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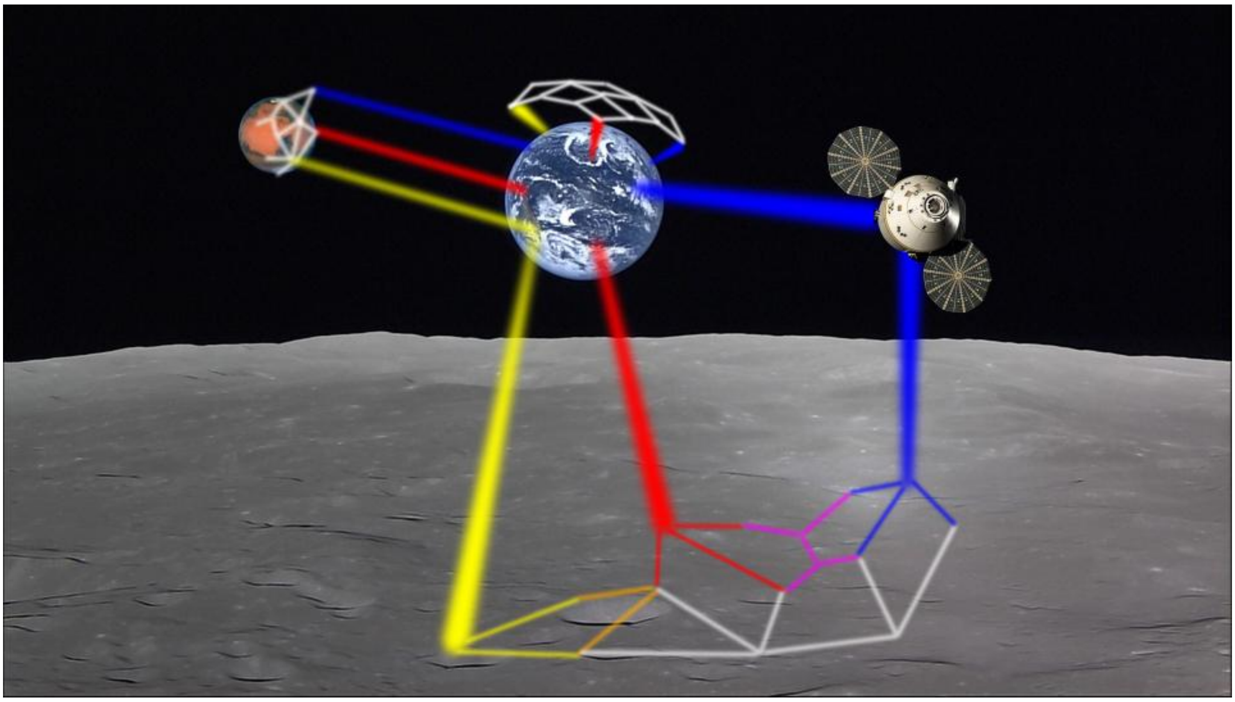
Report of the
Interagency Operations Advisory Group
Space Internetworking Strategy Group

Recommendations on a Strategy for Space Internetworking

November 15, 2008 (original text completed)
August 1, 2010 (Errata/Clarification added)



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NOTE TO EXPLAIN ADDITION OF ERRATA/CLARIFICATION:

The SISG originally completed this report in November 2008 to document Phase 1 of the SISG activities. Although it was not formally published at that time, this report contributed significantly to the conclusions reached at Interoperability Plenary-2 (IOP-2), prompting the following item (6) in the IOP-2 final communiqué:

> 6. The IOAG’s Space Internetworking Strategy Group (SISG) should formalize a draft Solar System Internetwork (SSI) Operations Concept and candidate architectural definition in time for IOAG-13 and should prepare a mature architectural proposal for review and endorsement at the third Inter-Operability Plenary meeting (IOP-3). At that time, the IOAG is requested to present an enhanced service catalog for endorsement. The IOP Agencies should ensure representation from their programs and projects to work with SISG to identify potential missions which may benefit from adoption of the SSI-related standards, leading to a gradual build up of in-space and ground-based space internetworking infrastructure.

This communiqué drove the SISG to undertake its Phase 2 activities, including a series of studies related to the SSI and development of an SSI Operations Concept. In accomplishing this subsequent work, the SISG refined some of the concepts that were documented in this initial report. Prior to publication of this document in 2010, the SISG decided to notate significant concept changes and updates via a list of errata/clarifications. Portions of text requiring errata/clarification are indicated by underlined text, and corresponding endnotes in Appendix H provide the updated concepts. Note that only large-scale concept changes are noted as errata/clarifications. The reader is directed to the SISG’s documentation of its SSI studies (*Solar System Internetwork [SSI] Issue Investigation and Resolution*) [9] and to the *Operations Concept for a Solar System Internetwork (SSI*) [10] for complete information.

Membership

The members of the Space Internetworking Strategy Group are:

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Members:

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I. Introduction

A. The purpose of the Space Internetworking Strategy Group (SISG)

While the Inter-agency Operations Advisory Group (IOAG) has previously addressed questions of interoperability between the member space agencies, it has not yet addressed the subject of space internetworking and international interoperability at the Network layer of space communications.

The SISG was chartered by the IOAG at the IOAG-11 meeting (Cebreros, Spain, June 2007) as a focused sub-team to study this topic. The following IOAG-11 resolution constituted the charter for the SISG:

> *The IOAG resolves to form a Space Internetworking Strategy Group to reach international consensus on a recommended approach for transitioning the participating agencies towards a future "network centric" era of space mission operations. The group will focus on the extension of internetworked services across the Solar System, including multi-hop data transfer to and from remote space locations and local networked data interchange within and among the space end systems.*

B. The purpose of this report

This report represents the final product of the SISG, and documents the rationale, conclusions, findings and recommendations that were reached by consensus within the group. This report was developed on an accelerated schedule in order to support the meeting of the second Interoperability Plenary (IOP-2) to be held in December, 2008. It is hoped that this report will contribute significantly to the conclusions reached in IOP-2 concerning the future direction of interoperability as supported by internetworking capabilities for future spaceflight missions.

C. Scope

This document contains only non-binding content (findings, recommendations and conclusions) from the SISG to the IOAG.

The technical scope of this study of internetworking is the functionality of the Network layer of the ISO OSI communications stack, including its dependencies and effects on lower and higher layers. Also some non-technical strategies are addressed, such as management strategies and governance.

Specifically, issues and strategies for lower layers (physical and link layer, spectrum issues, etc.) are not intended to be addressed in this report. They are addressed in a parallel study that is being conducted by NASA and coordinated with the IOAG agencies, the Coding, Modulation and Link Protocols (CMLP) Study. However this report on Internetworking will identify some requirements and functions that are expected from those lower layers in support of the internetworking strategies developed here.

D. Document Overview

This document consists of nine sections and five appendices. For the remainder of the document the following descriptions apply.

Chapter II provides the executive overview of the rest of the document.

Chapter III provides a view of “Interoperability today”

Chapter IV provides a projection of interoperability needs for the future.

Chapter V develops some management perspectives which transcend technical and requirements tradeoffs.

Chapter VI investigates the feasibility of candidate technologies to meet the interoperability needs.

Chapter VII provides the recommended change goals for transitioning to an internetworked architecture.

Chapter VIII provides a proposed high-level architecture as the basis for internetworking agreements between agencies.

Chapter IX provides the recommended transition strategy and roadmap which will move the IOAG agencies to interoperable internetworking.

Appendices are also supplied which provide additional details, and a glossary and acronym list.

II. Executive Summary

The Space internetworking Strategy Group (SISG), which was staffed by technical experts appointed by the IOAG agencies, met six times in plenary session between IOAG-11 and IOAG-12 (October 2007; March 2008; May 2008; September 2008) and conducted numerous dialogs via e-mail as well as two videoconferences. This report is the culmination of the first phase of the study by the SISG relative to the potential need for the IOAG agencies to evolve towards a new, internetworked paradigm for space communications.

The SISG has reached a consensus recommendation that the international community should begin the planning and development activities that are necessary to transition future space mission operations to rely on a new end-to-end *internetworked* model of data communications, using mission support infrastructure that spans across space. To achieve this goal, the SISG therefore recommends that the participants in the second Inter-Operability Plenary (IOP-2) in December 2008 should be asked to approve a significant international initiative that will develop and advance the proposed concept of an international "Solar System Internetwork" (SSI) in support of future missions of space exploration. The SSI is envisaged to be a voluntary confederation of space and ground based infrastructure that is contributed by individual participants (including government and commercial entities) and that is bound together by a common architecture and the adoption of common standards.

To meet projected mission requirements, the early phase of the SSI should begin in the ~2015 timeframe and by ~2025 a routine operational capability should be in place. In support of this transition:

a) The IOP-2 should task a sub-team to produce an initial SSI Program Development Plan (SPDP) by the end of CY2010, for review and approval by the IOP membership. This initial SPDP will describe a plan to develop a voluntary confederation of independent, cooperative infrastructure assets that support internetworking, and are autonomously owned and operated by diverse space mission organizations.

b) The IOP-2 should also task a sub-team to work with space mission organizations across the international community – including the private sector - to coordinate the activities of the SPDP, including progressive deployment of these voluntary SSI infrastructure assets in space and on Earth. This will also correspondingly expand the opportunities for participation in the SSI initiative to embrace with widest possible set of participants.

c) The IOP-2 should task a sub-team to develop an Architecture Definition Document (ADD) for the SSI. This SSI ADD would have very wide scope (operations concepts, cross-support architecture approaches, etc.) and it would reference lower-level CCSDS documents.

d) Concurrently, the IOP-2 should recommend to the CCSDS the development of a CCSDS Recommended Practice for a Space Internetworking Architecture, which would provide

the lower level foundation for the SSI ADD. The CCSDS should simultaneously begin the necessary program of SSI standards development.

In forming this consensus, seven top-level Summary Conclusions (SC01 – SC07) were formulated by the SISG. These SCs are expanded in the form of more detailed Findings and Recommendations in the various sections of the body of the report.

SC-01: The SISG notes that a major factor in enhancing the overall productivity of many space missions is their ability to draw upon shared communications and navigation services that are enabled by international interoperability and cross-support:

- *Interoperability* is the *technical capability* of two or more systems or components to exchange information and to use the information that has been exchanged;

- *Cross-support* is an *agreement* between two or more organizations *to exploit the technical capability* of interoperability for mutual advantage, such as one organization offering support services to another in order to enhance or enable some aspect of a space mission.

In the past decade, international cross-support has been beneficially demonstrated by several space missions at two major interfaces:

- Between spacecraft operated by one agency and ground infrastructure operated by another agency, enabled by the interoperability afforded by the CCSDS space link protocols and the CCSDS “Space Link Extension” (SLE) protocols;

- Between landed assets on Mars operated by one agency and an orbiting relay operated by another agency, enabled by the interoperability afforded by the CCSDS Proximity-1 protocol.

SC-02: Currently, terrestrial cross-support is primarily focused on the provision of services based on the internationally-standardized long haul CCSDS point to point links (TM, TC and AOS) and the ability to tunnel the termination of these links to remote locations using SLE. The emerging toolkit of CCSDS Cross-Support Transfer Services (CSTS) and Cross-Support Service Management (CSSM) will enable additional services to be defined in the future (thereby augmenting the present space link access capabilities) and are expected to enable a much higher degree of automation to be achieved when negotiating and implementing terrestrial cross-support. The SISG concludes that the current terrestrial cross-support needs to be expanded and consolidated across the agencies in several key areas:

- Service management needs to be widely and progressively deployed; it is just reaching maturity as a CCSDS Standard and its capabilities are expected to rapidly evolve;
- A Radio Metric service needs to be formalized.
- A bidirectional Space Packet service needs to be defined;

- A bidirectional CFDP service needs to be defined that implements the full set of CFDP capabilities;
- A Monitor data service needs to be defined.[i]

SC-03: Building upon this current success of terrestrial cross support, the SISG concludes that the international community now needs to address the development of future ***in-space cross support*** services (including cross-support on and around other Solar System bodies). The current in-space cross-support record is spotty:

- In spite of recent successes, in-space cross-support at Mars is presently quite rudimentary and involves a small number of nodes interconnected by CCSDS Proximity-1 links. These configurations are predominantly manually configured and there are no interoperable in-space data transfer services defined beyond basic capabilities for relaying bit-stream data.[ii]
- End-to-end data transfer is currently implemented by individual missions using the CCSDS Space Packet Protocol, but cross-support standards and infrastructure have not yet been built around it.
- CFDP has been deployed on several NASA missions with varying degrees of functionality, but its international deployment has been disappointingly slow.

The SISG notes a basic problem at the root of this situation: there is currently no agreed architecture for how in-space cross-support should be organized and operated. To move forward, integrated international agreement is therefore needed on an end-to-end service architecture, with a particular focus on the definition of in-space interfaces and the management of end-to-end interoperability. The SISG concludes that as a matter of urgency a CCSDS Space Internetworking Architecture recommendation should be created for this purpose.

In order to realize this end-to-end cross-support architecture (which is expected to become a key enabler for new international space mission initiatives), the SISG also concludes that space-faring entities should be encouraged to extend their cross-support services into space *via the build-up of re-usable, voluntary, confederated in-space communications and navigation infrastructure* which can offer services across organizational boundaries. Such in-space infrastructure includes space-based data relays and planetary surface communications facilities that are united via their provision of common, interoperable services using CCSDS standards. The IOAG should be responsible for coordinating the independent contributions of many diverse entities towards this build-up, including the necessary flight tests and demonstrations to validate and qualify the new techniques.

SC-04: Analysis of emerging Earth observation, Lunar and Mars exploration mission scenarios indicates that an increasing number of individual space missions will need the ability to confederate and share in-space communications resources and infrastructure in order to achieve goals that are greater than any one of them could individually accomplish. Three major trends can be discerned:

- In order to respond to rapidly occurring events, Earth observing missions are expected to need to automatically exchange space-based measurements with data gathered by IP-routed terrestrial sensing systems. The capabilities of a networked near-Earth infrastructure to support the monitoring of global change would better support such missions.
- While current Earth-orbiting data relay satellites primarily operate in a bent-pipe mode, there will be an increasing reliance on data relay satellites throughout the Solar System that will operate as potential routing nodes in and end-to-end data communications path.
- Richly connected, short-delay in-space communications systems will be increasingly characterized as being local area networks, potentially using IP routing. These networks may run inside a free-flying spacecraft, inside landed facilities, or between mobile systems on planetary surfaces.

The SISG concludes that there is a clear and emerging need for the international community to transition towards an internetworked approach to space communications which supports the ability to automatically route user data across multiple hops and multiple organization in the end-to-end path that interconnects a source and a destination. This transition is expected to begin circa 2015 for Earth and Lunar missions and circa 2020 for Mars missions.[iii] By 2025, it is anticipated that an operational internetworked capability will be routinely required by many space missions.

SC-05: The choice of space internetworking protocols is important. While there are regions of space in which conventional IP-based networking is expected to work well, it is inherent in the physics of space communications that between (and at the edges of) local regions of short-delay "always on" IP connectivity there will be many areas of disrupted or long-delay communications.

- The SISG notes that the emerging Disruption Tolerant Networking (DTN) technology is the only mature candidate protocol available that can handle the disconnection and delays inherent in many regions of space operations. Therefore the SISG concludes that future space networks should provide DTN as a primary end-to-end routing service and that the development of DTN to full flight readiness circa 2012 (to support missions launching circa 2015)[iv] should be a high priority.

- The SISG also notes that IP-routed network services can be beneficially deployed in those (low-latency and well-connected) space mission regions where the native IP suite functions well, although it is not yet clear where the technical boundaries of IP-routed regions should be drawn.

- The SISG is therefore concerned about the potential costs and cultural implications of deploying two in-space networking architectures – one IP-routed and the other DTN-routed. The SISG concludes that a space deployment strategy needs to be developed that clearly defines the relationship between an end-to-end DTN-routed infrastructure and an end-to-end IP-routed infrastructure and that provides appropriate technical and investment guidance to SSI participants. This strategy should be addressed in the CCSDS Space Internetworking Architecture recommendation.

SC-06: Study of the technological transition towards the future SSI raises several issues concerning the necessary evolution of related space-based infrastructure. The SISG concludes that:

- Space Packet service should continue to be offered to those missions that do not have requirements for the new internetworked architecture; a basic method for addressing and delivering CCSDS Space Packets needs to be established to enable their cross-support in the SSI.
- Future usage indicates a continuing trend towards higher data rates and in particular that forward-link use of the AOS frame will be required, thus needing new CSTS infrastructure to support this capability.
- The CCSDS Encapsulation Packet should be formalized as the standard convergence layer to support the bi-directional transfer of IP packets and DTN Bundles over the space link portions of the SSI. New CSTS infrastructure may be needed to support an Encapsulation service.[v]
- A common scheme for assigning and managing IP and DTN address spaces needs to be established for the SSI and an administration function needs to be established.
- In order to provide necessary end-to-end route management and execution, the CCSDS should develop standards and guidelines for how in-space data relay nodes should be organized and provisioned to support connectionless IP and DTN network services and should commensurately develop a set of standardized routing configuration, status and behavior parameters that must be exchanged between space agencies providing cross-support as nodes of the SSI.
- To support an anticipated increase in the number of SSI users, multiple access modulation and coding standards should be developed by CCSDS for use on the long-haul Moon-to-Earth and Mars-to-Earth links as well as in the near-Earth, near-Moon and near-Mars relay link environments, along with their associated data link establishment and management protocols.
- Routine file-based SSI operations encourage the use of novel application layer error detection and correction schemes to protect the end-to-end transfer of large size application data units. The CCSDS should begin to study such schemes, with initial focus on long erasure codes.

SC-07: Finally, the SISG concludes that a "roadmap" along the lines of Figure 1 should be developed in greater detail than presented here, and agreed among the SSI participants in order to steer the upcoming transitional period towards deployment of the SSI. This is forward work after the architectural concept and definition phase is complete (but between IOP-2 and IOP-3 timeframes), and will allow the participating agencies to provide SSI building blocks which dovetail with each other in a way that best capitalizes on each agency's ability to provide some portion of the SSI infrastructure. During this later phase:

- The IOAG should coordinate the execution of international flight tests and demonstrations of the new SSI capabilities. The initial series of flight tests should build upon those proposed by the current NASA "Space DTN Development Project", using deep space and ISS mission resources. Multiple organizations should be invited to join and participate in these campaigns.

- The IOAG should actively encourage individual missions to join the SSI confederation by indicating their willingness to contribute cross-support of space internetworking services. The IOAG should maintain an evolving catalog of such in-space mission deployments and the cross-support capabilities that they may offer, along with a corresponding catalog of available terrestrial cross-support.

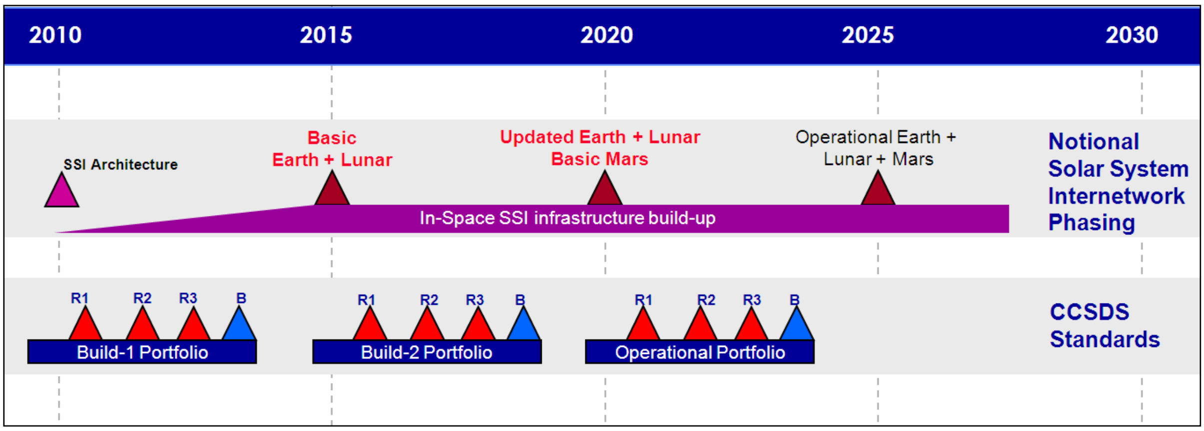


Figure 1: Candidate Roadmap for Solar System Internetwork Development

III. Characterization of “Interoperability Today”

A. Introduction

Interoperability is basically the ability for the assets (flight and ground) of one space Agency to interact with and exchange information with the assets of another. Cross support is an agreement between two or more space Agencies to exploit the technical capability of interoperability mainly with the purpose of using assets of one or more space Agencies to support operations of a space mission of another space Agency. They are key concepts to reduce the cost of developing systems for operating space missions because it enables sharing of resources among space Agencies.

To enable interoperability, the Consultative Committee for Space Data Systems (CCSDS) developed standard protocols to transfer telecommand and telemetry over space links, which can ensure interoperability among space and ground elements belonging to different Agencies. CCSDS also developed standard services called the Space Link Extension (SLE) services to transfer telecommand and telemetry on the ground (mostly between a ground station and a spacecraft control center). By using these CCSDS protocols and services, interoperability among elements of different Agencies can be guaranteed to some extent.

The following sections explain the current status of interoperability using the Reference Architecture for Space Communications (RASC) as the framework for describing interoperability scenarios. RASC defines four Views (Physical View, Service View, Communications View, and Enterprise View), each focusing on a different set of aspects associated with the space communications systems and scenarios. Annex A of this report provides an executive summary of RASC.

B. Interoperability by Ground Stations: Physical and Enterprise Views

Figure 2 is the Physical View (i.e., the physical configuration) of a typical space mission. A spacecraft is controlled by a control center using a ground station (or a set of ground stations).

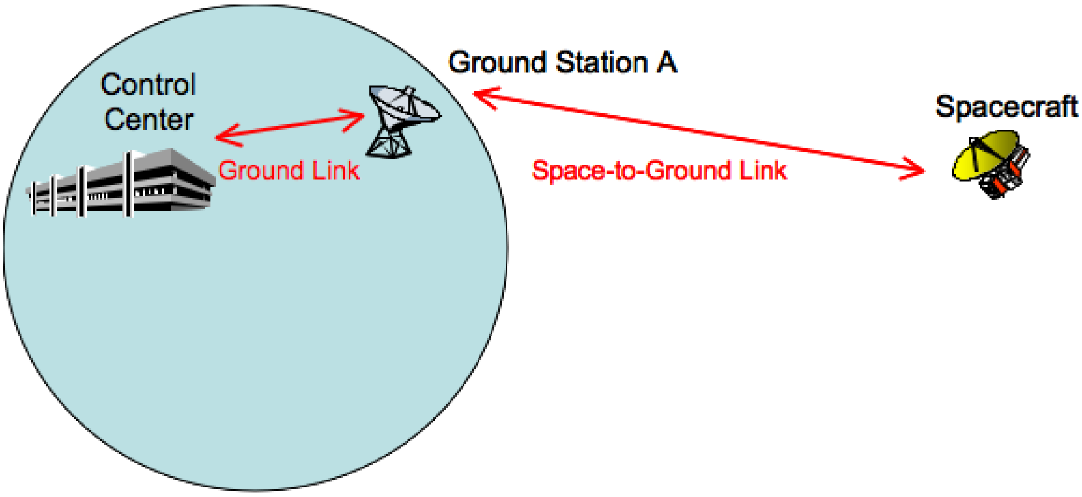


Figure 2: Physical view of a typical space mission

All of these physical elements usually belong to a single space Agency. Figure 3 shows the Enterprise View (i.e., the organizational configuration) of this mission, where the dotted box denotes the Space Agency that owns these physical elements.

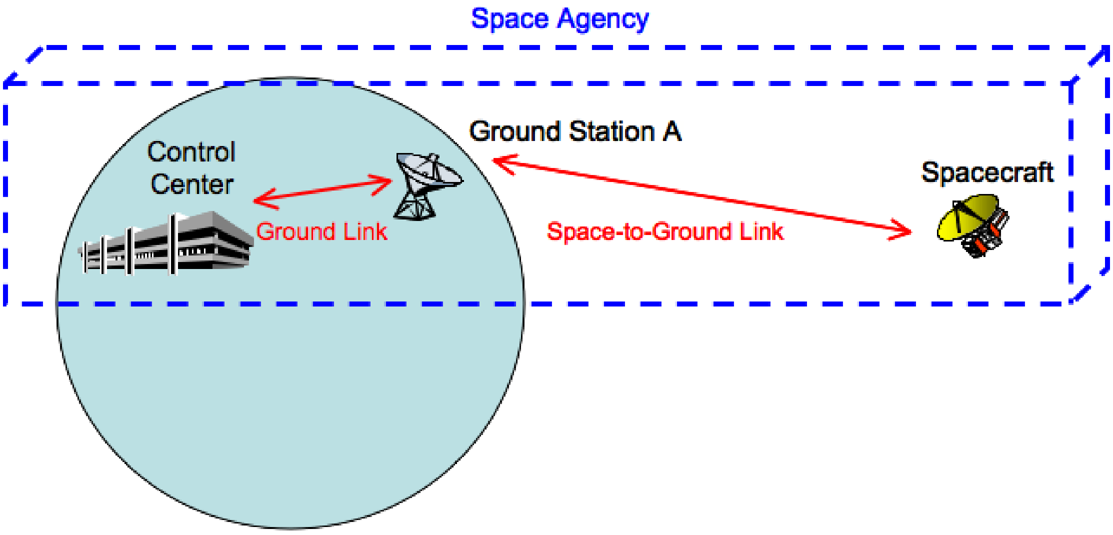


Figure 3: Enterprise view of a typical space mission

In order to increase the amount of data that can be received from the spacecraft or to enhance the capability of controlling the spacecraft in emergency situations, another ground station (or another set of ground stations) belonging to another space Agency may be used. In such cases, the ground station(s) of the second Agency is said to be interoperable with the spacecraft and the control center of the first Agency and provide cross support for the first Agency.

The Physical View for such a scenario is shown in Figure 4 and the corresponding Enterprise View in Figure 5. In this scenario, there are two physical interfaces that cross the inter-Agency boundary: one on the space-to-ground link between the spacecraft and ground station B and the other on the ground link between ground station B and the control center. These interfaces are called interoperability points (or cross support points) and indicated with a purple star in Figure 5.

