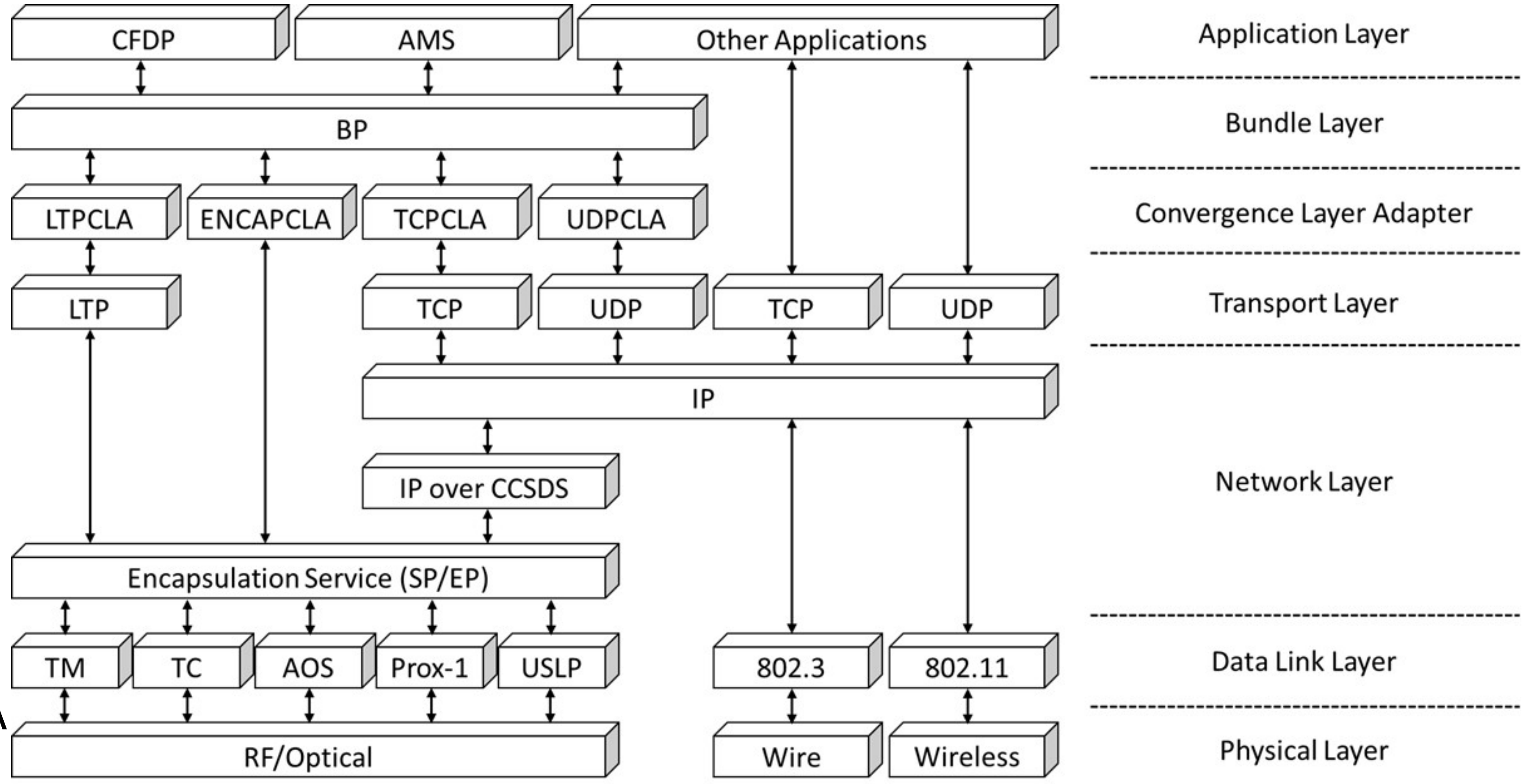
(Photo: ESA)

?

… And More!

- The roll-out study & scenario analysis evaluated the potential of novel new techniques:
  - Acceleration of routing via GPUs
  - FPGA implementations of core DTN functionality
- These would mitigate some of the issues that we saw in the study:
  - Implementation Issues
  - Performance
  - Ease of expansion/modification
- However, further work must be performed:
  - New DTN implementations, providing for GPU/FPGA capabilities
  - FPGA implementations: CGR, LTP, etc
  - Error correction mechanisms
  - Application Development for future missions & payloads



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CONCLUSION

Conclusion

- The study was concluded successfully:
  - Scenarios were refined to provide additional knowledge gathering
  - During emulation, problems were encountered with ION – Solved, bugfixes to be implemented in ION
  - VirtualBricks was implemented for SuSE/SLES
- DTN was found to be a valuable addition to future missions:
  - Although there is still work to be done…
- The DTN-EO project built a strong consortium with a wide range of skills in:
  - Mission Operations
  - Simulation
  - Software Engineering
  - **DTN!**