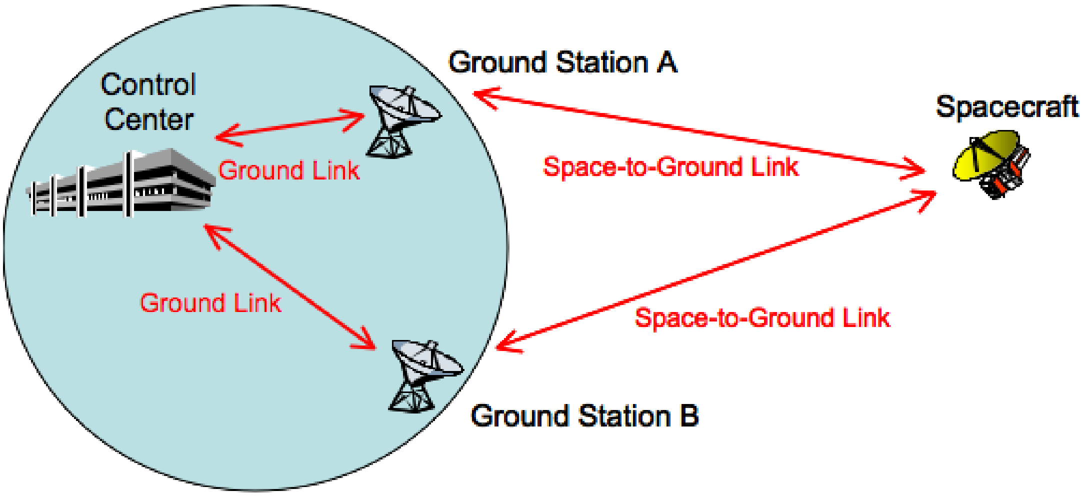


Figure 4: Physical view of a case of ground station interoperability

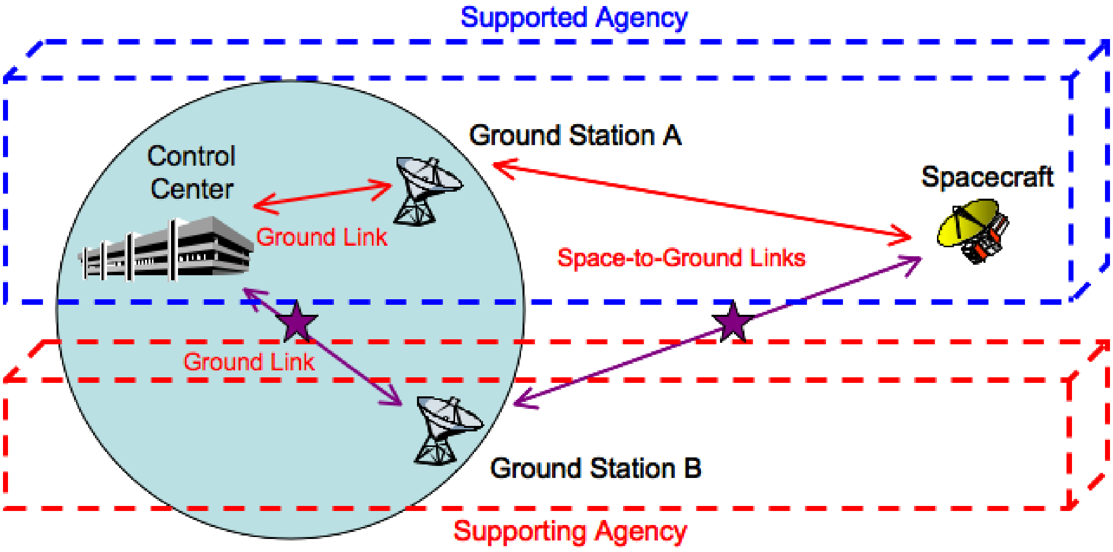


Figure 5: Enterprise view of a case of ground station interoperability

C. *Interoperability by Ground Stations: Service and Communications Views*

The Service View (i.e., the service configuration) for this cross support scenario is shown in Figure 6. In almost all the cases in which cross support is provided by a ground station, the supporting ground station provides the supported Agency with a service for receiving CLTUs (Communications Link Transmission Units, which are coded telecommand frames) from the control center on the ground link and transmitting them to the spacecraft on the ground-to-space link (for forward link), and another service for receiving telemetry frames from the spacecraft on the space-to-ground link and relaying them to the control center on the ground link (for return link).

There are two delivery modes used in this cross support configuration: online delivery mode and offline delivery mode. In the online delivery mode, which is used for both forward and return directions, data is relayed to the destination in realtime while the data is received by the ground station. In the offline delivery mode, which is used only for the return direction, data is delivered to the control center at a time later than the time the data is received by ground station.

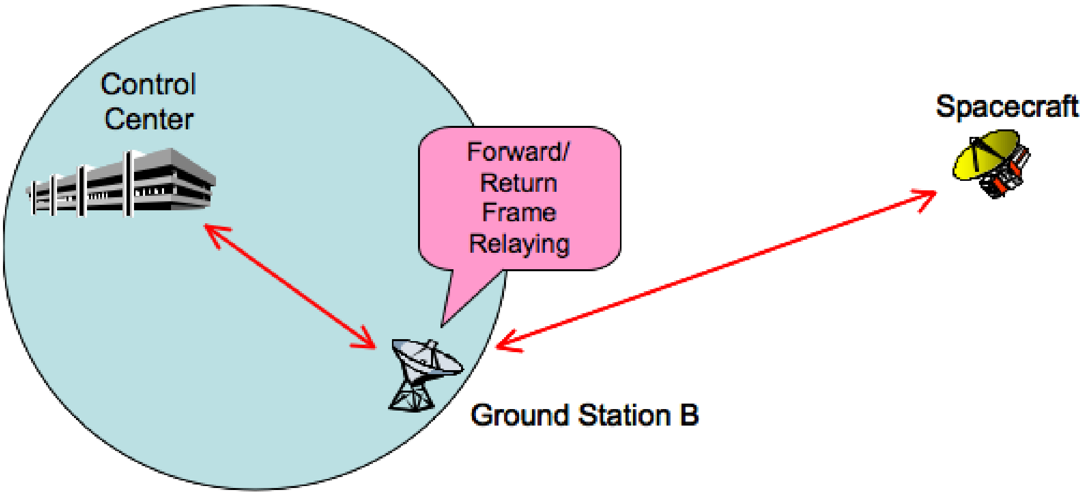


Figure 6: Service view of a case of ground station interoperability

The Communications View (i.e., the protocol configuration) for this scenario is shown in Figure 7, where the stack of protocols used on each link is shown. The communications protocols used on the space-to-ground link are the RF & Modulation Recommendation, the TC and TM (or AOS) Space Data Link Protocols and the Space Packet Protocol (and optionally the CCSDS File Delivery Protocol (CFDP[2])), all of which are published by CCSDS as recommended standards. As explained above, the ground station B relays frames (which are protocol data units of Space Data Link Protocols) or coded frames (in the case of forward link) between the control center and the spacecraft, and this means that the Space Packets carried in the frames are also relayed untouched by the ground station. Therefore, in this scenario, both the Space Data Link Protocols and the Space Packet Protocol (and CFDP when used) are used as end-to-end protocols between the control center and the spacecraft, and the ground station only plays the role of a bent pipe at the frame level (or at the Data Link layer).

To transfer frames between the control center and the ground station, SLE is used on top of TCP/IP. SLE can, in principle, be used to transfer packets, but all the space projects are using it to transfer frames right now.

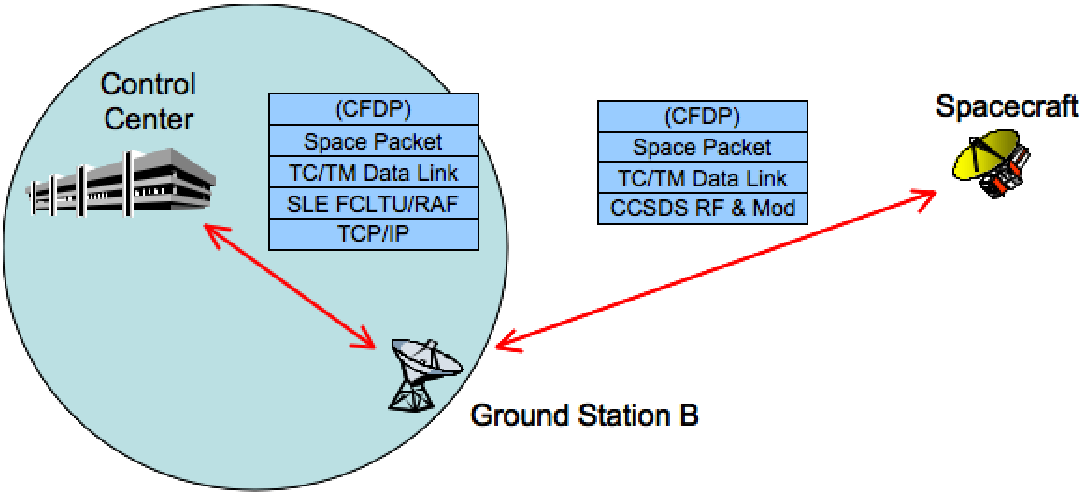


Figure 7: Communications view of a case of ground station interoperability

Figure 8 is a combined Service and Communications View that shows how the communications protocols are used to support the service provided by the ground station B.

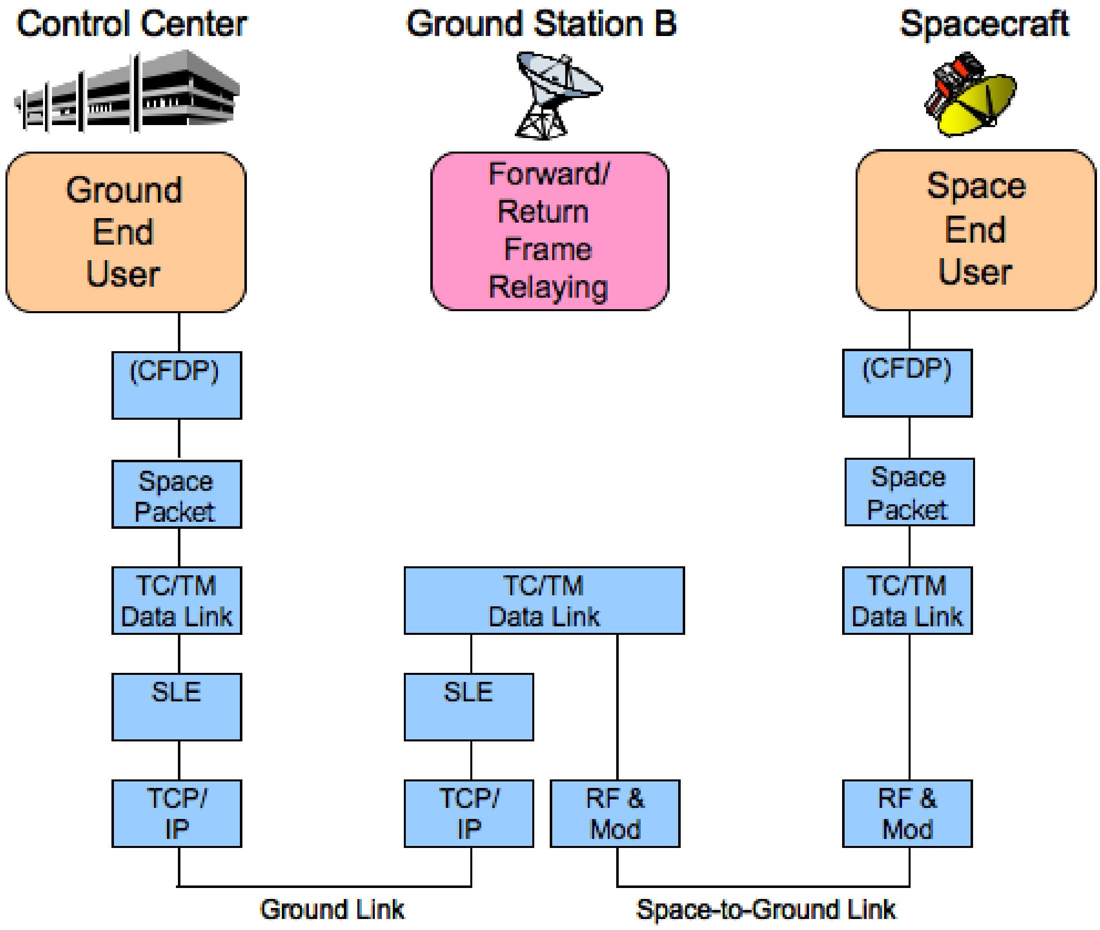


Figure 8: Combined service and communications views

The service(s) provided by the supporting Agency for the user Agency must be managed (that is, controlled and monitored) jointly by both Agencies. CCSDS is developing a standard called SLE Service Management for managing SLE services provided by a ground station, but this standard is still a draft and has only been used on an experimental basis.[vi] Figure 9 shows how this standard is used schematically.

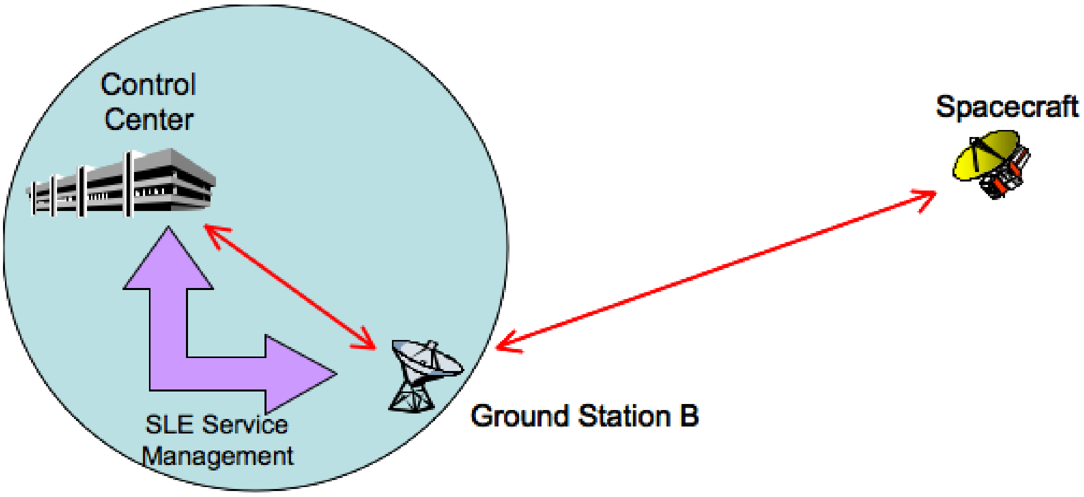


Figure 9: Service view with Service Management

D. Interoperability by Relay Satellites: Physical and Enterprise Views

There is another scenario in which interoperability is employed by space projects of today. This scenario involves a lander (or a set of landers) landed on a planet and an orbiter (or a set of orbiters) orbiting around the same planet. The orbiter belongs to a different space Agency than the Agency that owns the lander and it relays data between the lander and the ground. On the ground, a ground station (or a set of ground stations) belonging to the Agency that owns the orbiter communicates with the orbiter.[vii] The control center of the lander usually communicates with the ground station through the control center of the orbiter. Therefore, data exchanged between the lander and the lander control center is relayed by the orbiter, the ground station and the orbiter control center.

The Physical View for this scenario is shown in Figure 10 and the corresponding Enterprise View in Figure 11. In this scenario, there are two physical interfaces that cross the inter-Agency boundary: one on the space-to-space link between the lander and the orbiter and the other on the ground link between the orbiter control center and the lander control center. These interfaces are indicated with a purple star in Figure 11.

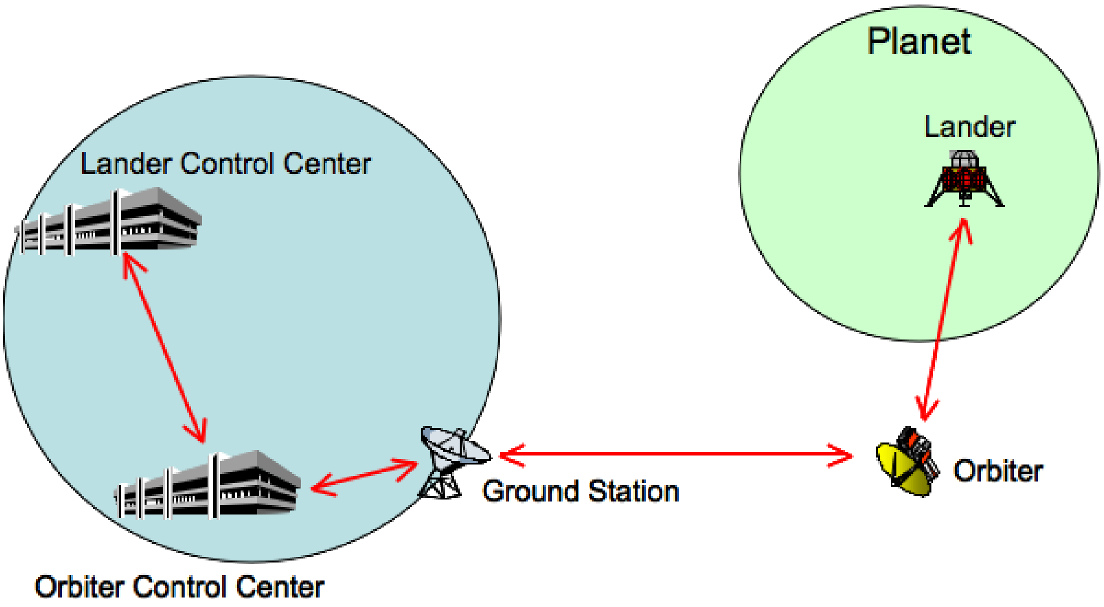


Figure 10: Physical view of a case of relay satellite interoperability

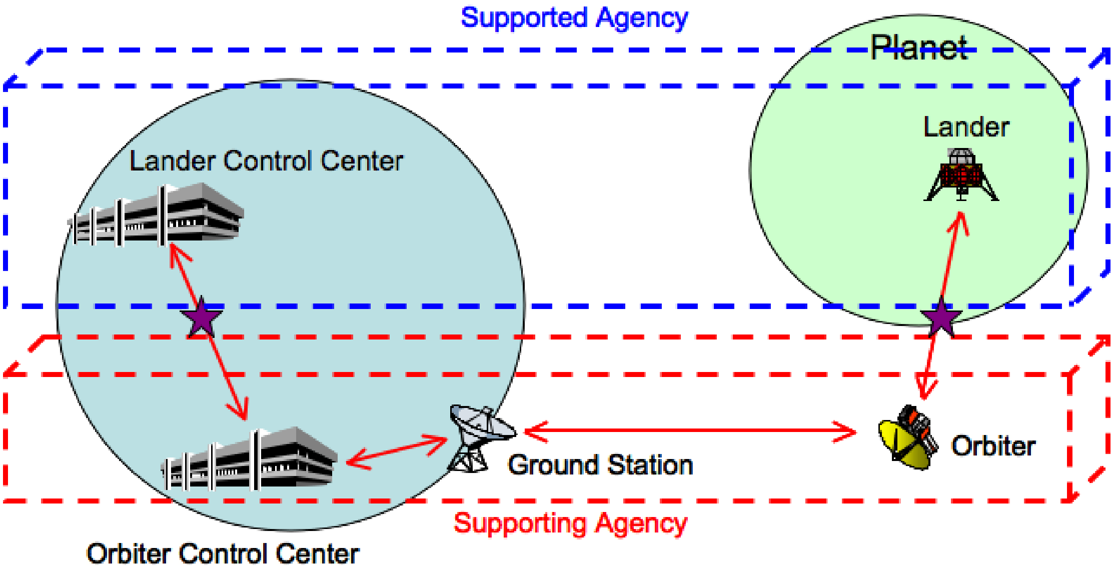


Figure 11: Enterprise view of a case of relay satellite interoperability

E. *Interoperability by Relay Satellites: Service and Communications Views*

The Service View (i.e., the service configuration) for this interoperability scenario is shown in Figure 12. Unlike the ground station interoperability case discussed above, what services are to be provided by the orbiter or by the orbiter control center is not established as international agreements. Most future projects will want the orbiter, the ground station, and the orbiter control center to relay files in a standard way, but there is no infrastructure to support it in a standard way.

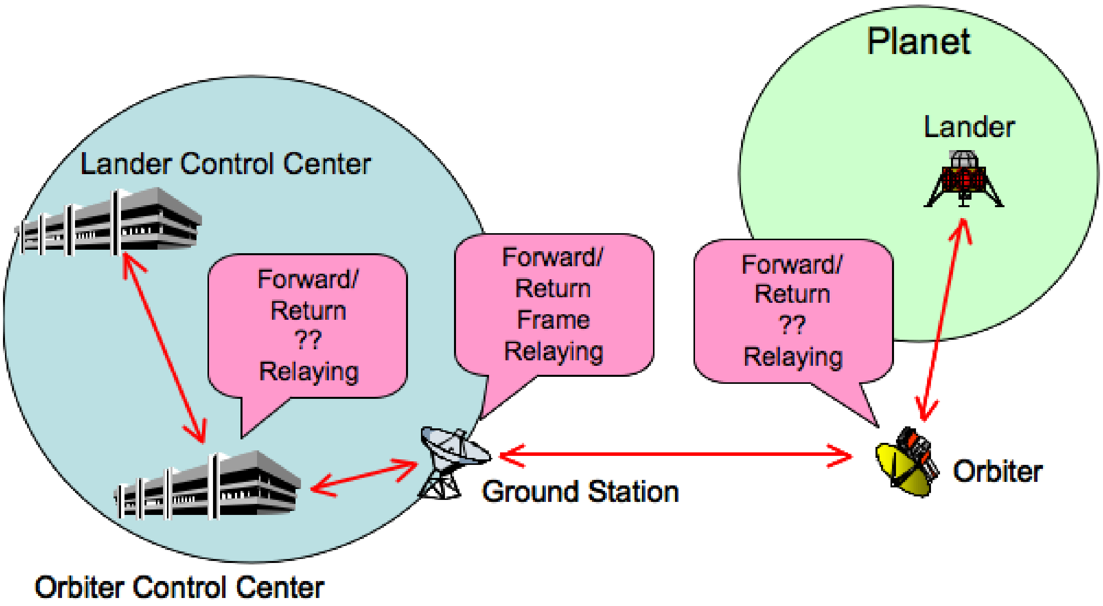


Figure 12: Service view of a case of relay satellite interoperability

The Communications View (i.e., the protocol configuration) for this scenario is shown in Figure 13. For the communications between the lander and the orbiter, CCSDS Proximity-1 Space Link Protocol is used but there is no international agreement about what data units should be transferred by this protocol. Presently, agreement on this is made on a project-by-project basis. There is no international agreement, either, about how to exchange data between the lander control center and the orbiter control center, and this is also determined by bilateral agreements.

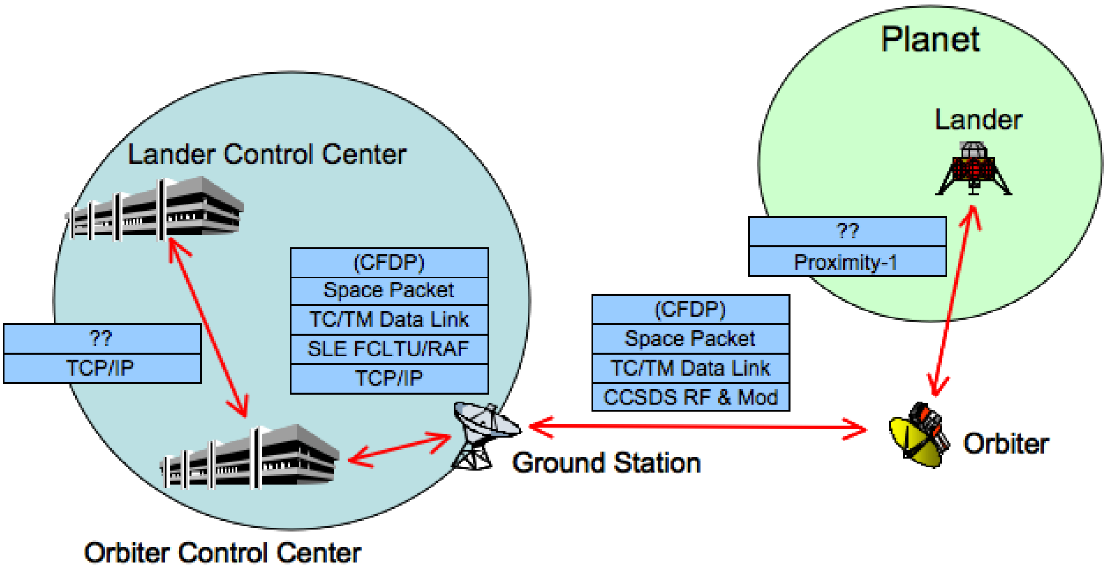


Figure 13: Communications view of a case of relay satellite interoperability

There is no international agreement on how to manage space-to-space services or end-to-end services, either.

F. *Interoperability on the International Space Station (ISS)*

The ISS is an unusual case of attempted and partially successful interoperability, but at the same time a positive case for onboard internetworking. This is a very complex system and a complex situation, and will only be briefly touched on in this report. Notable characteristics of the ISS communications architecture are:

The ISS downlink from NASA, ESA and JAXA use some form of CCSDS standards for TM, TC and AOS. However the versions of AOS are not compatible to the extent of data transparency. For example, although the entire ESA and JAXA streams come down through the NASA downlink, the NASA MCC cannot process parameters in those streams because of differences in the avionics architectures for each space segment. Those streams can only be routed to the ESA and JAXA control centers where they are processed. If needed, JAXA and ESA data which is not in the US downlink must then be retransmitted from Japan and Europe to the NASA MCC.

There is an onboard interface between the US and the Russian segment on a 1553-architecture bus, which allows some Russian data to flow through the NASA uplink/downlink, and vice-versa. However this is a limited capability on a parameter-by-parameter basis, and not a true internetworking capability.

Since the first instantiation of the ISS Avionics, upgrades have allowed agencies to utilize some traditional internetworking based on terrestrial internet protocols. Onboard Local Area Networks

(LANs) have been added for payload data exchange onboard. The Orbital Communications Adapter (OCA) project has implemented a flight-to-ground IP-based internetworking capability which allows the crew to place VOIP-based phone calls to the terrestrial POTS infrastructure, and exchange emails and perform other internet-based functions with ground users. (Note that for flight-to-ground internet-based communications, the OCA uses a custom framing approach that is not standardized.) Future updates to NASA's ISS avionics may further enhance the internetworking capabilities, laying the foundation for space internetworking for NASA's future exploration missions.

The current ISS capabilities illustrate that for large space segment systems, internetworking is a feasible technology, and terrestrial applications work in a spaceborne internetworked environment as long as the delay and latency times are minimal, and mimic the terrestrial environment. However, this does not adequately confirm the feasibility of internetworking beyond Low Earth Orbit (LEO). Further, the overall communications architecture supporting ISS communications (TDRSS relays, onboard busses, etc.) while accommodating limited internetworking for certain subsystems, does not have network layer routing capabilities that would qualify it as true flight-to-ground internetworking with the space segment.

G. Analysis of "Interoperability Today"

The following conclusions can be derived from "Interoperability Today" as described above.

- Interoperability by ground stations has been used successfully by several projects at the frame level. This has been enabled by CCSDS protocols and SLE services.
- The CCSDS standard on SLE service management is yet to be finalized and fully deployed by Agencies.[viii]
- Interoperability by relay satellites has been used by some projects, but there is no international agreement on how to do space-to-space interoperability. There is no space-based infrastructure that supports space-to-space interoperability in a standard way, either.
- In-space internetworking has been demonstrated to a limited extent on the ISS, but overall space-borne internetworking is not fully employed, and not fully verified as feasible in long delay mission environments, or in an architecture that supports the foreseen missions.
- There are no interoperable services other than services for relaying data.

Finding F-1: *In today's mission environment, network interoperability is limited to "best attempt" efforts to add SLE and cross support to ground stations, and very limited project-specific agreements for communications interoperability on the space segment. No communications interoperability for internetworking is agreed to other than taking advantage of the terrestrial internet for very limited ground interactions and unique ISS applications.*

Recommendation R-1: *There should be international agreement on how to do space-to-space interoperability and space-based infrastructure that supports space-to-space interoperability in a standard way.*

Recommendation R-2: *In-space internetworking should be fully verified as feasible in long delay mission environments.*

Recommendation R-3: *There should be international agreement on how to manage space-to-space or end-to-end interoperability.*

Recommendation R-4: *There should be interoperable services for timing, positioning, management, etc., in addition to services for relaying data.*

IV. Projection for Interoperability 2015-2030

A. Overall projection

1. Key Scenarios and Their Attributes

In order to understand how the interoperability and cross-support needs will evolve over time up to the 2030 timeframe the SISG agreed to perform an analysis based on some key scenarios. These are:

a. Lunar exploration;
b. Martian exploration; and
c. Near Earth (including Earth Observation) missions;

A standard set of attributes describing the scenarios to an adequate level of technical detail were agreed and in terms of attribute values snapshots have been taken for each of the scenarios today, 2015, 2020 and 2025.

2. Scenario Attributes: Instantiated Templates

The complete detail of the key scenarios and the attribute values characterizing these scenarios at those points in time where snapshots were taken is in Appendix G: The Scenario Template Table. The table reflects the inputs received from the different Agencies participating in the SISG. Where attribute values are based on the view of a single agency, these values are highlighted in the table by means of yellow background.

Most foreseen robotic DFE/DTE missions do not generally drive internetworking requirements, with the potential exception of interfacing to the terrestrial Internet, and are therefore not further discussed in the remainder of this document. As also this type of missions will require and benefit from cross support, nonetheless the pertinent scenarios have been worked out and are included in Appendix F.

In the remainder of this chapter, the Lunar, Martian and Earth Observation scenarios are further discussed and findings and recommendations related to the individual scenarios are presented. These are complemented by a discussion of trends that are common to the some or even all of the scenarios in section IV and therefore lend themselves to a common technical solution. Wherever a single technical solution can be found that will serve several scenarios, this will reduce the required investment and at the same time further interoperability.

B. Lunar mission projection

1. Introduction

The era from 2015-2030 is expected to see a significant increase in international space missions in the Lunar vicinity. A number of space agencies, as well as commercial entities, have announced their intentions to explore the Lunar environment and provide commercial services to users in the Lunar vicinity. The proposed mission set includes Lunar orbiters, Lunar surface landers, emplaced science payloads and rovers, as well as the buildup of a human exploration presence from an initial human Lunar return through establishment of a sustained, international human presence.

When developing an international strategy to support the buildup of the SSI, it is important to consider the evolutionary nature of space data systems in the 2015-2030 timeframe. We expect there will be a variety of protocols, datagrams (packets) and link behaviors, and the resulting complexity will require an integrated architecture to insure their support to missions. This is mostly a result of the expected gradual buildup of complexity and capability of the Solar System Internetwork (SSI) at the moon as missions evolve from basic observing orbiters and rovers to complex human systems and navigation/communication relays. Many missions flying in the early phase of this period will use the CCSDS Space Packet as the basic datagram for their mission communications. These missions may employ "standalone" point-to-point communications, or may rely on cross-supported Space Packet delivery services and file delivery services to provide a simplistic networked mission architecture. Shortly afterward (2018-2020), missions requiring truly addressed, routed communication architectures will appear. The missions include NASA's planned human exploration missions, as well as more complex science and infrastructure elements such as surface communications terminals and orbiting nav/comm. relays. These missions will need to co-exist in the same Lunar space internetwork architecture as those employing Space Packet methods. The proposed International Lunar Network (ILN) fills the gap, and will consist of orbiters and landed science payloads that while they depend on networked communications and cross-supported space communications infrastructure, will also be a combination of fully networked data systems employing IP and or DTN and non-networked missions using Space Packet. Following the deployment of IP (and in some cases preceding it), missions employing the DTN protocol will appear, and some IP users will transition to DTN services where appropriate. The result of this evolution over two decades will be a changing protocol landscape on which an interoperable Solar System Internetwork (SSI) architecture must evolve, servicing each mission's needs with a common architectural approach.

2. Lunar Mission Scenarios 2015-2030

Lunar mission scenarios in the 2015-2030 timeframe have wide variety in terms of mission class, space vehicle complexity, and interoperability needs. The only true constant throughout the 2015-2030 timeframe is that this period presents a strongly evolutionary trend in terms of mission complexity and the need for interconnectedness and internetworking.

As depicted in Figure 14, missions early in the 2015-2020 timeframe will consist primarily of individual orbiters and landed elements that make limited use of in-space cross support. In addition to orbiting imaging and remote sensing spacecraft, several agencies have announced plans to deploy Lunar surface science missions including rovers and emplaced payloads to investigate the Lunar structure and composition. These missions require direct earth communications, but may also include the capability to utilize relay services provided by either science orbiters or dedicated comm./nav spacecraft. These missions generally will rely on the Space Packet and/or mission unique CMD/TLM formatting, relying on bitstream and virtual channel packet, and file transfer delivery of mission data. In some instances, these early missions will employ the IP packet or an early form of the DTN bundle for communication. Some of the early adopters of IP and DTN also act as an operational "laboratory" to investigate IP and DTN's true behavior and utility in the space operations environment and allow for adjustments to the next generation of IP and DTN missions.

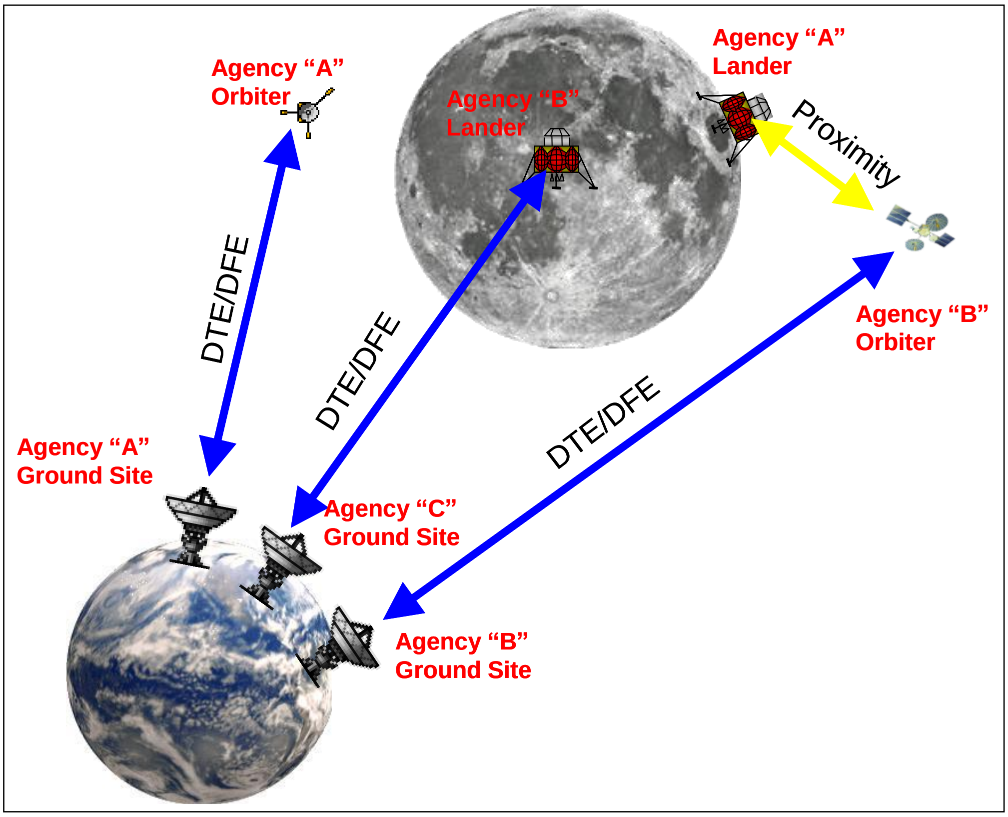


Figure 14: Typical missions in the 2015-2020 timeframe

In some cases, such as exploration of the Lunar far side or the interior of Lunar craters, the surface assets will be beyond line-of-sight with Earth, requiring cross-support from orbiting relay spacecraft. In these cases, the mission is not possible without the capability of relay and networked cross-support. These missions will rely much more heavily on cross-support services including packet (datagram) delivery, store-and-forward, and file delivery services. In these cases, it is expected that lessons learned at Mars will be applied at the moon, with landed missions of one agency leveraging the in-space relay assets of another agency through cross-support agreements.

Missions from other commercial entities are proposed and are being developed to meet commercial objectives including collection and return of scientific information, providing interoperable communications and relay as a salable service, and involvement of the general public in space exploration as a business model. While no commercial Lunar missions have yet to launch, the building momentum of the commercial space industry and the solid reputation of many of the announced industry and non-profit, non-government participants lend credibility to the likelihood of these missions to eventually join those of government space agencies in the Lunar vicinity.

An example of such a multi-agency initiative is the International Lunar Network (ILN) proposed by NASA and joined by nine space agencies. The ILN encompasses a Lunar science program including seismic and geological payloads distributed widely across the surface of the moon, and interconnected by a relay communications network. The ILN partners are actively pursuing commercial and multi-national participation for providing the communications infrastructure to service the science program. This same infrastructure deployed with ILN can service later programs, if the necessary interoperability and internetworking agreements can be developed in forums with the international and commercial participants. If successful, this will be a prime example of the type evolution of growing programs made up of heterogeneous participants (government, commercial, academic) that will drive the growth of Solar System Internetwork (SSI) requirements. Figure 15 shows typical cross support scenarios envisioned by the ILN partners, in which cross support points are indicated with purple stars.

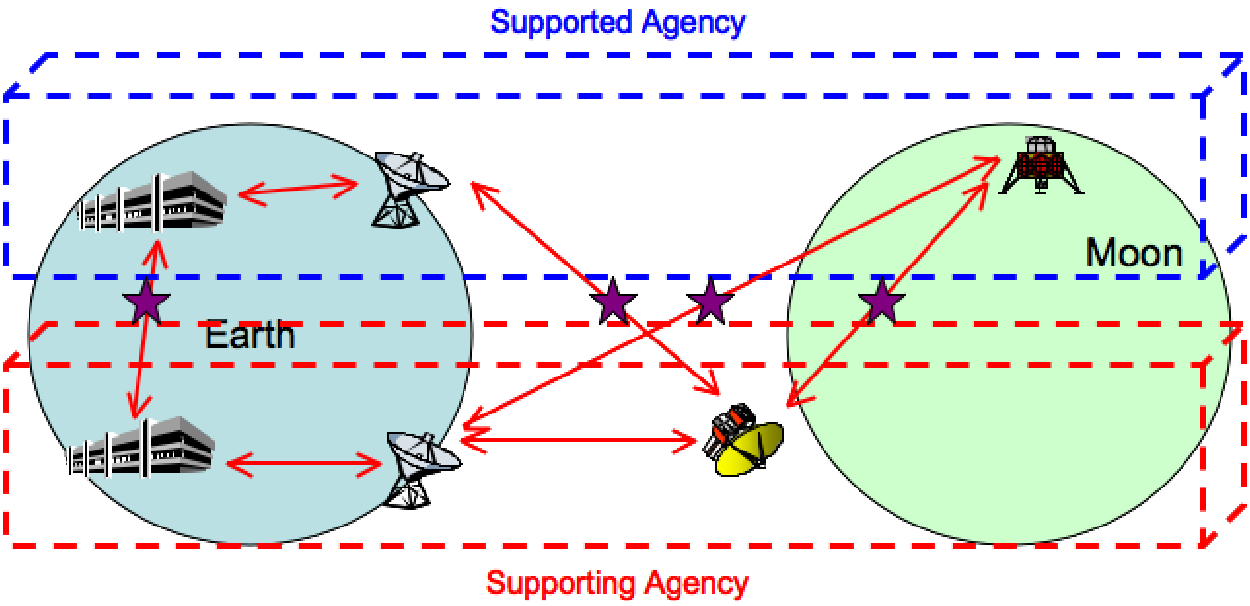


Figure 15: Typical typical cross support scenarios envisioned by the ILN partners

The proposed human exploration of the Moon, tentatively planned to resume in 2020, involves a steady build up of capability as the resources and objectives of the partner space agencies allow. Initially consisting of a human Lunar return “sortie” class mission, a manned lander will be deployed and the crew will conduct EVA operations. As depicted in Figure 16, a local network will be established around the landing location and at EVA work sites to enable communication between crew, mobility systems and payloads/science equipment.

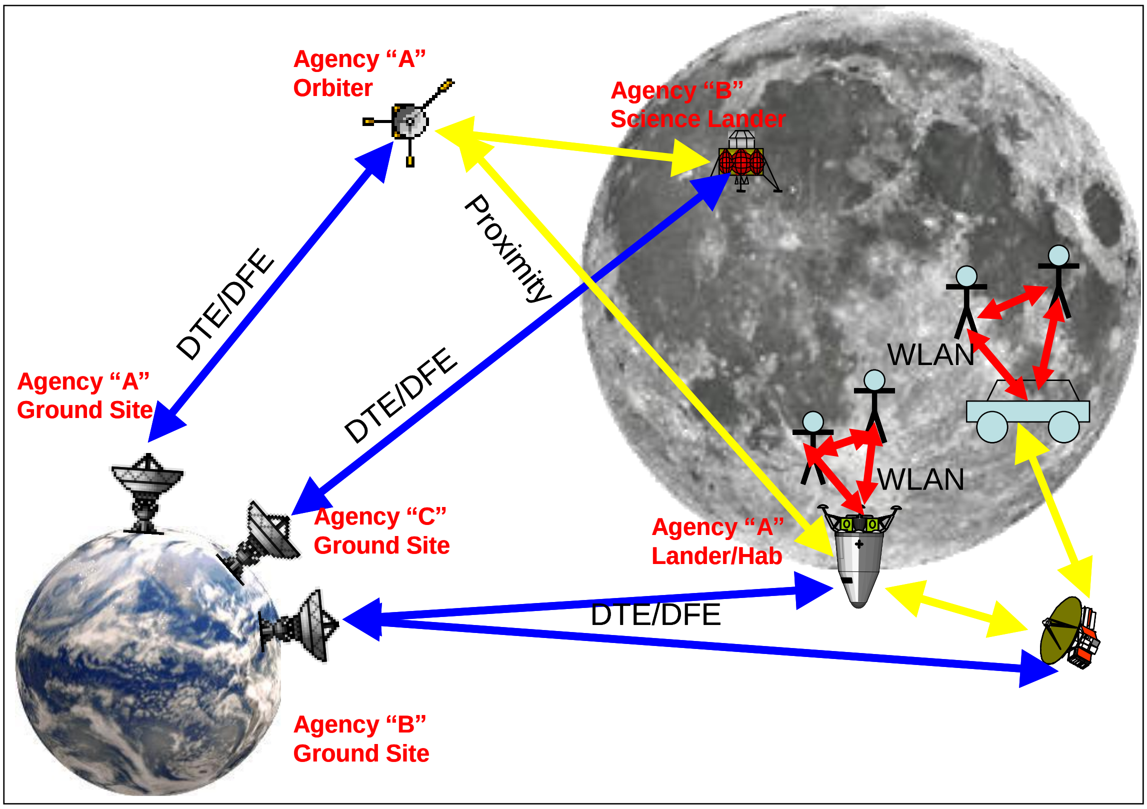
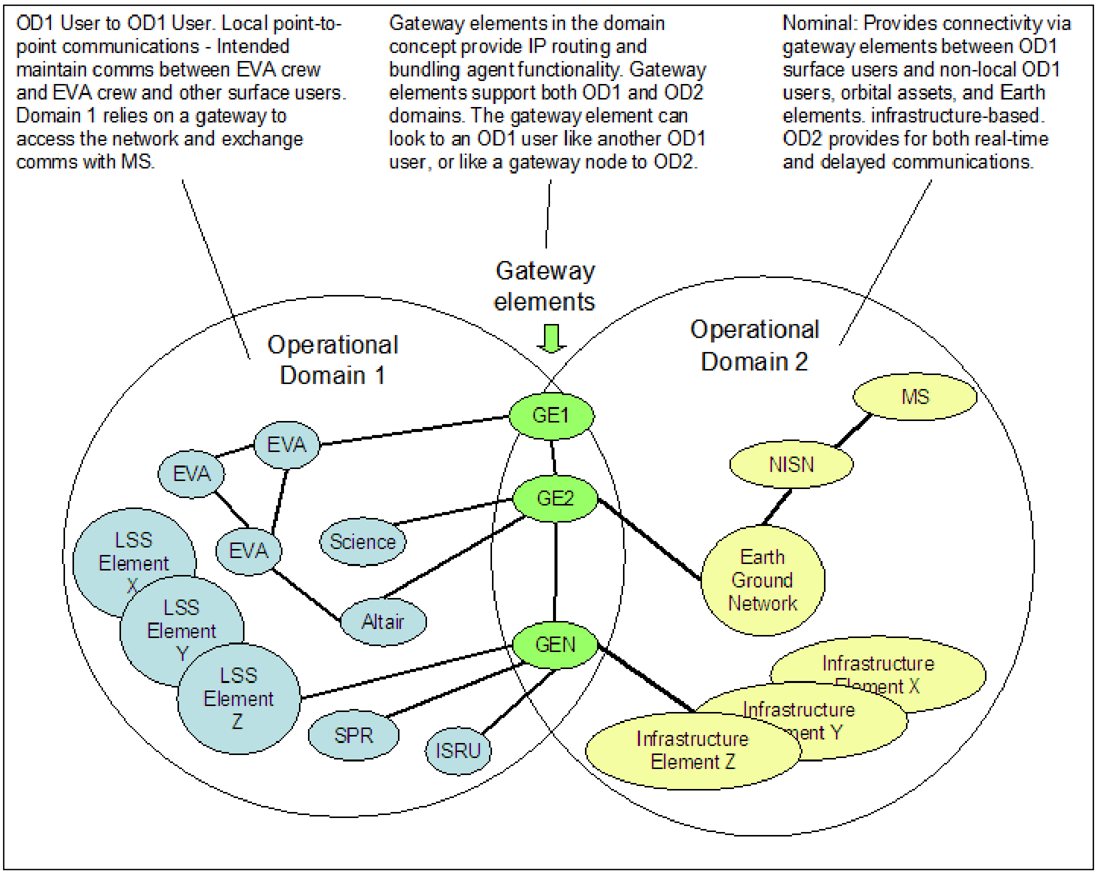


Figure 16: Human Lunar missions after 2020

As capability and systems are deployed, the human Lunar effort will establish an outpost presence, including habitation, power generation, communications, and long-duration surface mobility. These systems will be linked by an increasingly complex and robust communications network providing real-time voice, video, command/telemetry and mission/engineering data feeds both to and from Earth as well as between deployed elements in space. It is expected that systems and elements will be provided by many partner nations in this effort, and the demand for interoperable communications and networked connectivity will continue to increase.

Of interest here is the strong benefit expected from international relay / network cross support agreements to support a multi-national human Lunar exploration effort. As envisioned, the data connectivity between human Lunar systems forms an IP networked and routed architecture linking Lunar surface systems (including mobile assets such as rovers), orbiting vehicles, vehicles in transit between Earth and Lunar orbit, and Earth based control and operations centers, science centers and public outlets. Finally, as the human exploration of the Moon also serves the purpose of preparing for human exploration of Mars and other destinations, operations will be conducted using DTN and other techniques – in essence an operations testbed in parallel with the primary IP architecture - to develop and mature both the technology and operations concepts necessary for sustained human exploration beyond the Moon.


OD1 User to OD1 User. Local point-to-point communications - Intended maintain comms between EVA crew and EVA crew and other surface users. Domain 1 relies on a gateway to access the network and exchange comms with MS.

Gateway elements in the domain concept provide IP routing and bundling agent functionality. Gateway elements support both OD1 and OD2 domains. The gateway element can look to an OD1 user like another OD1 user, or like a gateway node to OD2.

Nominal: Provides connectivity via gateway elements between OD1 surface users and non-local OD1 users, orbital assets, and Earth elements. infrastructure-based. OD2 provides for both real-time and delayed communications.

Figure 17: Conceptual cislunar space internetwork model

We further envision the establishment of a segment of the larger Solar System Internetwork (SSI) that spans cislunar space. Depicted in Figure 17, this cislunar internetwork is conceptually modeled as “operational domains” bridged by “gateway elements”, where the end-to-end cislunar environment can be split into a primarily terrestrial domain and a primarily space-based or Lunar domain. In this model, communications would be based on terrestrial protocols, including IP and the eventual IETF implementation of DTN. Throughout the whole end-to-end environment, protocols would be used to the greatest extent possible. A combination of IP and eventually DTN would be employed to provide the end-to-end routed network behavior allowing the architecture to move away from traditional managed, switched circuit implementations.

As the entire cislunar space is contained within the approximately 10 second light-speed round trip time that is considered a limit for native IP, end-to-end IP would be supported throughout the cislunar infrastructure. This would exist in parallel with an eventual DTN backbone to support those services and applications that cannot tolerate disconnected or long delay environments. In addition, the infrastructure of the SSI must provide for delivery and cross-support of Space Packet datagrams to support both legacy missions and those users that do not require full internetworked connectivity.

The Space Packet, IP and DTN "triad" of cross-supported protocols will be enabled through the concept of "gateway elements". The gateway elements will provide the core network functions including the necessary infrastructure routing, relay, store and forward, security and data accountability required to implement and operate a routed network. Because of the evolutionary nature of both the network and the missions it serves, the gateway elements must support a combination of cross-supported services including native IP, native DTN and adaptations to provide for delivery and transfer of Space Packets for those missions that do not make use of true networking capabilities but still require either packet delivery or file transfer services. A key concept in the gateway element is the ability to act as a bridge between Space Packet, IP and DTN as appropriate for the mission that is being serviced and the class of cross-support required. Concurrent support of DTN, Space Packet and IP in the Lunar environment also offers an evolutionary "laboratory" to develop and demonstrate protocols, technologies and operations techniques necessary to extend the Solar System Internetwork (SSI) to other planetary destinations.

While experience gained in the benefits of interoperable cross support at Mars clearly shows the advantages of independent missions providing communications services to each other, true space internetworking has not yet been realized in the sense that will be required for future Lunar exploration. In both the near term (2015-2020) and long term (2020+) cases, data flows between systems in the Lunar scenarios can be categorized in the following ways:

Direct earth mission communications

Direct earth mission communications will be conducted over point to point DTE links between a ground station and a user mission spacecraft. This link will contain the principal telemetry and command information to operate the spacecraft, as well as mission data (imagery, remote sensing, etc.) for downlink using a file transfer service.

Direct earth routed communications

Direct earth routed communications will be conducted through an intermediary in-space asset. Routed communications could be either real-time or store-and-forward. In either case, routing of data could be through interoperable file transfer services or through packet delivery / routing services. As mission complexity increases through the 2015-2030 timeframe, it is expected that increasing use will be made of packet delivery services rather than bulk file transfer[ix], increasing the importance of in-situ relay processing and cross support agreements for routing, storage and forwarding of user packets as well as files.

In-situ relay routed communications

In-situ relay routed communications consist of two user spacecraft communicating through a local relay spacecraft without the data path including Earth.

Local area networked communications

Local area networked communications consists of point-to-point and many-to-many communications between spacecraft (and landed elements) in a local vicinity. This mode of communication would be used to pass information between cooperative science missions, provide for human real-time communication (e.g. voice between EVA astronauts) and mesh networks in a local worksite. It is expected that this form of communication will follow from commercial local wireless protocols and topologies that will be either adopted as they exist terrestrially or adapted to meet the space environment.

In all cases, each spacecraft or ground station involved in communications is the responsibility of a particular space agency or commercial interest. However, the process of providing the capability for networked communication through cross support involves the coordination of many agencies (and potentially non-government entities). It is necessary therefore to establish agreements and a common set of protocols and expected system behaviors to ensure interoperability can occur.

3. The Networking Business Case

In the Lunar mission scenarios, networking through cross-support provides several significant advantages over non-networked point-to-point configurations. In most cases, the advantages of a networking approach over traditional point-to-point communications are capability-enabling in that by using networking techniques, mission operations concepts are achievable that otherwise would be impractical or impossible. The following are the areas where networking offers advantages.