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BACKUP SLIDES

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Problems with ION/SABR

- Screening always ON in ION-3.6.0b and 3.6.1
  - Problem: lack of margin causes segment losses on the first LTP block sent after a contact opens, even on ideal channels.
  - Remedy: Screening was disabled in the code. As screening causes some LTP segments to be lost unless all clocks are synchronized with high-precision, an alternate solution would be to allow LTP to use the existing ION clock accuracy definition.
- UDPLSO inaccurate congestion control led to 20% underutilization of contact volumes
  - Problem: UDPLSO rate control sends LTP segment at a rate significantly lower than the nominal value set by the user.
  - Remedy: Improved version sent to Scott Burleigh to be included in the next ION release (ION 3.6.2).
- Deterministic block of ION at the end of the first contact
  - Problem: We noted a deterministic block of ION at the closing of the first contact.
  - Solution: As the problem seems to derive from the position of the “start command”, “s”, in the “ipnadmin” section of the .rc configuration file we have modified all configuration files accordingly and informed Scott Burleigh.
- Individual node stops sending LTP blocks for ten minutes before restarting during Science tests
  - Problem: We had deterministic ION blocks, whose cause is still uncertain.
  - Remedy (temporarily): By shifting forward contacts forward by 1s, the problem disappeared. We have modified the contact plan of Scenario A accordingly. It might be related to the “priorClaims” bug (discovered later, during tests on scenario C).
- Unidirectional link issues: impossibility of using LTP green on satellite links and TCP on terrestrial ones.
  - Problem: The selection of the green mode requires the setting of “unreliable” flag by the source. “Unreliable” bundles cannot be transferred on TCPCL links, even in the absence of any alternative.
  - Remedy (partial): We abandoned the idea of using LTP green on the unidirectional links, instead opting for UDP.

Problems with ION/SABR - Continued

- Unidirectional link issues: UDPCL causes IP bursts
  - Problem: IP bursts resulting from the encapsulation of a 64kB BP fragment into a UDP datagram, resulted in the loss of most bundles sent, although the channel was ideal.
  - Remedy: Insertion of a “TC-qdisk” traffic shaper in output
- CGR poor performance: SABR compliance in ION 3.6.1
  - Problem: The new CGR policy of considering only one route for each proximate node, introduced in ION-3.6.1 to make the code compliant with the latest CCSDS draft on SABR, caused a dramatic performance impairment.
  - Remedy: The problem is conceptual and can be definitively solved only by amending the current draft; we informed Scott Burleigh of the problem. In the meantime, we were forced to go back to ION-3.6.0b.
- CGR poor performance: priorClaims bug in 3.6.x.
  - Problem: Because of a trivial bug in “bpclm.c”, the waiting time estimation used by CGR was zeroed after the opening of the first contact. In the worst cases this led to estimated arrival times in the past. The consequences were particularly harmful in scenarios with longer delays.
  - Remedy: Bug fixed and the fix sent to Scott Burleigh.
- CGR logs: bugs and enhancements
  - Problem: a bug prevented additional information of “TRACE” commands from being printed. Moreover, it is extremely difficult to cross-match CGR log information with other sources of information because of the use of different time references (Linux vs. DTN, absolute vs differential).
  - Remedy: Bug fixed. Log enhanced with the possibility of printing times on the user preferred reference system.

Problems with ION/SABR - Continued

- LTP aggregation: impact on radiation time.
  - Problem: Radiation time is calculated by CGR by considering the current bundle dimension. The actual radiation time, however, depends on the dimension of LTP block in which the bundle is inserted, which can be several orders larger. We had 1kB expedited TC-ACKs bundles aggregated to 512k bulk bundles before being sent on very low Tx rates links.
  - Remedy: Amend LTP aggregation (to be done)
- CGR poor performance: other bugs?.
  - Problem: It is likely that other minor bugs are present, as in few cases we have observed suboptimal decisions.
  - Remedy: Improved CGR logs, as a first necessary step to verify code accuracy. Alternately, and from a purely academic sense, a method to dissect the CGR routing decisions.
- CGR Contact Blocking:
  - Problem: Long contacts with low bandwidth have a large volume, but are sub-optimal for transmission of large bundles. In one scenario, a link was blocked for 128 seconds. This revealed that there isn’t really a mechanism to discourage the transmission (or fragmentation) of huge bundles over hyper-constrained links.
  - Remedy (current): Don’t do that.

- Due to these problems, several mitigations were required:
  - our requirement for custody transfer proved to be essential; without it, bundles would have been permanently lost.