Traditional “non-networked” communications architectures require that all communication to/from a user spacecraft be brought to/from earth on direct, point-to-point links. This implies that communication between two spacecraft in the Lunar environment, whether in orbit or on the surface, requires the availability of line-of-sight communication between both spacecraft and Earth simultaneously. Additionally, the “two hop” path from the first spacecraft to Earth and then back to the second spacecraft introduces the light speed time of flight delays into the communication channel. Supporting local, in-situ routed networking of user mission data, it becomes possible to contain local communications to the close environment. This implies first that the time of flight required to communicate with Earth is not required, instead this is replaced with the significantly shorter round-trip time to and from the shared relay asset. Also, as communication with Earth is not required, the need for simultaneous availability of a link between both spacecraft and Earth is also not required.

This enables missions to operate and communicate beyond the line of sight with Earth as is the case for crater or "far side" operations. These two scenarios are depicted in Figure 18.

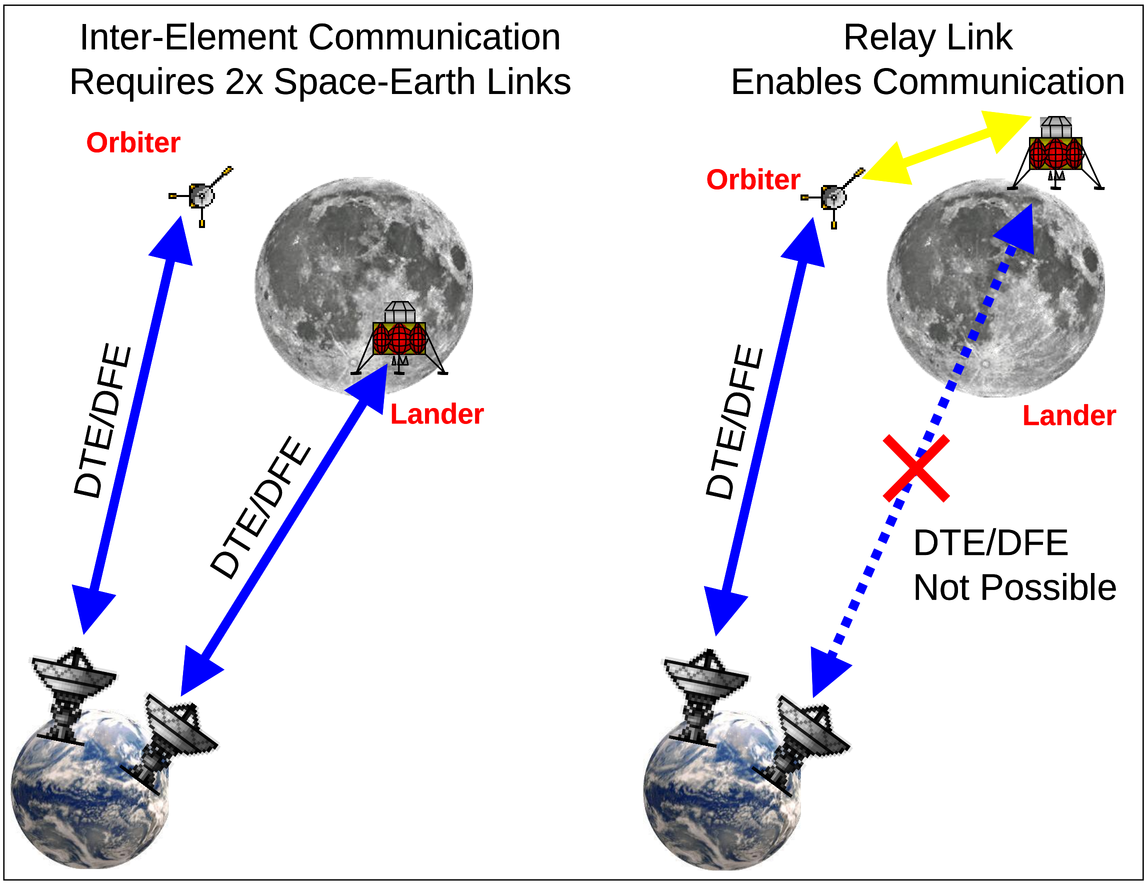


Figure 18: Direct to/from Earth versus relayed communications

The reduced delay enables modes of operation that include real-time (or close to real-time) coordination between assets (such as cooperative robotics or sensorweb missions). A greatly shortened latency between networked elements is essential to effective communication for human exploration as it is necessary to enable real-time communication (voice and video) as well as telerobotics and teleoperation of systems supporting the human exploration effort. Apart from the latency improvement, eliminating the need for Earth line-of-sight enables missions that simply would not be possible without networked relay cross-support such as excursions into crater regions and exploration of the Lunar far-side.

Once networked operation is established, the robustness of the overall mission can be improved. If a mission can form a network with more than one other spacecraft, its available communications paths increase. As depicted in Figure 19, as the number of possible communication partners increases, the number of available communication paths also increases significantly. While this increases the complexity of the overall mission communications architecture, it also improves the robustness of the architecture, providing protection against failure of one mission element as well as against communications interruptions caused by geometry (such as craters or highland topology). By enabling a user spacecraft to communicate through multiple paths, the robustness of the overall mission end-to-end communications architecture is improved.

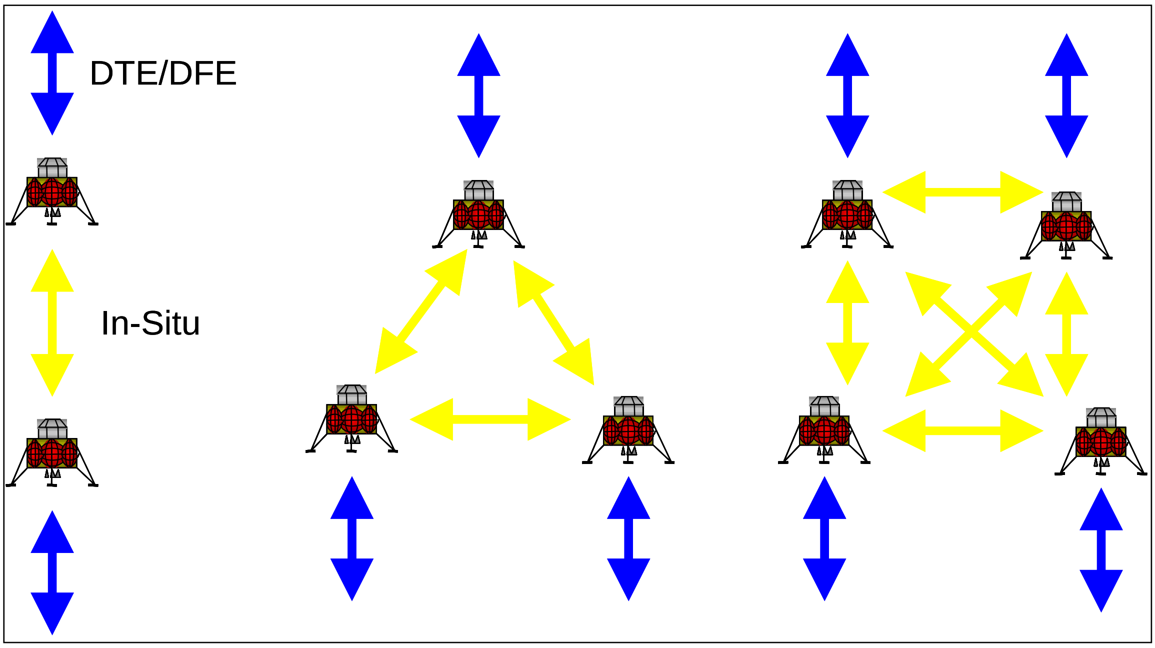


Figure 19: Benefits of increasing path diversity

4. The Interoperability Business Case

As previously stated, many space agencies and commercial organizations have declared their intent to deploy and operate robotic orbiters, landers and human systems at or on the Moon. Each mission is a significant investment in time, money and risk. It makes sense, therefore to look for opportunities to leverage each agency's individual investment in such a way that the whole is greater than the sum of the parts. Networked communications and true internetworking of space assets is such a way.

As discussed in the previous section, networked communications significantly increase the operational flexibility and robustness of missions, as well as enabling mission classes otherwise untenable. In addition, networked communications offers additional redundancy and resiliency to failure of an individual asset or to conditions that do not permit line-of-sight communication with Earth. It is clear that the use of relay communications, and networks built upon the relayed, routed data concept offers many advantages to traditional point-to-point communications. This comes at a cost however, in that the assets providing the relay service must also themselves be deployed and operated.

If, however, agencies (and commercial organizations) reach agreement for mutual cross support of missions then each organization's individual investment can be leveraged to build a robust, highly diverse networked communications architecture. The terrestrial analog would be the meshed network comprised of commercial telecom providers in which data flows and capacity are essentially commodities and an outage on one network is routinely "picked up" on another. This spreads both investment cost and risk across the group of participating agencies rather than forcing each mission to expend the resources and assume the risk alone.

By agreeing to cross-support missions of each other's agencies, each partner agency can gain the benefit of shared resources and infrastructure.

In order to enable cross-support of networked communications, the following must be established:

- Interoperable physical communications layers including spectrum allocation, modulation and channel coding, and communications data link layer standards.
- Interoperable network architectures and agreement on a set of common datagrams (e.g. IP, Space Packet, DTN Bundle) that will be cross-supported.
- Agreement on a standard set of cross-support services at the data link, datagram (packet) and possibly application layer (e.g. file transfers and store-and-forward delivery services).
- Agreement on the behaviors that can be expected by a user accessing an infrastructure relay node that is providing cross-support. Such behaviors include route determination and traffic prioritization, store-and-forward and expected data delivery order.
- Agreement on the operational configuration and management of shared infrastructure providing cross-support, including router/network addressing, naming and name resolution, route path determination heuristics (e.g. closest neighbor, highest reliability, balanced bandwidth, etc.), link establishment and scheduling, and end-to-end status and data accountability.

Finding F-2: *Lunar scenarios currently envisioned add new requirements that exceed the capabilities of current point-to-point links, such as visibility in craters and far-side operations; They also add new requirements for cross-support between international partners most likely involving routing through in-space assets.*

Recommendation R-5: *In support of envisioned Lunar collaborative missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

C. Mars Mission Scenarios

1. Introduction

A number of space Agencies have announced their intentions to participate in programmes involving missions to Mars. In advance of human exploration that will take place in the 2030's, a variety of unmanned, precursor robotics missions are either under way or planned. Such missions involve landers, rovers, and orbiters operating as a network of cooperating elements. Individual missions are rarely self contained and instead rely heavily on inter-Agency cross-support, either for primary scientific data return, or for back-up and contingency operations. Furthermore, the Mars infrastructure is assembled in stages with new infrastructure often reliant on that available from previous missions.

While the benefit of internationally agreed standards is already being demonstrated in present missions, actual mission interoperability is still, to a large extent, reliant on additional local agreements made on a project by project basis. This occurs, for instance, because of the limited scope of some standards and the options they contain. The work required to establish these ad-hoc agreements is considerable and may be acceptable from an individual project viewpoint. However, when a longer term, multi-mission, multi-Agency infrastructure is considered, the use of fully specified cross-support standard will be key to keeping mission development and operations costs and risk to an acceptable level.

2. Mars Mission Scenarios Circa 2015

Figure 20 depicts a typical Mars robotic mission scenario circa 2015. It consists of:

- Multiple landed elements
- Multiple orbiting relay satellites
- Multiple Ground stations
- Multiple Mission Control Centres (in the picture mission control centres and ground stations are combined in the GDS)

While each of the above elements is the responsibility of an individual Agency, data transfer between the elements may involve the use of resources from cooperating or supporting Agencies.

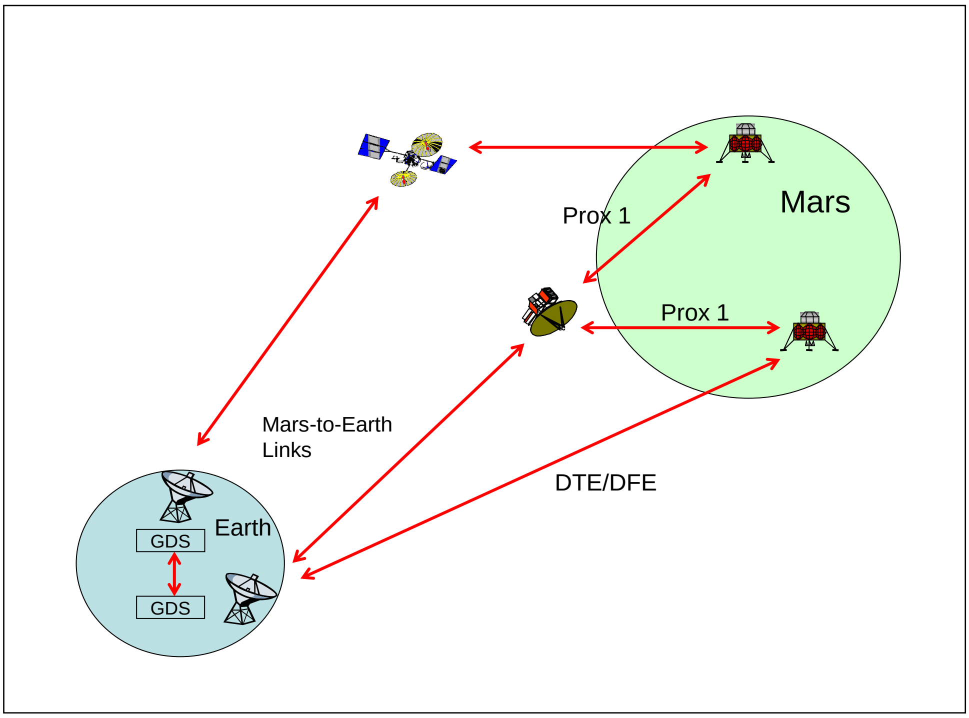


Figure 20: Mars scenario circa 2015

Data Flow description

Although low rate, direct to earth (DTE) and direct from earth (DFE) communication is typically available to landed elements[x], a key feature of Mars relay operations is the store-and-forward data relay process. Since visibility, to the orbiter, of both Earth station and landed asset rarely occurs simultaneously, data are transmitted to the orbiter when an uplink path from Earth or Mars is available, stored onboard and then transmitted to Mars or Earth when the downlink path becomes available.

In the forward direction, the user creates data files that it wants transferred from a relay spacecraft to the Mars asset during a scheduled over-flight. These data files are sent directly from the Ground Data System (GDS) to the relay spacecraft where they are loaded into the onboard data store. These data files are then relayed to the designated Mars asset during the over-flight.[xi]

Simultaneously, in the return direction, data generated by the Mars asset is transmitted to the relay spacecraft. Scheduling (view periods) determines when the relay spacecraft transfers the data received from the Mars asset to Earth. The relayed data from the asset is extracted from the relay spacecraft's telemetry and delivered to the user.

Cross support points

Figure 21 illustrates the primary cross support points used in the present Mars Missions:

- Cross-support point 1 is used for exchanging files (destined for, or received from, the Mars landed asset) between ground control centres[xii];
- Cross support point 2 is used for two-way exchange of files between the cross-support orbiter and the Mars landed asset.
- Cross support point 3 is used between control centre and cross supporting ground station. Note that these services are not necessarily used in the present scenarios

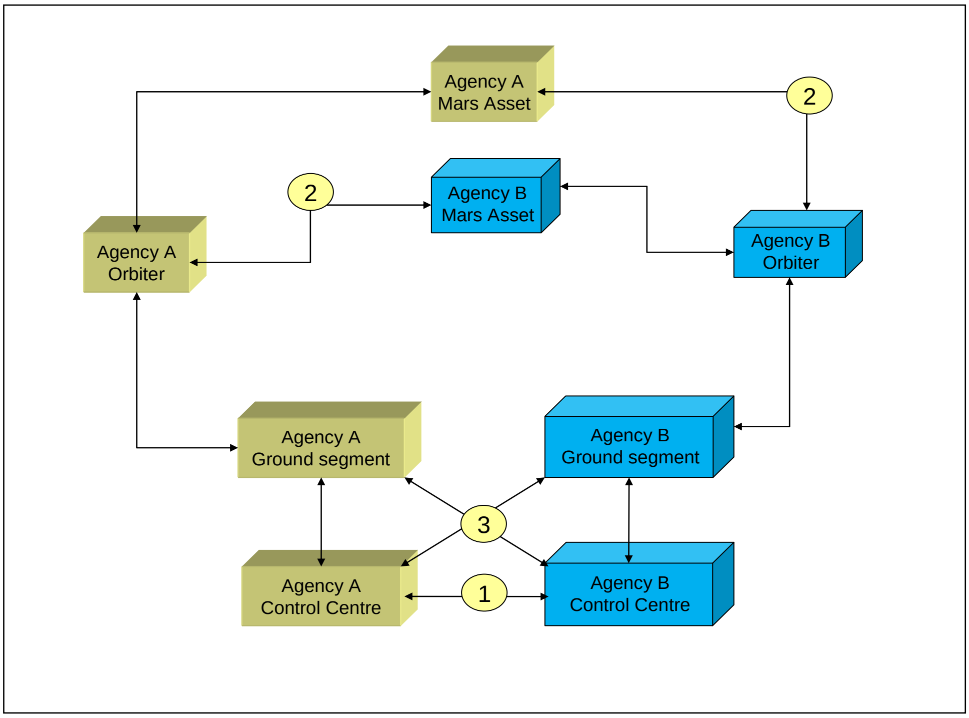


Figure 21: Primary cross-support points

Analysis and recommendations

Existing solutions

Although CCSDS has developed a set of Recommended Standards applicable to the Mars scenario, infrastructure, equipment and missions were being specified during the development of the Recommended Standards. There is, as a consequence, some variation in the approach taken to the provision of CCSDS services, and this variation has introduced a number of shortcomings and the need for mission specific and ad-hoc solutions.

Figure 22 illustrates a typical return link implementation. The following limitations may be noted:

- The CCSDS Proximity-1 Recommendation used between a Mars asset and cross-support obiter has two options: user defined data (UDD) and packet service. In many current implementations only the UDD service is available on all cooperating elements. The UDD service provides for the transfer of a stream of bits with no recognition of the data structure being transferred. Thus, non-standard, project specific mechanisms are required for those Agencies wishing to transfer packet based data.
- CCSDS has developed a standard protocol for transferring files – CFDP but this protocol is currently not implemented, operated, and exposed as a cross-supported service over the end-to-end data path. The result is that the file transmitted by the Mars asset is relayed using several different mechanisms all of which must be developed on a project specific basis.
- Additional information concerning the quality of the file transferred by the Cross-supporting Agency to the user GDS is provided in a project specific manner.

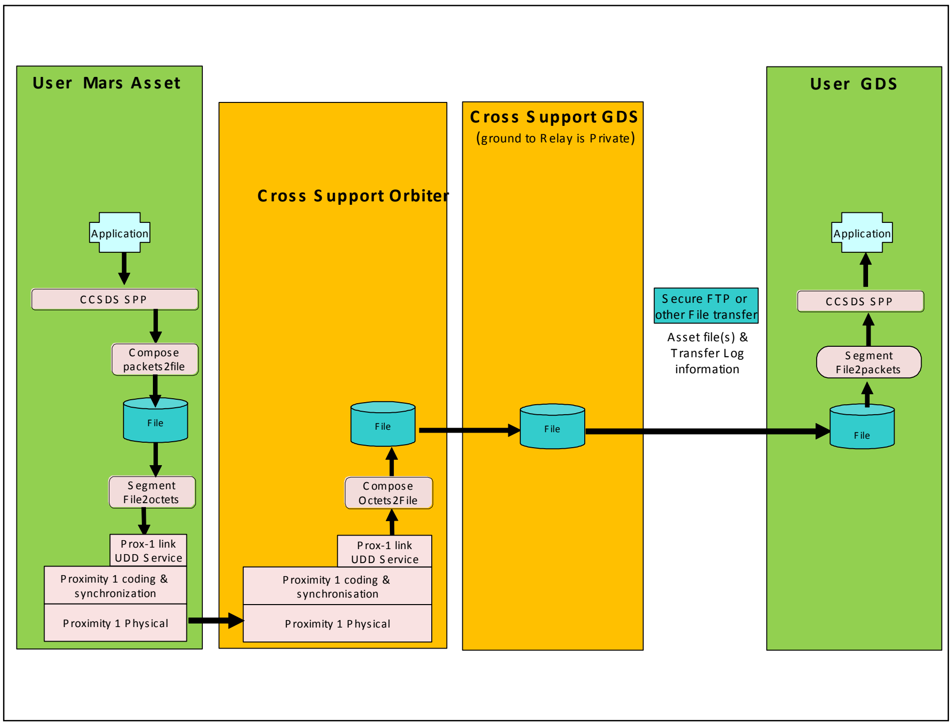


Figure 22: Typical return link implementation

Figure 23 illustrates a typical forward link scenario where similar limitations are inherent:

- The orbiter Proximity 1 implementation only supports UDD service
- CFDP-based file service is not yet implemented and used as a cross-support service. That means although the Class -1 CFDP could be used between the user GDS and the user Mars asset, it must

rely on the receiving user Mars asset to delimit the packets containing the CFDP PDUs and to accomplish the transfer of individual files.

- Ancillary information required for file delivery by the Cross Support GDS must be conveyed using ad-hoc mechanisms; this includes addressing the user Mars asset, selection of transfer parameters, and the timing of transfer from the Cross Support Orbiter to the user Mars asset.

In addition, the cross-support service is limited to the delivery of the content of a user-constructed file from the GDS to the Mars landed element. While this may be acceptable for nominal operations involving the update of files located in the Mars asset, it requires significant capabilities (processor, onboard communication, mass memory) to be fully operational – a burden that is not well-suited to those landed vehicles designed with simplicity in mind. In contingency situations these capabilities may not be available or may be degraded and limited. In such cases a low level command capability which relies on minimum functionality being available on the asset is considered a necessary feature.

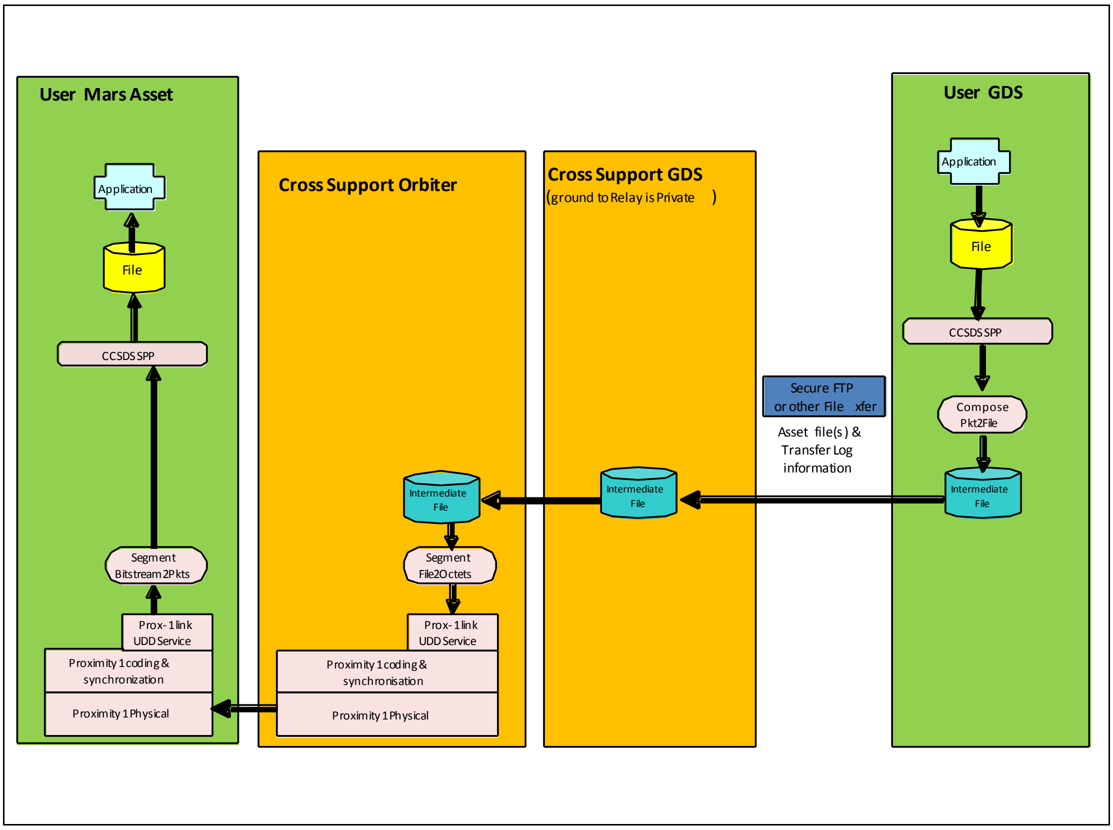


Figure 23: Typical forward link scenario

CCSDS defined cross-support services

A contributing factor to lack of standardisation in the present Mars implementations is due to a corresponding deficiency in the CCSDS cross-support recommendations. Currently these are limited to the definition of the Ground interfaces as covered by the CCSDS Space link extension services (SLE). These in turn are restricted to frame level and do not include the transmission of packets (forward packet service is specified by CCSDS but not yet generally implemented as a cross support service), files and ancillary data such as accounting and radiometric data. In the space segment, no cross-support services are defined and missions must rely on protocol level recommendations which, in themselves, do not constitute cross-support agreements.

Observations

The current infrastructure at Mars, and the Missions presently scheduled for the 2008 to 2015 time frame, are designed to relay the returned data collected by a User Mars Asset to Earth as a single file, the file being defined by the start and end of a lander orbiter communications session rather than having any end-to-end context. In the forward direction, files (possibly including auxiliary control information) are delivered to the orbiter but are then forwarded as a stream of octets to the Mars asset.

This methodology infrastructure has a number of shortcomings which may be attributed, in part, to the lack of a clearly defined CCSDS cross-support services. In this respect a number of observations are made:

1) It should be recognised that cross-support is not only applicable to ground operations rather it should address the space cross support points and also the quality of service provided between ground and space cross-support points. SISG should therefore recommend:
    - Definition of cross-support services that cover CCSDS packet and CFDP-based file transfer across all elements in the end-to-end communications chain[xiii]
    - Extension of the existing SLE services to include the transfer of files, transfer of packets, ancillary information such as radiometric tracking, link monitor data, navigation and accounting data
    - Inclusion in the cross-support services of a mechanism for low level commanding of a Mars asset utilising a cross-supporting orbiter. This may mean formalizing the use of frame or packet structure to deliver hardware commands by a cross support orbiter to a user Mars asset.
    - Inclusion of a Network Time service local to the Mars networking environment[xiv]
    - Inclusion of the Tracking and Navigation services local to the Mars networking environment
2) The cross support service should identify the naming and addressing scheme and a method for attaching metadata for data traversing cross-support infrastructure to avoid ambiguity and conflicts in, e.g., lander and orbiter addressing domains.

3) A service management infrastructure for overall cross support should be defined.

Within these overall activities some important details of principle should be incorporated. These are specifically:

- All Orbiters should implement both the UDD and packet services defined by the Proximity-1 protocol.
- CFDP should become the standard protocol for transferring files and should be cross-supported by all elements within the end-to-end communication chain
- The possibility to deliver a low level command in the form of a packet should be included in the cross-supporting orbiter and reflected in the ground cross-support service. Packet integrity should be maintained between the ground cross support point and the Proximity-1 packet or frame at the space cross support point.[xv]

Based on the discussion above, the figures which follow provide a few forward link examples of the end-to-end communication in a networking environment. Key features of the depicted Mars scenarios are as follows:

(1) The Mars networking architecture extends the CCSDS cross support service model to the flight side of the communication systems. In a sense, for the Solar System Internetwork (SSI) it is envisioned that there exists a *network service providing* system, i.e. the cross support GDS and the cross support orbiter, and a service user system, i.e., the user GDS and the user Mars asset.

(2) Predicated upon this network service model is the end-to-end file delivery capability (See Figure 24, Figure 26, and Figure 27). All file transfers are handled using CFDP over the CCSDS Space Packet Protocol, which in turn utilises the packet service of Proximity-1 for data delivery to the user's Mars asset.

(3) End-to-end packet delivery is provided for supporting low-level commanding. Two modes of packet data delivery are offered: the packet stream delivery by a Throughput Mode (See Figure 25) and the packet delivery by a Store-and-Forward Mode (See Figure 26) where a dedicated application located on the orbiter is able to access packets delivered as files to the orbiter via CFDP from ground and send individual packets to the Mars asset.[xvi]

(4) The SLE Forward File Service, a new standard to be defined by the CCSDS, plays a crucial role in tying together the file transfers by all elements on the end-to-end path. Chief among its value-added functions beyond the present CFDP are: (a) It provides a standard underlying file transfer capability for the ground-to-ground interface, i.e. between the user's GDS and the cross supported GDS, via a selected variation of the commercial FTP; (b) The accounting information synthesized over that for all individual file transfers will be provided based on the standard information defined by the CCSDS.

(5) Cross support to in-situ applications is enabled by this networking architectural approach (See Figure 27). This is an important capability as we see potential demands on this by coordinated surface missions and sample return vehicles.

(6) The Mars networking architecture characteristics depicted here, while elaborated by the forward link examples, is highly symmetrical between the forward and return links, in terms of their protocols, data flows, and processing. That means little or no special customization on either link is necessary.

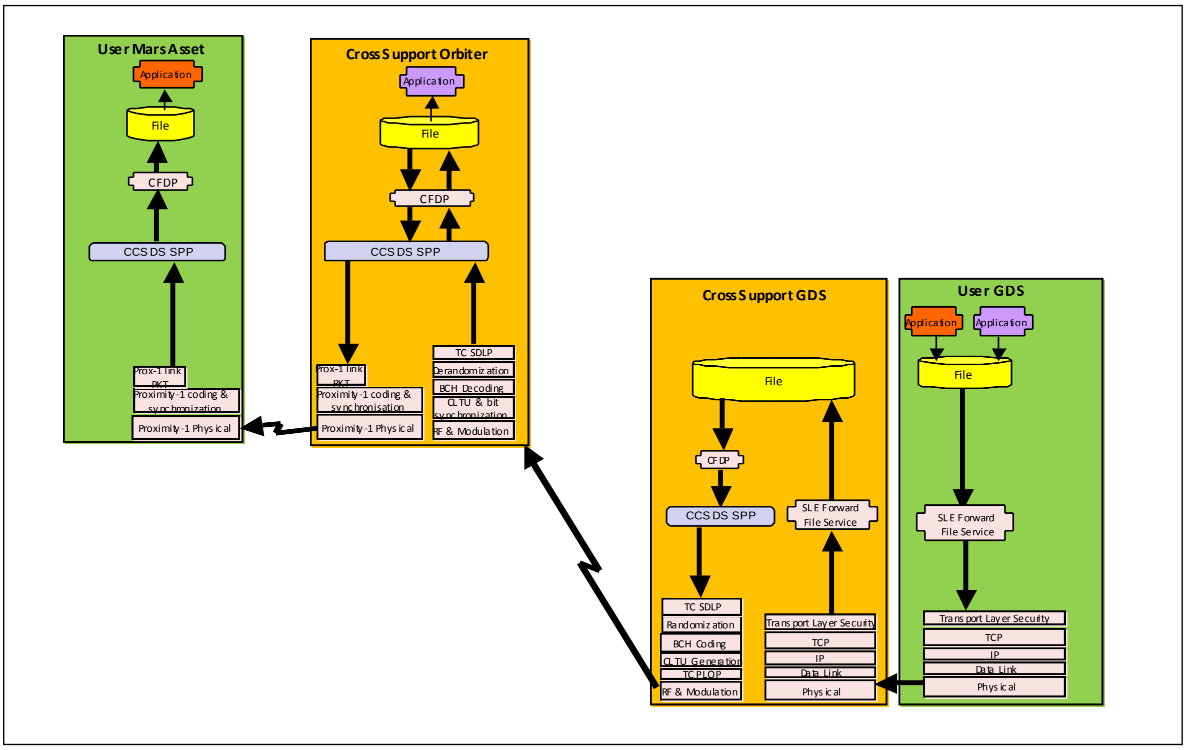


Figure 24: Forward link example of Mars scenarios – ETE File Delivery

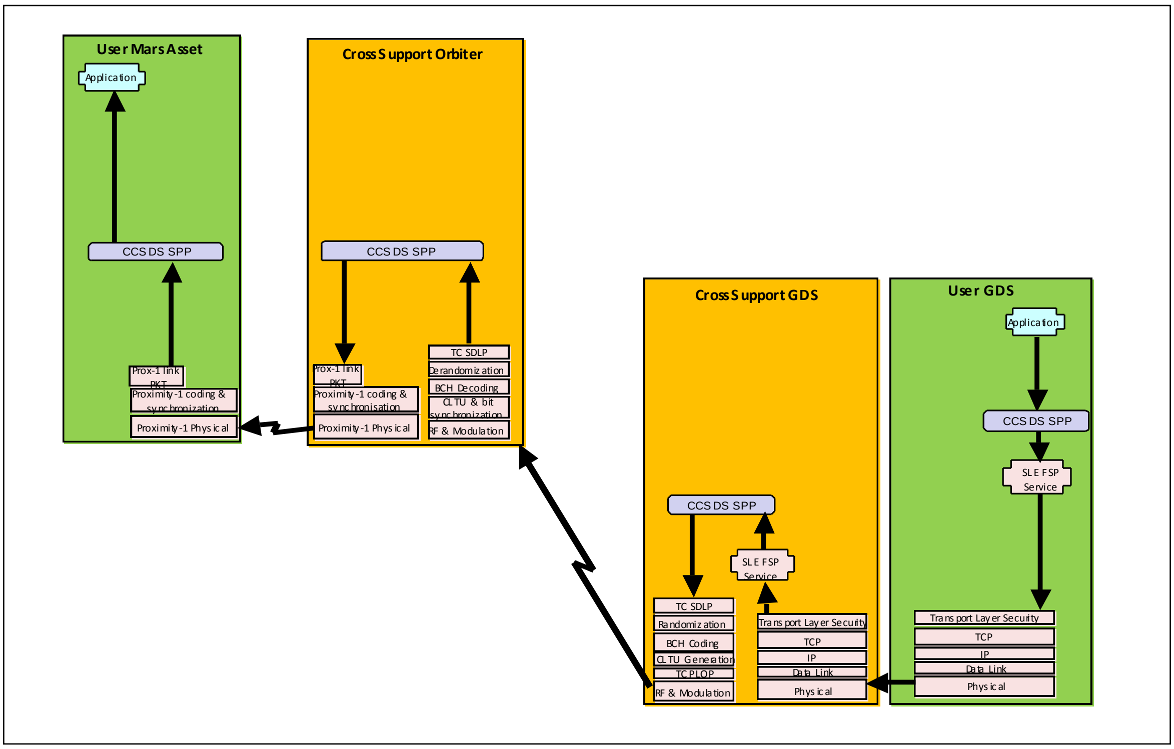


Figure 25: Forward link example of Mars scenarios – ETE Packet Delivery in Throughput Mode

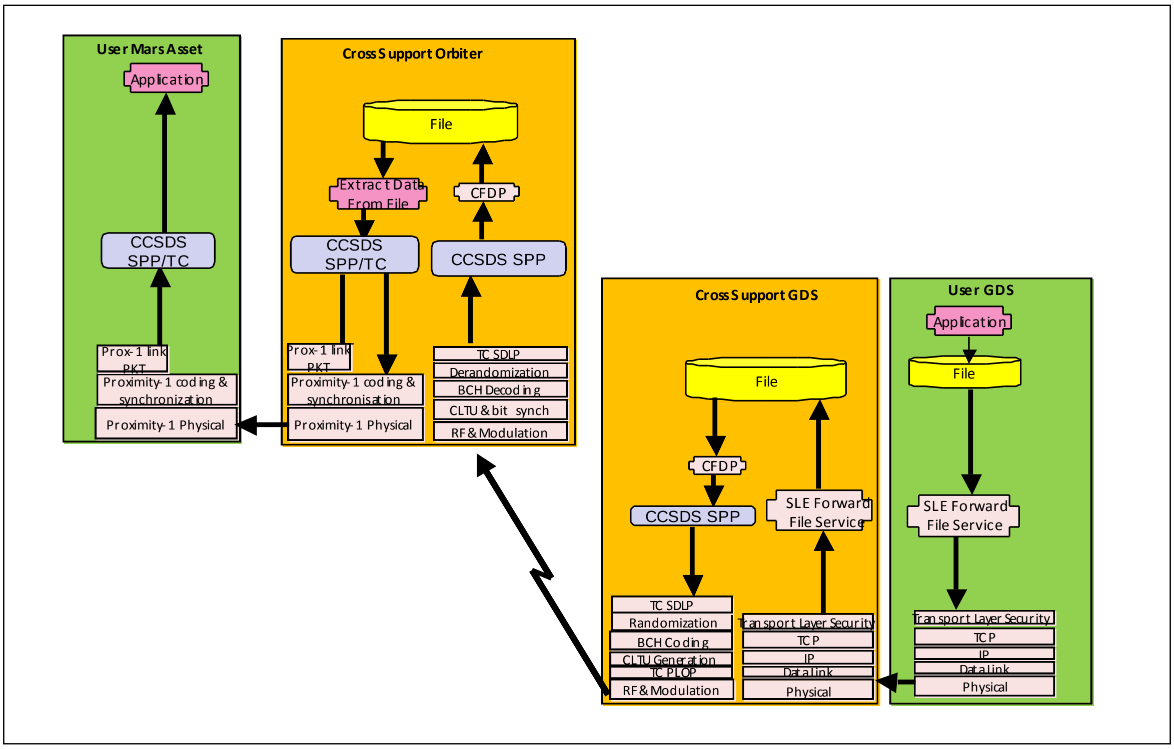


Figure 26: Fwd link example of Mars scenarios – ETE Packet Delivery in Store-&-Forward Mode

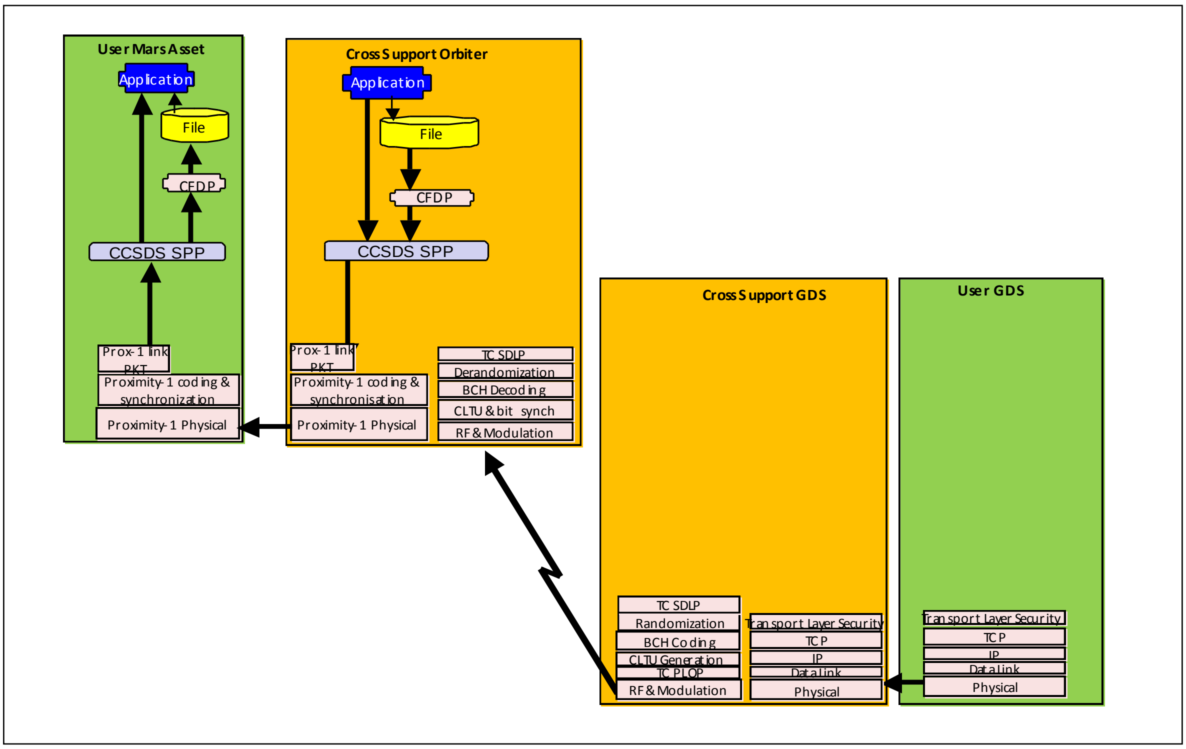


Figure 27: Forward link example of Mars scenarios – In-Situ File and Packet Transfer

New Services local to Mars Networking

Two new service types, the Network Time Service and the Tracking/Navigation Service, local to Mars networking environment are also recommended. They are enabled by the Mars relay orbiters (or the cross support orbiters as depicted in the Figures above) and the available proximity links.

1) Network Time Service: This service correlates the time epoch of a user spacecraft clock to UTC over a return proximity link, broadcasts a timing reference message over the forward proximity link to the user's spacecraft at Mars, and/or determines the bias of a user clock epoch relative to UTC.[xvii]

2) Tracking/Navigation Service: The availability of the proximity links offers certain radiometric data types for navigating the user Mars spacecraft. This includes the Doppler/range data on RF link between an approach spacecraft and the relay orbiter for precision approach navigation during the entry, descent, and landing (EDL) event, the 1-way or 2-way Doppler/range tracking on proximity link for surface position determination for a rover or lander, and the 1-way or 2-way Doppler tracking on proximity link for tracking an orbiting sample canister. Figure 28 gives a description of this service.[xviii]

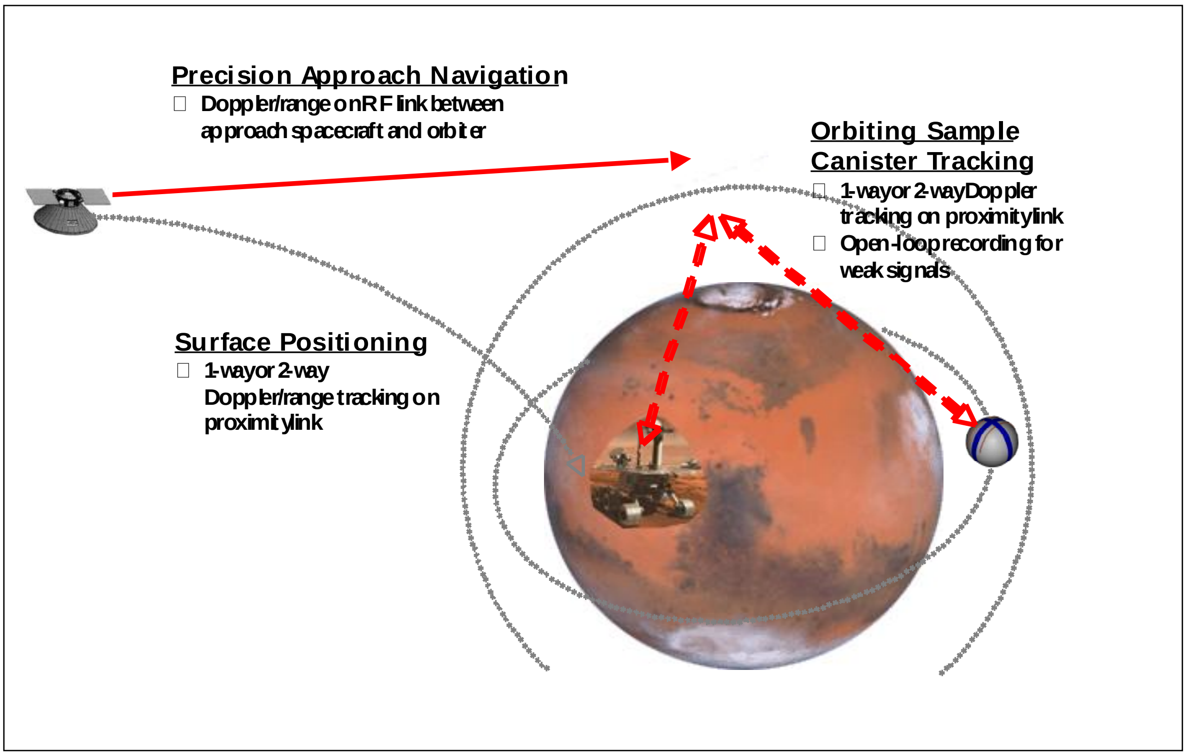


Figure 28: Tracking/Navigation service local to Mars networking environment

3. Mars Mission Scenarios Circa 2025

Figure 29 illustrates a typical Mars robotic mission scenario circa 2025. The key differences compared with current mission scenarios is the inclusion of surface to surface communication between multiple landed assets and the complexity of possible forward and return paths available using multiple Agency Assets. The surface communications are expected to be based on commercial wireless standards in combination with the standard internet suite of protocols.

The increase in complexity requires important consideration as it will significantly increase the need for well defined and standardised cross-support services. Any project specific solutions may undermine the possibility for generic interconnection whereby identical back-up capabilities are available from multiple elements.

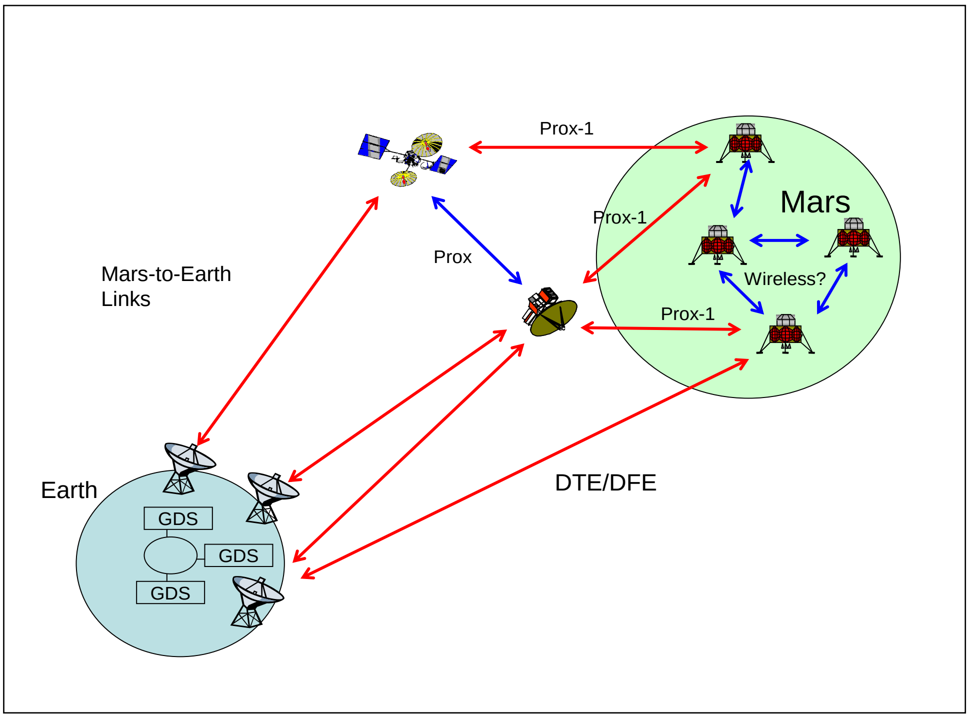


Figure 29: Mars mission scenario circa 2025

Data Flow description

The end-to-end data flow is very similar to that required for the existing missions with the addition of information transfer between landed elements. Local communication between landed elements is expected to be based on commercial wireless standards in combination the standard internet suite of protocols. It is currently unclear if additional services will be required above and beyond CFDP to relay data between landed elements and the GDS.

Analysis and recommendations

The future Mars missions will result in a complex network of elements developed by different Agencies in a phased deployment. Multiple communication paths will become available to and from ground and new infrastructure will rely on and complement existing elements. The specification and use of cross-support services and their associated protocols will be a key aspect for each mission as without these the infrastructure will fail to operate in an optimum manner and the costs of managing and coordinating non-standard elements will be exorbitant.

The interoperating community illustrated above demonstrates a greater architectural symmetry than that of the more immediate missions in that, in addition to a network on earth, we have a deployed network at the planetary end. This, coupled with the intervening delayed, disrupted, and disjoint links is exactly the model on which the Delay/Disruption Tolerant Networking (DTN) programme is based.

DTN is based on features present in CFDP but extends CFDP in two ways:
- By separating the existing CFDP functionality into individual protocol layers in order to support a wider set of applications (not just file transfer)
- By extending the existing CFDP features to cover aspects such as security and multipath route selection

DTN offers the prospect of core network architecture able to operate in the long delay and disjoint connectivity environment of Mars and at the same time offers sufficient flexibility to be able to interoperate[xix] with IP based protocols used locally on Mars.

The precise applicability of DTN needs to be addressed including an assessment as to whether it can support specific services such as emergency commanding and other low level services.[xx]

It should also be made clear which underlying services and protocols in long haul, proximity and planetary links are required as bearers for the DTN protocols.

Today it is not feasible to predict all of the requirements for future Mars missions, especially when human exploration is concerned. However, the availability of a core infrastructure based on DTN should offer a sound communications backbone on which new applications may be built.

Finding F-3: *Mars missions in the 2025 timeframe will be increasing collaborative, and will be characterized by a local network infrastructure on Mars which locally uses routed IP protocols. Exact requirements are not stabilized, but it is clear that some form of interagency routed infrastructure based on IP and/or DTN will be required.*

Recommendation R-6: *In support of envisioned Mars collaborative missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

Recommendation R-7: *The cross-supported architecture for circa 2015 should include: cross-support services that cover CCSDS packet and CFDP-based file transfer across all elements in the end-to-end communications chain; Extension of the existing SLE services to include the transfer of files, transfer of packets, ancillary information such as radiometric tracking, link monitor data, navigation and accounting data; Inclusion in the cross-support services of a mechanism for low level commanding of a Mars asset utilizing a cross-supporting orbiter; an interoperable Network Time Service and a Navigation/Tracking Service; a naming and addressing scheme and a method for attaching metadata for* *data traversing cross-support infrastructure to avoid ambiguity and conflicts in, e.g., lander and orbiter addressing domains; A service management infrastructure for overall cross support.*

D. Near Earth Scenarios

1. Scenarios

This study of Near Earth Scenarios only considers robotic missions. The rational for this was that (1) The ISS program is past it's development phase; (2) Future manned missions in development are reaching beyond Near Earth to Lunar space, and; (3) the accelerated schedule for this report.

Robotic Near Earth missions, which include missions ranging from suborbital missions out to missions at Earth-Sun Lagrangian points, will continue to be a majority of the future Near Earth mission set. As the costs for spacecraft development and access to space reduce, more complex missions may become achievable for the same costs as the present day. This increased complexity may be seen in advanced instruments generating higher data volumes, as well as missions comprised of a constellation of spacecraft. Near Earth spacecraft will be a key element of a future Earth Science Sensor Web (see Figure 30), where many different types of sensors exchange information to increase measurement precision, provide notification of science events, or to provide other coordination.

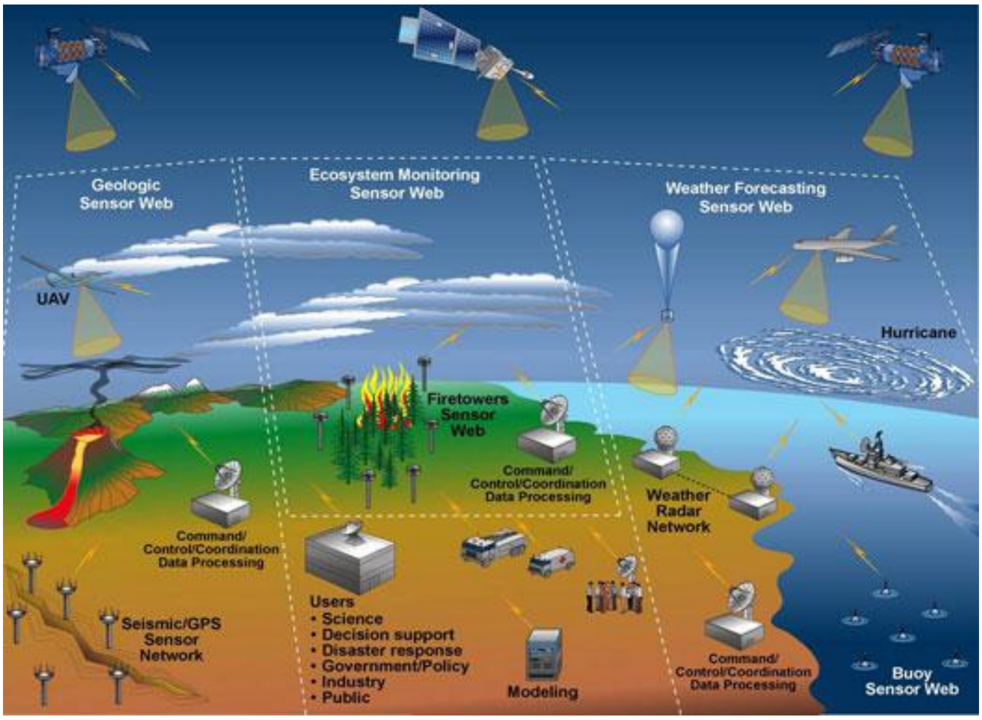


Figure 30 - Earth Science Sensor Web

(Source: NASA report ESTO AIST Sensor Web Technology Meeting Feb 2007)

In the area of Space Science, this approach has been extremely successful in coordinating Gamma Ray burst measurements using the GRB Coordinates Network (GCN) (see Figure 31).

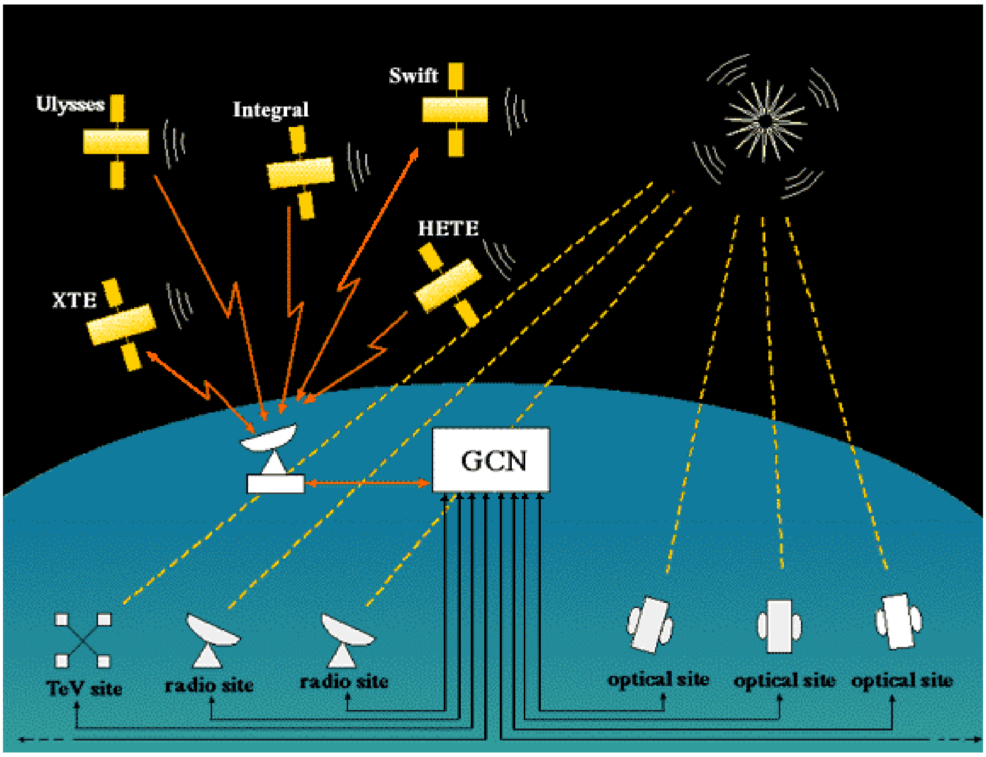


Figure 31 - Gamma Ray Burst Coordinates Network (GCN) (Source: http://gcn.gsfc.nasa.gov)

Since Gamma Ray bursts are very short in duration, minimal latency in the distribution of burst notifications greatly increases the probability of coordinated measurements.

Spacecraft will typically have lower rate RF links for tracking, low-rate telemetry, and command at S-Band or X-Band. Higher data rate telemetry links will evolve from current X-Band links to Ka-Band or possibly optical communications links.

2. The Networking Business Case

The Sensor Web is by definition a network of sensors. The sharing of data between sensor web elements will be facilitated by middleware-based messaging across a heterogeneous array of communications links. Keys to achieving the key goals for the Sensor Web autonomous sensor operations include sensor rapid response, autonomous planning, and increased data transmission through the use of multiple downlink access points. As the number of sensors increases, manual configuration of all of the possible data paths to meet these goals becomes untenable. The recurring operations costs will greatly outweigh the costs for each sensor element and the operations costs will directly impact the amount of science return, since fewer sensors will be able to be supported within a fixed budget.

The use of a packet-based, networked approach for data distribution will minimize the latency by allowing the network data units to route directly to their destination directly to or from the termination of the space link. The use of DTN will further increase the network performance by allowing network data flow as the spacecraft links come and go.

3. The Interoperability Business Case

Requirements for rapid response and distribution of information drive a need for increased network access for each sensor. This does not necessarily imply continuous communications contact for spacecraft, but it does imply minimal latency between the generation of information and the delivery of the information. The NASA Space Network is currently capable of providing Demand Access Service (DAS) to LEO users, allowing users such as the SWIFT and GLAST gamma ray science missions to rapidly deliver notifications of gamma ray bursts. The DAS service utilizes the S-Band Multiple Access service of the TDRS satellites to provide full orbital coverage. Though full orbital coverage utilizing ground stations is practically impossible, due to the number of ground stations required, interoperability provides the lowest cost method for increased data return and minimized latency for Sensor Web type missions.

Finding F-4: *Near Earth missions are the most numerous missions, and the costs benefits of internetworking are therefore potentially large. Additionally the science benefits of such technologies as Sensor Webs are not achieveable in any other way.*

Recommendation R-8: *In support of envisioned Near Earth missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

E. Overall Scenario Analysis

1. Commonalities

Looking at the trends reflected in the attribute values characterizing the different scenarios and their evolution over time as shown in Appendix F, there are a number of trends that are common to all scenarios analyzed. These are:

- An increase of data rates both on the forward and return link.
- Migration to higher frequency bands (except for EO forward link) and more bandwidth efficient modulation and advanced coding schemes.
- Except for the DFE/DTE type missions, data relays (GEO, at moon, at Mars) become more and more important. In GEO we will have bent pipe relays while at Mars and probably at Moon the store and forward regime will apply such that automatic routing capabilities and delay/disruption tolerant architectures may become cost effective and operationally beneficial.

- From a protocol layering point of view, the interactions will move up the protocol stack from the link layer as used today via network to application layer protocols such as file transfer, but for mission safety reason the low level commanding capability will have to be retained. In part the transition to file based operations is also linked to the higher data rates that cannot be easily supported by the conventional TC protocol drawing on procedures such as COP-1.
- With larger portions of data such as files being handled as a whole, novel coding techniques such as long erasure codes can be used to optimize the data delivery reliability.

2. Scenario Specifics

Comparing the inputs received from the different agencies for the different scenarios, it becomes obvious that except for the Lunar scenario the expectations in terms of the technological evolution and operational needs match relatively well and the differences are rather minor and/or limited to some specific details. The significant deltas in the attribute values of the Lunar scenarios are mostly attributable to the fact that only the NASA input covers the aspect of human exploration and draws upon the related resources in place today. Attribute values that appear unique to the Lunar scenario are:

- Very high data rates (> 1Mb/s) and AOS framing on the uplink.
- Possible use of IP end-to-end including the Earth Moon trunk (DTN/BP + LTP may enable the use of the same technology on Earth-Moon and Earth-Mars trunks).
- Unique modulation scheme (CDMA/DSSS) inherited from TDRSS / SN.

3. Analysis and Recommendations

The commonalities between the different scenarios identified above can be summarized in the following findings:

Finding F-5: *There is a strong trend towards higher data rates on the space links which in turn calls for higher frequency bands offering higher bandwidth. Nonetheless, bandwidth efficient rather than power efficient modulation schemes will be needed.*

Finding F-6: *If the decoding process needed for a given coding scheme is less complex, such coding scheme is better suited for higher data rates and for the forward link as a low complexity decoder can be implemented as flight hardware.*

Those two findings result in recommendations regarding the evolution of the physical (RF and Modulation) and coding layer. Such recommendations have been developed by a NASA-ESA team on the basis of the NASA CMLP study and will be presented to the IOAG in that context. Therefore, these recommendations are not repeated here.

Finding F-7: *The transition to file based operations concepts enables the use of novel application layer error detection and correction techniques such as long erasure codes.*

This finding results in the following Recommendation:

Recommendation R-9: *In view of mostly file based operations, IOAG agencies should embark on developing novel coding techniques designed to error protect the end-to-end transfer of large size application data units.*

Finding F-8: *The dependency of missions on suitable space-borne relays is growing which in turn requires some form of routing capability. Such routing may initially be based on CCSDS Space Packets or other routable data structures such as IP packets or DTN bundles, which will then be carried by encapsulation packets. All these options require the CSTS services be upgraded to support packets.*

The consequences of this finding are already covered by previous recommendations and therefore no related recommendation is put here.

Finding F-9: *In general, a given Agency will invest into novel capabilities only if these capabilities respond to identified needs that can be derived from this agency's mission model, but not just for the sake of being able to provide cross support to another agency.*

Recommendation R-10: *In order to maximize the chances of being able to provide mutual cross support, the IOAG agencies should strive for agreeing on a common approach for Lunar and Martian missions whenever technically feasible.*

As a final recommendation for this section, the prior recommendations for Lunar, Mars and Near Earth scenarios and missions can be rolled up into one summary recommendation:

Recommendation R-11: *In support of envisioned Lunar, Mars and Near Earth missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

V. Management Projection for Internetworking

The bulk of this report depends on an analysis of current and clearly forecast mission needs in order to establish the potential need for internetworking for the next generation of spaceflight missions that are currently in some stage of planning.

However, it must be recognized that missions (programs and projects) are naturally conservative, and they will usually not advocate or adopt new technology because of budget constraints and risk. This can stagnate the advancement of new mission capabilities, especially when their mission priorities are to apply resources to (for example) science results with current technology, rather than to apply resources to new technology or infrastructure. In this case, the role of advancing new technology falls to management, standardization bodies and infrastructure-providing organizations.

Accurate farsighted forecasts can identify of where important technology is maturing, and can enable the next set of capabilities for new missions. But the “right balance” is where the farsighted forecasts are not so far out as to be “science fiction”.

In the case of Internetworking applied to space missions, there are two signs that indicate that the technology is not “science fiction” but instead is ready for application to missions, even though missions may not yet be advocating the new infrastructure.

The first sign is where one mission has already declared a requirement for and a grasp of this new technology domain. <u>In the case of internetworking, NASA’s Constellation Program is pursuing an aggressive approach to adopting Internet Protocols (IP) and Delay Tolerant Networking (DTN) in their plans for Lunar exploration[xxi]</u>. The presence of one mission with this policy is a strong indicator that the technology is feasible and can potentially bring benefit to other missions, even though more conservative missions are not yet pursuing that approach within their own limited single-mission scope.

The second sign is broad adoption in other industries. In the case of internetworking, the terrestrial world and many other industries have clearly benefited from automated routing and the other benefits that internetworking provides. Clearly no communications technology is more broadly adopted today in other industries than internetworking protocols. Further, the pursuit of DTN by the IRTF and other organizations make it clear that DTN technology will materialize. Clearly some “adaptation” will be required for space-borne applications for IP and possibly for DTN. But in both cases, the simple fact that there are enormous commercial benefits for terrestrial applications bolsters the case that there are also benefits for space-borne applications. Therefore, it is time to consider the adaptation and adoption of internetworking for upcoming missions and in-space applications.

With both of those indicator signs being "positive" for internetworking, the management level conclusion can only be that even though funded and established missions have not yet recognized the need to set a foundation of internetworking, infrastructure-providing organizations and standards organizations should be establishing an internetworked environment for spaceflight missions. In the near term, we can expect the same benefits and efficiencies that other industries already achieve. Further, this will ultimately bring unanticipated benefits to both existing and future missions as those missions learn how to take advantage of the new internetworked environment in ways that we cannot yet imagine.

Management must also address the multi-mission life-cycle view of potential benefits of internetworking in a way that no single mission will. Across our many missions we see these characteristics:

Figure 32: Missions concepts move towards distributed users, some in the office environment.

1. Most missions have many different types of users (widely distributed scientists on the ground in the office environment, remote robotic controllers, onboard crew that want the same capabilities/interfaces as they had when they were on the ground, etc.). All of these users currently employ internetworking technology in their daily tasks.
2. Many are long duration missions; they will evolve from their initial concepts and requirements, and they will change their operational requirements, concepts and scenarios over the lifetime of the missions. Long duration missions also influence the distribution of tasks to the office environment.
3. The types of traffic that missions need to handle (TM/TC, voice, video, science data) are varied from a life-cycle standpoint, but the transport of that data is most cost-effective if it is the same underlying approach throughout the life-cycle of the missions. This means we need to "target" an approach that can remain stable for those long-duration missions.

For those many missions, in order to minimize development costs, incompatible (and hence costly) interpretations of standards, maintenance and evolution costs, we will need an early and widely-agreed to "target" on the kind of networking approach that will be utilized. And we need to specify that "target" to a level of details that is agreeable to all potential parties and will minimize such costs in the long run.

The management entities over terrestrial projects had challenges (although on a larger scale) similar to the space mission characteristics above, and to meet those challenges they adopted the Internet Protocol (IP) approach to internetworking. The resulting terrestrial infrastructure is ubiquitous and well supported, and the pervasive environment has features (such as DTN) and capabilities that can be called upon. There are many commercial products and an abundance of skilled workers in this area, and management wants to take advantage of them. Management doesn't want to have to train a narrowly specialized workforce in a technology that is "proprietary" to spaceflight.

Finally, one more trend provides a third management-level incentive for internetworking. As the next generation of missions stretches the limits of affordability, we are already seeing a dramatically increased trend towards internationally cooperative missions. This is particularly true in the case of Human and Mars missions where costs are so high that they need to be shared between multiple nations and agencies. This trend brings with it two driving requirements – (1) the need for interoperability within missions in order to be able to share data and assets and; (2) the need for interoperability across missions where infrastructure is incrementally deployed and utilized, as is planned for planetary surface infrastructure. When this trend is coupled with an increasing technical complexity of the future missions (which itself results from the architecture of cooperative missions), then it becomes intuitively clear to management that the mission architecture of cooperative missions is a major driver towards not only interoperability in general, but space internetworking in particular.

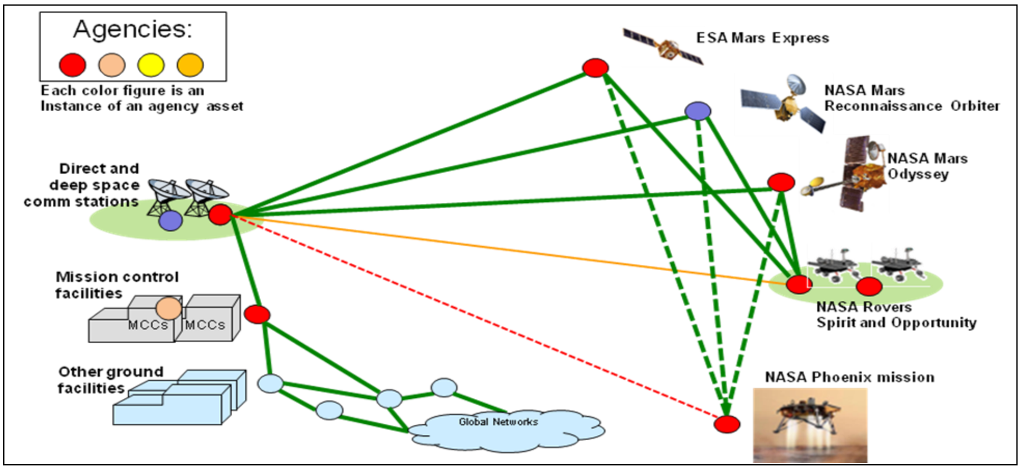


Figure 33: Illustration of the complexity of current Mars multi-agency efforts

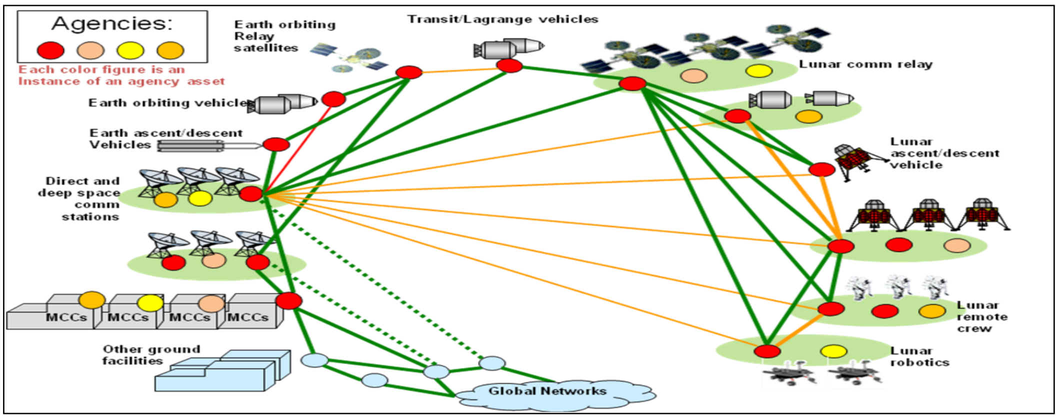


Figure 34 - Illustration of the complexity of future Lunar multi-agency efforts

In summary, a management view with foresight and vision will recognize that the spaceflight industry and the IOAG agencies should move towards the concepts and benefits of internetworking regardless of whether current missions or project managers yet recognize all the benefits that such infrastructure would provide. The management projection for missions that are not yet "on the books" is a forecast for increasing cost, increasing complexity and as a result increasing internationally cooperative missions. The burden on management is now to develop a plan and approach that implements the technology and realizes the benefits.

Finding F-10: *Considering the well-established benefits from the ubiquitous terrestrial adoption of internetworking and considering the plans for NASA's Constellation program*[xxii] *to further mature internetworking technology for space-borne applications, it is likely that the technology is ready for application to spaceflight missions, and it will bring benefits to those missions.*

Finding F-11: *Missions (programs and projects) are very conservative, and the burden of moving to a new technology must be driven by management, standards organizations, and infrastructure programs.*

Finding F-12: *The drive towards international cooperative missions, with increasing cost, increasing technical complexity, and increasing need to share data and assets, is in itself a driver towards space internetworking.*

Recommendation R-12: *The IOAG agencies should develop a consensus that space internetworking is an important new approach that the agencies are ready to move from concept to implementation. An international collaborative program should be instituted to prepare the technology for usage by missions (programs and projects).*

VI. Candidate Technologies and trade-offs for future Space Communications

A. Overview of Candidate Technologies

As shown in chapter III, the current Space Communication Architecture is based on a Ground Network communicating point-to-point with a satellite (usually Control Centre ↔ Ground Stations ↔ Satellite) with the Ground Stations handling the standard operations with the Space Link and exchanging CCSDS standardized data (e.g. CCSDS Packets/Frames/CLTU for TM/TC and other data for radiometric measurements) with other nodes of the Ground Network. Today's cross support is limited to the Ground Network and is based on the utilization of elements (Ground Stations, Control Center, etc.) of different Agencies/Organizations in order to enhance mission operations (e.g. ground coverage) and hence mission return. The cross support access points within the Ground Network are often mission specific and are agreed between the User and the Provider.

CCSDS has successfully standardized the exchange of basic data (TM/TC/Radiometric Data) via the Ground Network cross support points by means of the SLE transfer services (i.e. RAF, RCF, ROCF, CLTU, FSP, for TM/TC and Ranging/Delta DOR with file exchange "after processing" for radiometric data). Such standardization effort is today limited to the exchange of data structures belonging to the CCSDS Data Link Layer with the exception of one TC Packet Service (i.e. FSP) and it still misses service(s) supporting the AOS Data Link Layer structures for the forward link.

For these reasons, the CCSDS effort is continuing and will include in the near future service management and additional transfer services.

Cross support of space-to-space or space-to-landed elements is addressed by the CCSDS standard for Proximity links but its utilization has been limited to a few initial mission specific experimental examples (e.g. cross support MEX → Phoenix EDL and surface operations, MEX → Spirit/Opportunity) and it still misses an end-to-end approach.

The scenarios depicted in chapter IV call for an incremental approach to the concept of cross support/interoperability which includes the above. A satellite or a fleet of satellites providing data relay services, can be viewed as a remote network of its own, i.e. a remote space network. In the same way a landed element, or a set of landed elements exchanging data between them, can be viewed as a remote planetary network. We will have to integrate such networked islands into an overall network which can interconnect terrestrial, space and planetary networks as to enable end-to-end data transfer in a way that benefits projected and future missions. It is obvious that such infrastructure cannot be set up by a single organization but will require close cooperation and coordination of all parties contributing to this future network. To that end we will have to extend the well proven cross support principles, as applied today to Ground Networks, to such space and planetary network architectures, starting from the definition of cross support access points and developing inter-network communications based on an architecture that can cope with the associated routing requirements as well as with the specifics of space links such as intermittent connectivity, possibly high error rates and long round-trip delays.

Within the ISO OSI standard 7-layer communications model, the routing requirements imposed by future inter-network (Ground/Space/Planetary) connectivity imply that cross support access points can no longer be at link layer as today but have to be at network layer or above. Interoperability in the future therefore requires compatibility at least at the network layer and below between the cross supporting Agencies/Organizations.

Taking into account the above, 3 technologies for data exchange between the different networks have been analyzed by the SISG:

- CCSDS Space Packets
- IP in Space
- DTN

B. CCSDS Space Packets

The usage of CCSDS Space Packets offers the advantage that the supporting backbone ground and space infrastructure is available and operational today. The main limitation of this technology is that CCSDS Space Packets have been conceived for data transfer in point-to-point or low-complexity network topologies. Their routing/addressing capability is therefore quite limited, but sufficient to support upcoming missions such as BepiColombo and ExoMars. Furthermore, if this were really essential, the address space could be extended by e.g. accommodating part of the address in the packet secondary header.

As the missions in flight demonstrate, the CCSDS Space Packet capability is adequate as the underlying data transfer mechanism for applications required both for near Earth and deep space mission operations.

C. IP in Space

IP in Space is conceived as an extension of the available terrestrial IP functionalities to “in space” (up to Lunar distance) or “planetary IP island” networks.

Although the terrestrial IP technology is very mature and widely deployed, IP it is not qualified for space applications and critical issues such as routing table management, accountability, emergency commanding also in case of a routing malfunction, security etc. would need to be solved before ‘IP in Space’ can be adopted for space operations.

Compared to CCSDS Space Packets, IP provides for a much larger address space and IP infrastructure offers dynamic node to node routing.

The essential requirements for IP to work are the availability of "permanent connectivity" and "limited (to few seconds) round-trip delays". IP therefore implies the availability of a rich (in terms of redundancy) infrastructure with permanent connectivity via multiple alternative communication paths and short delays between the communications end nodes.

In view of the NASA plans to adopt IP for the upcoming (in the second half of the next decade) Lunar missions (see chapter IV), the aspects of cross support for IP in space have been analyzed by the SISG. The support of 'native' IP at the cross support points would require major modifications/extensions in the existing CCSDS compatible infrastructure while only missions up to Lunar distance would benefit from it because of the IP constraints stated above. Consequently, Agencies not requiring 'native' IP for the support of their own mission model most likely will not invest in such capability if only needed for the provision of cross support.

The issue has been discussed within the SISG and it has been concluded that IP in space can be cross supported today by CCSDS compliant infrastructure provided that CCSDS encapsulation services are used. This implies that cross support for IP can be provided to a User Agency only as a tunnel between two cross support interface points, as the cross supporting Agency will not unpack the encapsulated IP packets and as a consequence will not perform any routing on the basis of the IP headers.

D. DTN (Disruption/Delay Tolerant Networks)

DTN is an emerging technology based on the Bundle Protocol and "store and forward" transmission with custody transfer. As such DTN has no requirements for permanent connectivity and for short round-trip delays and therefore it would support the full range of missions extending from Near Earth to Deep Space scenarios. Considering also that DTN is expected to provide addressing and routing capabilities equivalent to IP, it is considered more suitable than IP for space applications.

Transmission of DTN bundles is accomplished using services of different underlying protocols. For legs affected by disruptions and/or delays in the end-to-end path of the network (e.g. the interplanetary legs), the DTN Bundles are transferred by means of the Licklider Transmission Protocol (LTP), a reliable retransmission protocol between two adjacent nodes. On other legs TCP/IP may be used.

In the ISO/OSI standard seven layer communications model, the bundle is on top of the transfer layer and can be considered as a 'container' suitable for the transport of any payload data.[xxiii]

The "store and forward" characteristic of DTN implies that information regarding the scheduled connectivity to the adjacent nodes in the candidate transmission paths must be available at each DTN node. To do this, "intelligence" will have to be added to the affected nodes (Ground Stations, Spacecraft, Landed Elements, etc.) and suitable services to distribute the schedule information will need to be available. As said, DTN (and its LTP usage) is an emerging technology and there are still quite some open issues which need to be answered (and tested) as e.g. addressing in the space contexts, routing algorithms, bridging between different lower layers protocols at waypoints, etc.

Many of these problems are being addressed for the usage of DTN for terrestrial applications (military, commercial, etc.). It is important that the in-space development of DTN should comply as much as possible with the internet standards for DTN being developed by the IRTF, to capitalize on the experience, lessons and commercial technology that will support it. If unique adaptations are required for space-based DTN, they should be kept to a minimum, in accordance with the CCSDS philosophy to first adopt or adapt existing technology and to develop unique technology only when necessary.

On top of questions similar to those listed above for ‘IP in Space’ (management of routing tables, security, accountability, emergency commanding etc.) for DTN there are questions on performance which are dependent on size and distribution of storage available along the path, and questions on nodes using several (underlying) protocols with the relevant addressing/conversion issues. The suitability of DTN for different applications (e.g. file transfer, messaging, emergency commanding, time synchronization) in space needs to be verified, starting from a list of the services to be supported.

E. Conclusions on Candidate Technologies

It shall be noted that both novel technologies considered above (i.e. IP and DTN) will require major modifications/extensions in the existing CCSDS compatible infrastructure.

Of the technologies considered above, DTN appears to be the most attractive for future inter-network communications. It is expected that the final DTN specification will allow a single implementation able to cover a wide range of communications scenarios both in terms of round-trip delay and topology complexity and to get dynamic routing tuned to the specific needs of the space environment with strictly scheduled connectivity of individual hops.

Ideally, all cross support interfaces should be such that they provide a native implementation of the novel end-to-end protocol. For instance, each cross-support interface along the end-to-end path should be able to deal with DTN bundles. However, it is unrealistic to assume that all agencies would migrate to this new technology at the same time; actually some agencies in view of their mission models may never adopt such inter-networking architecture. Fortunately, even such agencies can still provide very valuable cross-support by e.g. accepting a stream of CCSDS packets by one of their relay spacecraft and delivering this stream of packets to the supported agency. These packets may encapsulate IP packets or DTN bundles, but that is not of concern to the supporting agency. In space, the Proximity-1 protocol would work and on ground the data exchange could be based on SLE services. It should be noted, however, that the existing SLE services have been conceived to extend the space link at Data Link Layer and therefore the currently supported space link data units are the transfer frames. In order to provide in future a suitable tunnel for encapsulation packets, the SLE services will have to be upgraded to handle packets. In this way the supporting agency can multiplex / demultiplex the internally used packet streams with those establishing the cross support tunnel.[xxiv]

In the following chapters of the report, the communications architectures for the different technologies considered above are reported.

VII. Recommended Change Goals

A. In-Space Cross Support

At the first Interoperability Plenary, held in Paris in 1999, a major commitment was made by the Agencies to embark on the deployment of a "SLE" (Space Link Extension) service infrastructure on an international basis. During the past eight years, remarkable progress has been made in this deployment and the "SLE" concept has been broadened into the generic concept of "Cross Support Transfer Services" (CSTS) and "Cross Support Service Management" (CSSM). The general CSTS/CSSM concept is shown in Figure 35.

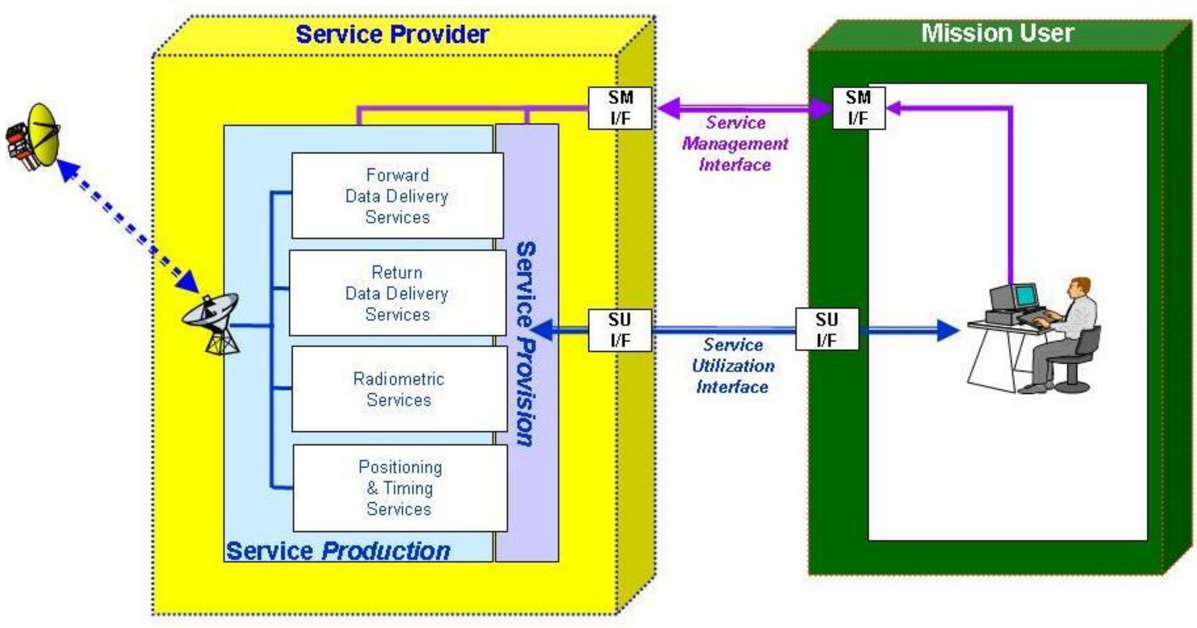


Figure 35: Current Cross Support Services

The success of this standardized deployment of ground-based cross support has been well demonstrated. This is largely because the current space communications and navigation infrastructure is *dedicated infrastructure*, operated as a multi-mission service by network organizations that are independent of the flight projects.

In contrast, in-space cross support – as evidenced by the nascent Mars relay network – currently relies on a close collaboration with the flight project community, since the relay systems are both owned by and tightly coupled with the scientific goals of their parent missions. Lacking a clear architecture for in-space cross support that parallels the CSTS/CSSM guidance that has been provided on Earth, local optimizations tend to be made (by mission personnel) in the various flight communications designs without full consideration of their end-to-end consequences.

The future international migration towards collaborative, internetworked space operations offers two opportunities:

- To begin considering space-based communications assets (such as data relay spacecraft and surface networks) as *dedicated infrastructure* that is simply a remote extension of the current ground networks -- and to manage and confederate them as such, on an international basis.
- To extend the CSTS/CSSM models to define the local data communications and navigation services offered by such *space-based infrastructure* -- and the protocol mechanisms by which users can request and receive them -- in cross support configurations.

The message here is clear: as shown in Figure 36, the success of the CSTS/CSSM model of terrestrial cross support needs to be mirrored in space.

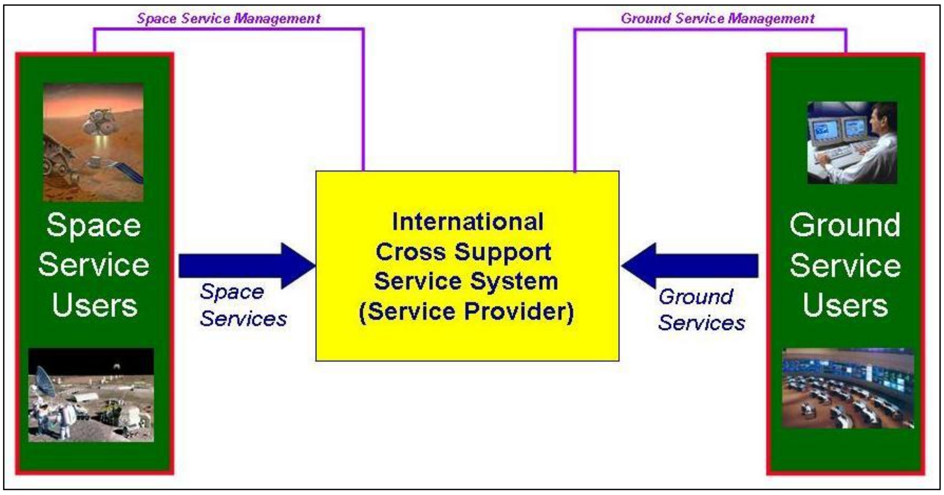


Figure 36: Future Cross Support Services

Finding F-13: *The IOAG agencies have a need to extend their current ground-based cross support services into space via voluntary contributions to re-usable in-space communications and navigation service infrastructure, with a view towards its becoming an enabling capability for new international space mission initiatives. Such infrastructure includes space-based data relays and planetary surface communications facilities that are united via their provision of common, interoperable services using CCSDS standards.*

Recommendation R-13: *The IOAG should ask the CCSDS to accelerate the creation of an overall Cross-Support Service Architecture that extends the current terrestrial* *services by defining the services offered by in-space infrastructure as well as their associated profiles of data communications and service management standards.*

Many of the necessary components of in-space cross-support that are necessary to achieve this future (e.g., CFDP, CCSDS long-haul and Proximity links) already exist. What is needed is a grand unifying vision for how they may be brought together within a consistent architectural framework. That vision is *space internetworking*.

Within the terrestrial Internet, many diverse applications operate across many diverse data links by all flowing through a common "thin waist" – the Internet Protocol (IP). For space operations, the IP suite will certainly work in environments that are close to what it was designed for – richly connected, short-delay, bidirectional, always-on and "chatty" data communications. Unfortunately, many space communications environments display almost the inverse set of characteristics – sparsely connected, medium-to-long-delay, often unidirectional, intermittently available and (as a consequence of physics) unavoidably taciturn.

Consequently, the in-space cross support infrastructure will need to be based on a dual-platform of internetworking technology:

- "Islands" of IP-based communications in places where the IP suite works well. This includes inside spacecraft, close to Earth, within the cislunar system, on and proximate to other Solar System bodies, interconnected by;
- A routed network architecture which can operate effectively where IP cannot.
- A routed network architecture which can transparently bridge IP "islands" across long delay and highly disrupted connections.[xxv]

Finding F-14: *Given that DTN is the only candidate protocol that is approaching the level of maturity required to handle the disconnection and delays inherent in space operations, future in-space cross support should be based on a DTN-routed architecture, interconnecting local "islands" of IP connectivity.*[xxvi]

Recommendation R-14: *The SISG recommends that the IOAG/CCSDS should embark upon a program of DTN technology and standards development.*

B. Transition to DTN

Fortunately, the DTN technology is a direct by-product of the current CCSDS space communications architecture: many of its key concepts (custodial, store-and-forward routing) were transferred directly from CFDP. The basic DTN protocol suite – the Bundle Protocol (BP) running over the Licklider Transmission Protocol (LTP) – has also been designed from the outset to be directly compatible with being carried over all four current CCSDS space link protocols using CCSDS Encapsulation. DTN therefore joins IP and the Space Packet as candidate protocols for use at the Network layer of the CCSDS stack (Figure 37 and Figure 38).

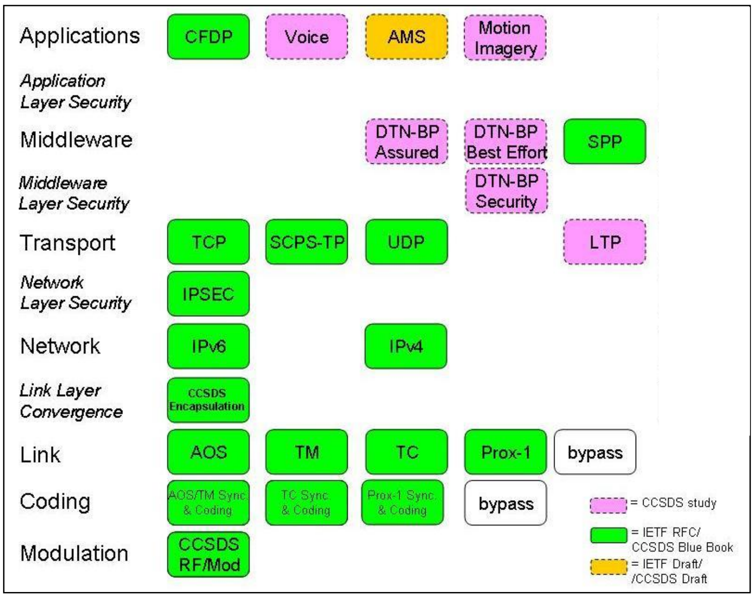


Figure 37: DTN, IP and Space Packet in the CCSDS stack[xxvii]

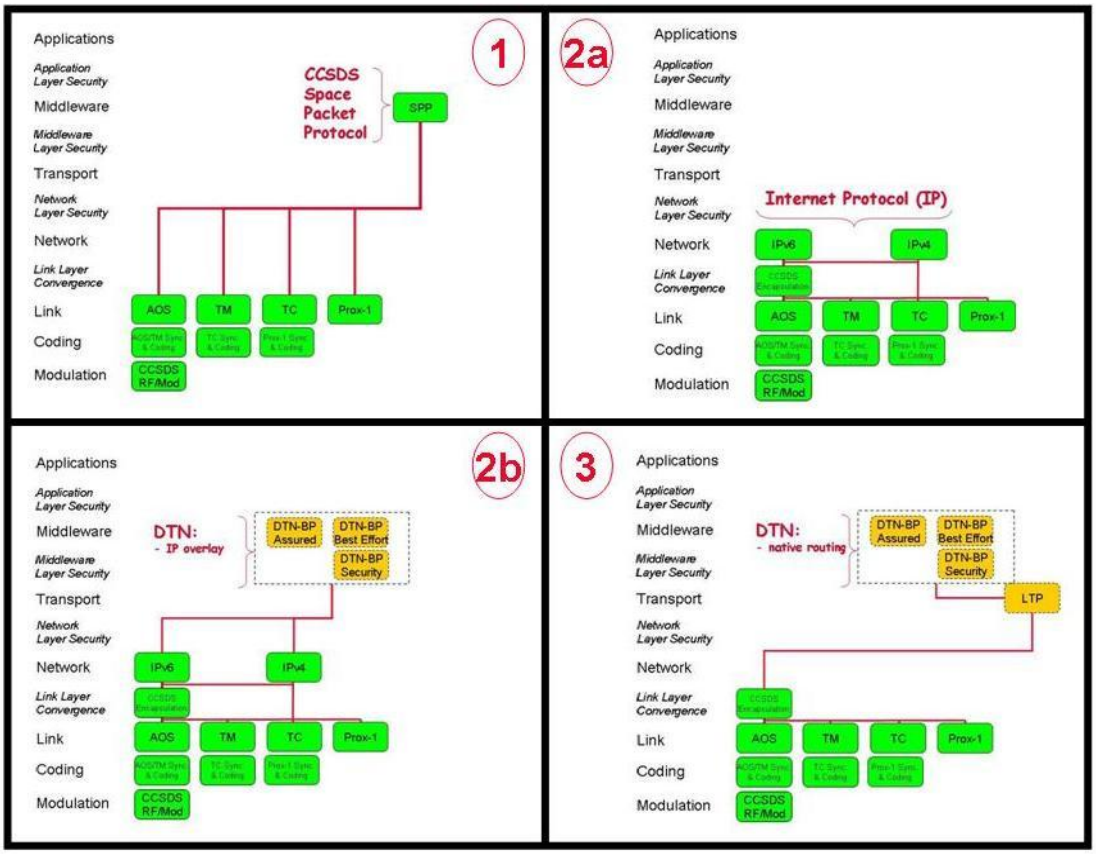


Figure 38: Options for Space Internetworking

The space community is thus ideally positioned to make a smooth and evolutionary transition into the new era of space internetworking:

- We can continue to use the Space Packet where desired.
- We can add the power of an IP-routed architecture where the Internet protocol suite is appropriate for the environment.
- We can add DTN (when the technology is ready) everywhere else.

C. Timescale

The drivers for evolving towards an internetworked space architecture appear at present to be clustered around four phases of activity:

a. The build-up of robotic infrastructure on and around the Moon, beginning in ~2015 and as evidenced by the proposed “International Lunar Network”.

b. The build-up on Earth-observing webs of space and land based sensors, also beginning in ~2015 and as evidenced by proposals such as "Global Monitoring for Environment and Security" (GMES) initiative.

c. The beginning of long duration human presence on the Moon, beginning in the early part of the 2020 decade and as evidenced by NASA's "Exploration" initiative.

d. Expanded international robotic exploration of Mars, beginning in the ~2020-2025 timeframe and as evidenced by the "International Mars Architecture for the Return of Samples (iMARS)" initiative.

Recognizing that the inherent lag between developing the necessary technology and standards and deploying them into space mission infrastructure is somewhere between four and eight years, then a flight-ready DTN capability is needed by the end of CY2011 to support the projected build-up of robotic Lunar missions starting in ~2015 and human missions in ~2018.

A recommended flow of activities and an associated schedule is shown in Figure 39.

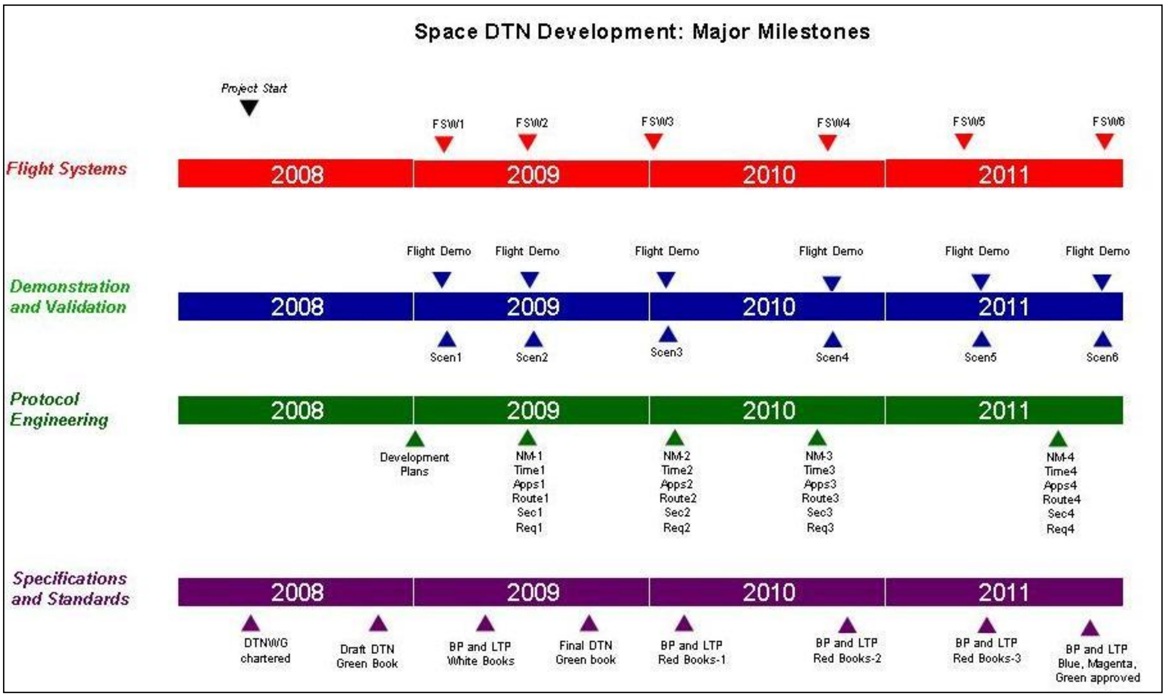


Figure 39: Proposed "Space DTN" Development Program

Such a Space DTN development program should include five main parts:

- CCSDS coordination with and adoption of IRTF efforts to develop and standardize commercial DTN implementations, relying on adaptation and new development only when necessary.

- Specifications and Standards: the international coordination and standardization within CCSDS of the core DTN protocol suite for space applications.
- Protocol Engineering: the adoption, adaptation and if necessary, development of related protocols (network management, time, routing, security, etc.) that will be required to support initial mission deployment.
- Demonstration and Validation: the conduct of flight and ground test activities to exercise the protocols in actual space mission environments (deep space, ISS, etc.) and to demonstrate robust, high-TRL operations to the future mission design community.
- Flight System Engineering: the development of flight software reference implementations and integration tools that assist mission designers in the infusion of the new technology.

The overall goal should be to increase the Technology Readiness Level of "Space DTN" from its current level (~TRL5) to at least TRL8 by the end of 2011. A nominal TRL progression plan is shown in Figure 40.

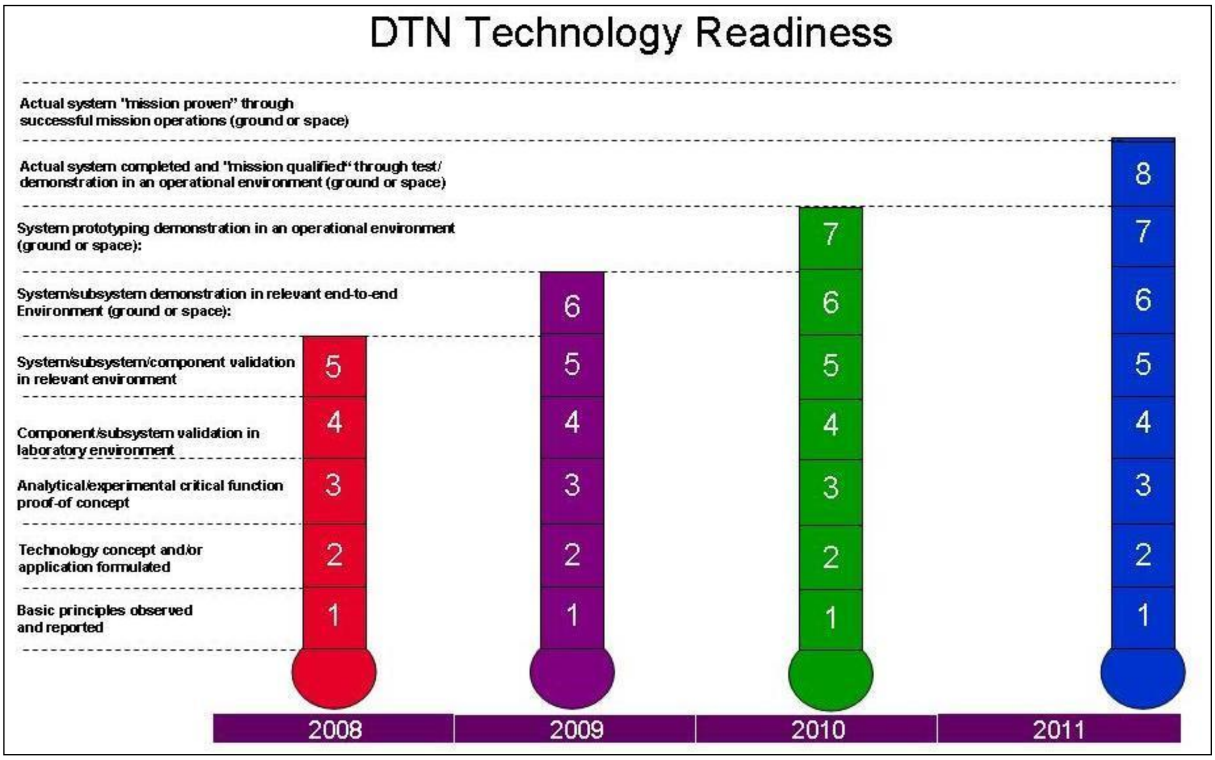


Figure 40: TRL progression of "Space DTN"

D. Deployment Profiles

It is proposed to begin the transition to space internetworking in two phases:

- ***Phase 1*** (2010-2020) will use the ground-based CCSDS Cross Support Transfer Services to tunnel mission user data flow to the ground stations using “SLE”:
  - The current standard CCSDS Space Packet (CSP) service need to be formalized as an end-to-end cross supported CSTS service, both in space and on the ground. However, it is unclear whether any additional international routing infrastructure – beyond the current Agency-specific Space Packet routing and data handling schemes – will be defined around the CSP service.[xxviii]
  - A CCSDS-standard IP-routed service needs to be formalized as an end-to-end cross supported CSTS service, both in space and on the ground, and implemented by those Agencies wishing to provide native IP service to their mission customers.
  - A CCSDS-standard DTN-routed service needs to be formalized as an end-to-end cross supported CSTS service, both in space and on the ground, and implemented by those Agencies wishing to provide native DTN service to their mission customers.
- ***Phase 2*** (2020-2030) will potentially extend the IP and DTN services by placing IP and DTN routers at each participating ground station.

The Phase 1/2 deployment scenarios for IP and DTN are shown in Figure 41 and Figure 42.

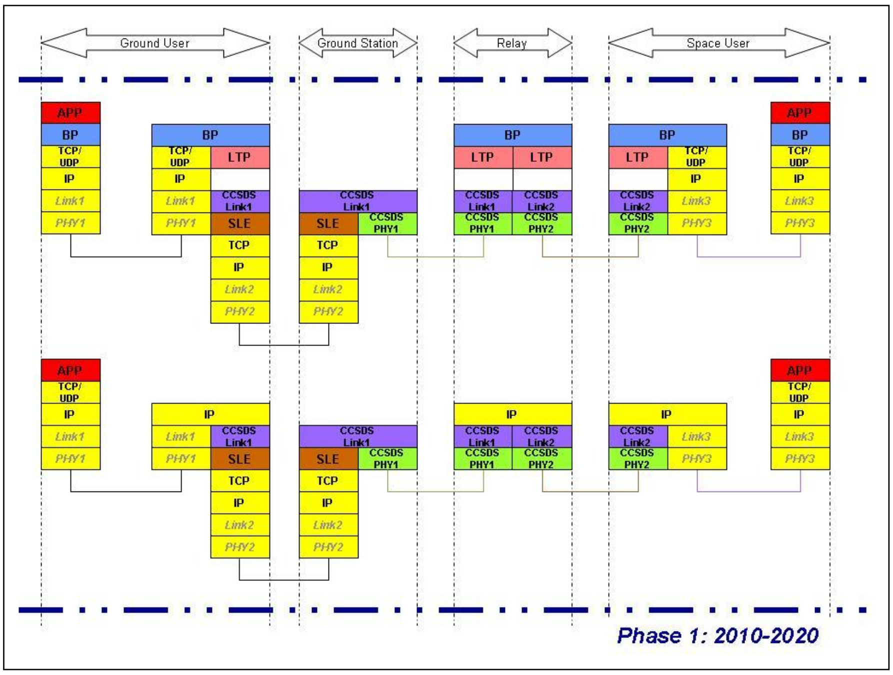


Figure 41: Phase-1 Deployment of IP and DTN[xxix]

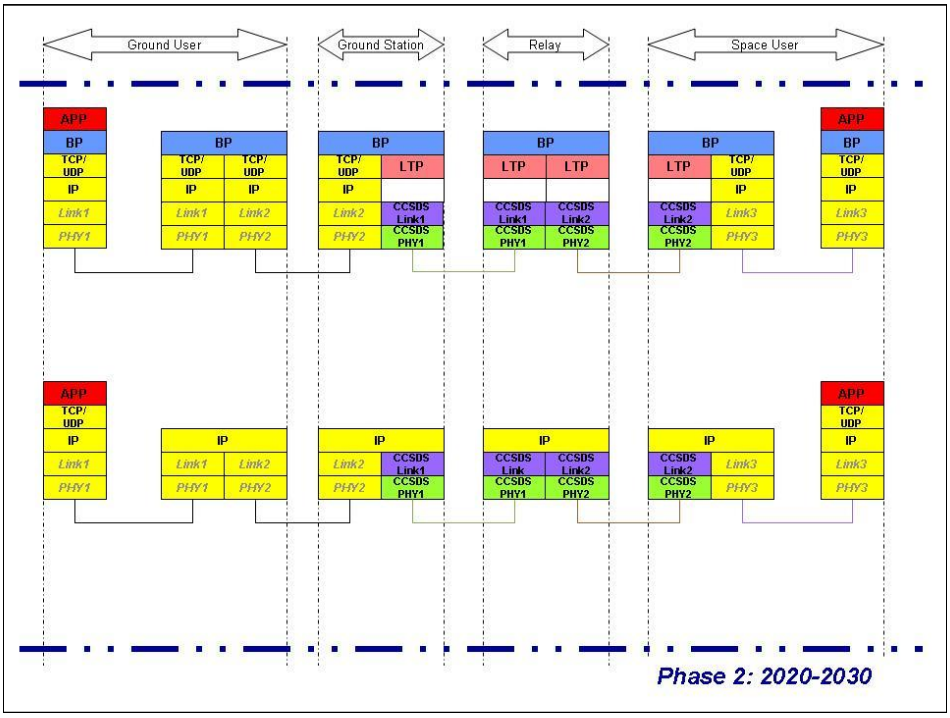


Figure 42: Potential Phase-2 Deployment of IP and DTN[xxx]

E. Specifications

The “known-knowns” of the technical specifications within the deployment profiles are as follows:

- “CCSDS PHY1” consists of the evolving family of CCSDS Radio Frequency and Modulation standards for long-haul RF channels.
- “CCSDS Link1” consists of three parts:
  - The current set of CCSDS channel coding standards: Convolutional, Turbo, Reed-Solomon and the (emerging) LDPC.
  - The three current CCSDS long-haul link protocol standards: TM, TC and AOS
  - The CCSDS Encapsulation standard.
- “CCSDS PHY2” and “CCSDS Link2” are defined by the Proximity-1 standard.
- “CCSDS PHY3” and “CCSDS Link3” for onboard use will be defined by the CCSDS-SOIS activity.
- BP and LTP (and the associated DTN routing and management protocols) will be standardized by CCSDS.
- The Applications will include CFDP, AMS, Voice and Motion Imagery.

The “known-unknowns” of the deployment profiles are as follows:

- The path for CCSDS “PHY2” to evolve if new multiple access schemes are required for planetary relays is not yet defined.
- The consequent path for ‘Link2” to evolve beyond Proximity-1 if new multiple access schemes are required is unclear.
- The standards that will be selected for “PHY3” and “Link3” for planetary surface communications are not yet defined.
- The impact of optical communications on “PHY1”, “Link1”, “PHY2” and “Link2” are currently unknown.
- The precise profile of the Internet Protocol Suite (IPS) that will be deployed internationally to support IP service, including the associated network management, has not been defined.
- The evolution of the Applications is currently unclear.

F. Gap Analysis

1. Gap Analysis Introduction

In order to establish the interoperability necessary for cross-support of space missions, standards must be developed to which space systems, space communication systems, and ground systems (including control centers and network operations centers) can be built. For many years, industry, academic and government-sponsored standards organizations, including the CCSDS, IEEE, ISO and IETF have worked to develop the necessary standards to provide interoperable telecommunications and data between users, systems and organizations.

Interoperability, and in particular internetworked interoperability, requires agreements between users and networks as to the standards employed in the design and operation of missions. Interoperability is necessary at the physical, link, network, transport, and in some cases the application layers. Each layer of interoperability provides greater coordination and ability to leverage shared assets to achieve common goals. However, as each layer of interoperability is achieved, the flexibility of design space available to users and network operators is reduced. If interoperability standards and cross-support agreements are architected and chosen in a thoughtful manner, the total advantage can be great. If, however, the agreements or set of standards is overly restrictive, missions and end-users can be limited in terms of the operations concepts they employ or the class of mission that is designed. Care must be taken to balance the restriction of available choices to a manageable set while ensuring enough design and operational flexibility that missions are not artificially constrained. Achieving an interoperable space internetworked architecture requires this careful balance.

Traditional mission communications architectures could generally be mutually exclusive in their selection of standards and operations concepts as the particular physical and link layer standards were of prime importance to cross-support agreements. Mission content above the link layer was generally hidden from the space communications infrastructure, and the links are treated as virtual point-to-point connections, regardless of the true underlying networks used to pass traffic from control center to spacecraft. The CCSDS Space Link Extension (SLE) and the SLE cross-support agreements follow this model.

In contrast, an internetworked environment such as that envisioned for the Solar System Internetwork (SSI) concept employs network layer datagrams as the fundamental cross support element rather than point-to-point space links. Accompanying the network layer datagrams is the necessary information to address and route datagrams - be they IP packets, DTN bundles or some other agreed quanta of information – from its source to its destination. In an internetworked environment the source may be a control center or spacecraft, which is similar to the traditional point-to-point architecture of today. In contrast, however, is the concept that destinations can be another control center, a space vehicle, or a set of flight vehicles and ground based systems. Such scenarios arise when the “network” includes vehicles and control centers from several countries or collaborative missions where information from one mission is used to directly inform another. Destination of datagrams is determined within an internetwork by addressing of the datagram rather than by managing the “end point” of pre-planned link. The need for collaborative space communications networks to understand the addressing, naming, and delivery methods (routing) of datagrams across the internetwork drives the need for understanding of the network layer of the protocol stack, and in some cases, higher layers as well.

2. State of Internetwork Interoperability

A rich history of standards and cross-support agreements exists for provisioning, managing and operating interoperable space links and providing cross-supported space communication services. A rich history of standards and concepts also exists for networking and internetworking in the terrestrial environment. What is lacking at present is the set of common standards and agreed to methods by which cross-support for internetworking will be provided in the space communications environment.

3. Physical Layer

The physical layer has been largely defined in sufficient detail to support basic cross-supported internetworking. CCSDS provides the necessary standards for RF modulation and channel coding for single user, point-to-point RF links. Modulations and coding have been identified for single user point-to-point long-distance communication, as well as single user point-to-point proximity (orbit-to-surface) communication. The SFCG has established recommendations and agreements on the use of spectrum, including the function of various bands and the recommended channelization necessary to provide both compatibility (non-interference) and interoperability (communication between two or more flight/ground systems).

The scenarios discussed in this recommendation, however, identify several additional physical channels that need to be clarified. In particular, these are long-distance multiple access schemes to enable multiple user connectivity within an orbital region (similar to the TDRSS Multiple Access / Demand Access Service) and short-range multiple access schemes for use in establishing communications between several elements in close proximity on destination surfaces and in collaborative formation flying missions.

Recommendation R-15: *Multiple access single-point to single-point modulation and coding techniques should be identified and codified as CCSDS standards for use in the near-Earth, Moon-to-Earth and Mars-to-Earth environments.*

Recommendation R-16: *Multiple access multiple-point to multiple-point modulation and coding techniques should be identified, adopted and codified as CCSDS standards for use between closely spaced in-space elements and for local planetary surface mesh communications.*

4. Data Link Layer

As is the case with the physical layer, the data link layer has largely been established in sufficient detail to provide for a collaborative Solar System Internetwork (SSI) architecture. The CCSDS TC/TM formats as well as the CCSDS AOS data link protocol provide the necessary basic framing technique to organize information and allow for link synchronization and support of error correction coding techniques. Additionally, the CCSDS Encapsulation Packet (ENCAP) protocol provides the necessary “shim” between the space link layer and a variety of network datagrams, including the Internet Packet and the DTN Bundle.

Some work is required to standardize the behavior of the ENCAP packet to enable end-to-end network connectivity beyond simple datagram delivery, and this effort is currently underway. Additionally, as the DTN standard matures, adaptation and incorporation of DTN bundles into the CCSDS link layer

Recommendation R-17: *The CCSDS Encapsulation Packet should be adapted to provide a standard convergence layer to support end-to-end network connectivity required by the Internet Packet and DTN Bundle.*

Recommendation R-18: *Standards for multiple access data link establishment and management should be developed, adopted and codified within the CCSDS family of data link protocols.*

5. Network Layer

The network layer has the lowest maturity in terms of codified standards accepted for use with interoperable space communications systems. Standards are in place that support the CCSDS Space Packet and Internet Packet today, with extensions planned to support the DTN bundle. However, the higher layer functionality in terms of addressing, routing path and routing behavior, store and forward, data accountability and security remain to be addressed. Many of these areas have been addressed for the traditional “single control center, single user mission” case, but an internetworked environment moves the architecture from single-source, single destination connected via a primary communications provider to multiple-source, multiple-destination traffic connected by a potentially rich set of concurrent and dynamic links provided by a variety of international partners. Additionally, operating on individual datagrams as the basic quanta of information is a significant technical and operational change for agencies and organizations that have thus far been familiar with handling “links” as the lowest common denominator for cross-support.

A notable exception is the Mars Network. At Mars, mission elements of several agencies cooperate to provide cross-support through the exchange of “files” as the basic unit of information. Agencies providing network cross-support for missions accept streams of packets or bitstreams as files transferred from ground stations or user spacecraft. Once the destination is in view, the carried files are transferred inline with mission data (in the case of Mars-to-Earth relay) or as direct forward transfers to the user spacecraft (Earth-to-Mars relay). While these cross-supported behaviors begin to test the concepts of internetworking and network cross-support, they are highly managed and are not operating at a datagram level. Some missions use bitstreams, some use delivery of packets. The concept of CFDP as a true cross-support enabler has not been realized.

The architecture proposed by this report identifies a “triumvirate” of network datagrams consisting of the Space Packet, the Internet Packet and the DTN Bundle. Space Packet provides legacy support and is available to missions with extremely limited networking requirements. It must, however, be delivered across the cross-supported Solar System Internetwork (SSI). The true network architecture consists of DTN and IP co-existent within the end-to-end internetwork. Essentially DTN provides either end-to-end information transfer (where appropriate) or provides the bridging function between “islands” of IP connectivity. In the Earth-Moon system, IP exists end-to-end and is co-existent with DTN. In the deep space model (such as Earth-Mars links), DTN is the primary backbone datagram which carries either native DTN bundles or provides a transport service to bridge IP networks at Earth and in deep space.

To realize SSI-based cross support, it is necessary to go beyond agreement on standards and move to agreement on operations concepts and inter-mission and inter-agency behaviors. While a relay spacecraft may be able to receive uplinked packets destined for another mission, unless it can interpret the addressing, delivery criteria and quality of service properties, it is unable to truly behave as an element of an internetwork. Instead it is acting as a highly advanced file transfer point that bridges two point-to-point links. To enable internetworked cross-support, the following must be investigated, developed and standardized between agencies and organizations wishing to cooperate:

Recommendation R-19: *The CCSDS should identify, adopt and codify standards for structuring space communications infrastructure relay nodes to support native IP and native DTN services as well as providing bridging between DTN, IP and Space Packet at the network end-points.*

6. Addressing

Datagrams, whether Internet Packet or DTN Bundle, must contain within them the information necessary to determine the “next hop” in the end-to-end network path. The Internet Packet and the DTN Bundle natively contain the addressing information necessary to travel across a network. What is necessary is to inform the relay element - be it an in space orbiter, ground station, or planetary/destination surface system – of the relationship between the addressing schemes of the datagram and the physical links available to the relay node. The relay must also be aware of the address space that is reachable through each of its available (or upcoming scheduled) communications links.

The Space Packet can make use of application layer routing in some very specific instances, but for the most part, it is not capable of true network behavior and so must depend on other mechanisms such as CFDP cross-support services.

Recommendation R-20: *A common method for assigning and managing IP and DTN address spaces should be established for the Solar System Internetwork.*

Recommendation R-21: *A method for addressing and delivering CCSDS Space Packets should be established to ensure reverse support of Space Packet in the Solar System Internetwork.*

7. Routing Behavior

Terrestrial networks make use of routing protocols that perform detection of route paths and maintain tables containing the relationships between physical links (router ports) and address spaces. Through these protocols, routers are able to exchange information about the address spaces to which they can pass data, resulting in a network that is aware of the end-to-end communication pathways that allow packets to travel from source to destination. These protocols are not just standards defining the bit structure of router messages. They also contain implicit agreements on the behavior of the various routers to exchange information about state and available routing pathways.

Unlike terrestrial networks where the “best” route can be determined by sensing the flow of packets through the network, choosing the best route through the partially and periodically connected space network will require knowledge of not only the capacity of each of the nodes, but also an understanding of when communications between two nodes will be available and under what circumstances they can be used. For example, communication through a network relay node in space requires knowledge of the relay’s orbital motion relative to the user, as well as antenna pointing and communication system configuration knowledge. Robust multiple access techniques such as that employed by the NASA Tracking and Data Relay Satellite System (TDRSS) Multiple Access service provide some flexibility, but knowledge of the user’s orbital motion is still required to establish communication with the relay. Similarly, a user may have line of sight to two or more relay nodes, but those nodes may in turn not have line of sight with the next destination. In this case selection of the appropriate “next hop” route depends on knowledge of when relay nodes will have the ability to pass information to the destination. Although the routing behaviors are different, understanding of the routing path relationships through the network applies whether an IP based or DTN based technique is used.

The current CCSDS standards have focused on the mechanics of transferring information between systems, but not the agreements of what the information means, how to interpret it, and how to coordinate the states and configurations of network nodes to provide end-to-end routing behavior across federated networks. While methods are in place within the CCSDS standards to permit the exchange of routing information between nodes in the network, the operational agreements have not been developed or established to clearly define how two federated organizations will exchange and act on this data. What is required is a definition of the minimum set of state, configuration and function that must be agreed to between two agencies in order to provide network cross-support, or even between multiple agencies or commercial network service providers. In addition, organizational agreements on configuring and managing routing nodes must be established to ensure that behaviors are predictable and consistent as a packet or bundle traverses the various network nodes.

Recommendation R-22: *The CCSDS should identify and adopt a set of well defined router configuration and status parameters that must be exchanged between networks of space agencies providing cross-support as a node of the SSI.*

Recommendation R-23: *The IOAG should identify and adopt a set of well defined network routing behaviors that will be cross-supported in order to provide necessary end-to-end route management and execution between the nodes comprising the Solar System Internetwork (SSI).*

Recommendation R-24: *The IOAG should establish and coordinate a body responsible for management and administration of the cross-supported SSI name and address spaces.*

Recommendation R-25: *The CCSDS should identify and adopt a set of well defined approaches for defining, determining and exchanging communications capability and current/future availability information needed to build a distributed understanding of the "next best hop" component of the network route.*

8. Quality of Service

In a sense the mechanisms for quality of service are present in current CCSDS standards, but they do not meet the needs of a networked environment. The concept of "virtual channels" provides the means to segregate traffic of varying priority and to isolate low criticality information from high priority information. This structure is, however, built upon the point-to-point link model and does not lend itself well to an end-to-end networked architecture in which packets and bundles are the native routed quanta.

Both terrestrial IP and proposed DTN architectures provide the concept of quality of service, traffic prioritization and traffic segregation mechanisms. It is necessary however to do two things to provide cross-support. First, a standard means of defining network layer (packet or bundle) quality of service must be defined in terms of priorities of information, lifetime or "staleness" of data; and delivery methods (guaranteed, best effort, etc.) must be established and agreed upon. Second, operating agreements must be established between space agencies and other organizations participating in the SSI such that these quality of service properties are understood and respected between the participating organizations.

Recommendation R-26: *The CCSDS should identify and adopt a set of well defined quality of service attributes and identifying parameters that must be exchanged and respected between networks of space agencies providing cross-support as a node of the SSI.*

Recommendation R-27: *The IOAG should identify and adopt a set of internetworking quality-of-service cross-support agreements to ensure that functional elements of various agencies acting as nodes of the SSI respect QoS attributes and provide QoS behaviors in a consistent manner.*

9. Command and Control

In general our current interoperability standards focus on providing mechanisms that allow one mission-center/spacecraft pair to use the communications resources of another (for example, the routing of NASA MER data through the ESA MEX).

As we move forward into a more sustained human/robotic presence on other bodies we will increasingly have instances where assets from multiple nations will need to not only communicate, but coordinate their activities in near real-time – potentially without support from their Earth-based control centers. This could be as simple as being able to understand the health of another's assets, or as complex as being able to share joint command/control.

In order to meet these needs, a new series of standards and interoperability agreements will be needed which allow us to: 1) transparently and unambiguously exchange the definitions of commands, state, and status in a manner that could be used to assess the health and potentially control the asset; 2) exchange commands, data, voice and video between systems regardless of the communications mechanisms they are using (e.g., cross-support/mediation between systems using an IP service with those using DTN packets), 3) define and enforce the rights/privileges allowed by the asset to other assets or command centers (including delegation of authority, joint commanding, etc.)

Recommendation R-28: *The IOAG should identify the appropriate level of command and control interoperability needed to support multinational joint operations of human and robotic assets.*

10. Exchange of command/control definitions

Current standards, such as XTCE, provide a common mechanism that can be used to define command and telemetry definitions and packing maps. However, in order for one asset to be able to use these definitions to assess the health of another asset or even command it, it must have access to a much richer set of meta-data and models. These would include: 1) common and unambiguous naming (we must clearly know what a parameter means and ideally all assets would use the same name when referring to the same capability); 2) association of the command/state/status definitions to physical aspects of the asset (sensors, subsystems, etc.), calibration data, alarm values, etc; and 3) protocol needed to appropriately version and exchange this information between assets.

Recommendation R-29: *The CCSDS should identify and adopt a set of well-defined mechanisms for exchanging the definitions of command/control data sufficient to allow joint/collaborative command/control of a heterogeneous set of multinational assets*[xxxi]

11. Interoperable exchange of command, data, voice and video

Current CCSDS standards provide a menu of solutions that can be adopted by individual missions to meet their specific needs (for example, a command could be packaged in TCM, AOS, as a file in CFDP, or as a DTN bundle.)

As we move towards joint/collaborative operations, it will be essential that assets/missions making different selections are still able to interoperate (e.g., a robotic vehicle using the telecommand standard and a manned vehicle using commands wrapped in IP packets can successfully command each other if necessary). As communications delays back to Earth increase, the capability to interoperate will increasingly need to be supported in-situ.

Recommendation R-30: *The CCSDS should identify and adopt a set of well-defined mechanisms (e.g., mediators/adaptors) to enable in-situ and remote interoperability between multinational human and robotic missions choosing to implement different, but approved, CCSDS standards. At a minimum, should include voice, video, data (health & safety, caution/warning, state and status), commands, and files).*

12. Define/Enforce Rights and Privileges

Currently, the rights and privileges for an asset are implicitly defined by the command/control relationship with its command center. As we move forward into multinational joint operations, there will be instances where command authority may need to be delegated to another. For example, in some instances, an agency may want to allow another asset to view the status and telemetry of its assets (but in other cases it may specifically prohibit this). Additionally, an agency may want to delegate the ability to issue a “halt” command to a robotic asset to astronauts when they are working in close proximity) or completely transfer control from Earth to in-situ in the case of a communications outage.

In order to enable this type of operations, it will be necessary to be able to define and enforce the rights and privileges that one asset has on another and a potential set of specific conditions they apply.

Recommendation R-31: *The CCSDS should identify and adopt a set of well-defined, interoperable mechanisms and standards which will allow systems to define and enforce the rights and privileges between assets.*[xxxii]

13. Gaps Identified for Interoperability

The scenarios presented in the prior sections of this report provide insight into where gaps exist and where new standards and agreements must be developed in order to accomplish the mission set. The following table maps the identified gaps to the desired mission scenarios.

Table 1: Mapping of Capability Gaps to Mission Scenarios

	Near Earth	Lunar	Mars
Physical	• Multiple Access modulation/coding standards for long-distance links • Multiple Access modulation/coding standards for multi-user proximity operations	• Multiple Access modulation/coding standards for Earth-to-Moon links. • High rate forward/return modulations for infrastructure network "trunk" links. • Multiple Access modulation/coding standards for Lunar Orbit-to-Surface and Surface-to-Surface mesh communications.	• Multiple Access modulation/coding standards for surface-to-surface mesh communications • High Rate forward/return modulations for infrastructure "trunk" links.
Data Link	• Multiple access link establishment / negotiation protocol to support mesh networking.[xxxiii] • Extension of CCSDS ENCAP packet to provide end-to-end network support of Internet Packet and DTN Bundle.[xxxiv]		
Network	• Standards for router configuration and status. • Standards for network quality of service attributes. • Cross-supported method for delivery of Space Packets with additional address information across the Solar System Internetwork. • Cross-supported infrastructure gateway function between Space Packet, Internet Protocol and DTN bundle based network segments.[xxxv]		
Cross-Support Agreement	• Support of multiple-access modulations/coding • Support of multiple access link establishment protocols • Support for native IP and DTN as cross-supported datagrams within the Solar System Internetwork • Support for CFDP as a cross-support agreement to enable deliver of files and Space Packets. • Establishment of an address/naming coordination function within the IOAG • Support of standard router behaviors between cross-supporting network segments.		
Command and Control	• Definition of various levels of appropriate command/control interoperability between multinational human/robotic assets. • Support for the unambiguous definition and exchange of command/control.		

G. Governance

To ensure the compliance to the Space Internetworking Architecture by each participating agency, a robust governance process will have to be defined by the IOAG and executed by the designated governance body and all participating organizations. Such a governance process is especially crucial during the space internetworking era since the network environment will involve a variety of service nodes as well as client nodes owned and operated by multiple agencies.

It is expected that this process will evolve, in terms of formality and sophistication, as the component systems of the space internet backbone are gradually deployed. We may start with some minimal governance during the nascent stage and ramp up to more governance when the internetworking matures.

At the core of the governance approach is the IOAG Space Internetworking Architecture document. Developed as a CCSDS recommendation, it defines the standard services, protocols, and interfaces concerning internetworking. Such an architecture standard will serve as a guiding document for the agencies to plan, design, and implement their network assets to be deployed as individual nodes on the space internetworking environment. This Space Internetworking Architecture document should also be the basis of any bilateral Service Agreements between a service providing agency and a user agency for addressing the interfaces concerning a service node and a client node in the space internetworking environment. These Service Agreements will be the documents which have binding authority and their compliance to the internetworking architecture must be ensured by the participating agencies.

There will also be a need for a multi-agency governance body to centrally coordinate the resolution of any issues concerning the architecture compliance and coherence end-to-end. This may include unique assignments of network-layer addresses, unique assignments of DTN identifiers, operational management and documentation of the standards, etc. Any potential non-compliance will be brought to this central coordination group for resolution or waiver approval. The modus operandi of this “governance” body will be more coordination than control, since the components of the internetworking system will be "owned" by many parties. Nevertheless, in order to function as an effective group, it may have to be delegated with pertinent authority by the Inter-agency Operations Plenary (IOP).

The Space Internetworking Architecture document, although developed by the CCSDS, will be endorsed by the IOAG member agencies through the Interoperability Plenary (IOP). It will be updated on a periodic or as-need basis to include changes in internetworking services, protocols, and interfaces. Proposed changes to the architecture shall be initiated from the IOAG as resolutions directed to the CCSDS.

Finding F-15: *A specification for the Space Internetworking Architecture must be developed as the basis for future bilateral agreements between cooperating space agencies.*

Recommendation R-32: *The IOAG should direct the CCSDS to develop the Space Internetworking Architecture document as a Recommended Practice or Recommended Standard, and the IOAG strike an agreement among the IOAG agencies that the specification will be the basis for bilateral agreements between cooperating agencies.*

Recommendation R-33: *The IOAG or a designated sub-team should study the potential need for additional governance mechanisms which should be agreed to between the IOAG agencies for cases where operational concepts for internetworking drive common operational needs (allocation of common addresses, routing operations, etc.) and for situations where multilateral agreements (versus bilateral agreements) may be most effective.*

VIII. Proposed Space Internetworking Architecture

A. Background

This section does not attempt to justify the transition to a networked architecture for space communications. Rather it describes how such an architecture could be realized using Delay / Disruption Tolerant Networking (DTN) as the primary data structure for routing and interoperability. DTN was chosen because it is the most mature technology for providing end-to-end, routed communications in environments that might contain intermittent disruptions and network partitions.

1. Delay / Disruption Tolerant Networking (DTN)

Delay / Disruption Tolerant Networking was originally conceived as the “Interplanetary Internet” and was funded by DARPA and NASA to devise a method of providing end-to-end communications in environments with long and possibly variable delays, and where contemporaneous end-to-end connectivity does not always exist. The original use case was to enable communication between a user connected to the Internet on Earth and a rover on the surface of Mars using a Mars relay orbiter that could not simultaneously communicate with both the rover and the Earth.

When considering the long propagation delays and scarcity of communication resources between Mars and Earth, it quickly became obvious that mechanisms that serve the terrestrial Internet well such as ‘chatty’ protocols, access to distant / synchronized resources such as DNS and certificate authorities, and end-to-end retransmission didn’t fit well in the interplanetary communications environment. The DTN architecture eventually evolved to embrace the following principles:

- Don’t engage in unnecessary chit-chat – build complete transactions and make network accesses count
- Don’t plow the same ground twice – hold the gains you’ve achieved
- Don’t depend on information from inaccessible/remote places if you can avoid it – build a sequence of local control operations and use late binding
- Don’t force homogeneity – allow different network components to use environmentally-relevant optimizations

Figure 43 illustrates how the DTN architecture addresses some of these principles.

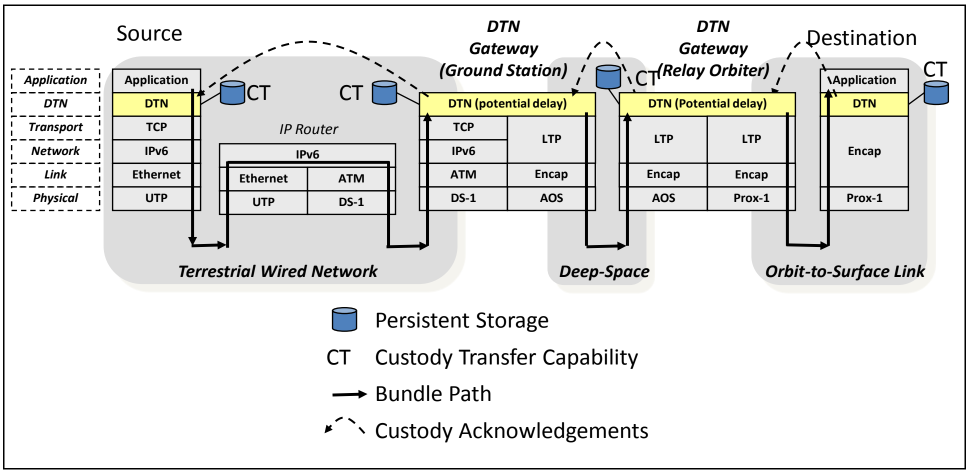


Figure 43: DTN Network

With an influx of interest from academic and commercial communities, the Interplanetary Internet was expanded to include terrestrial applications such as sensor networks. In the process, the name changed to 'Delay Tolerant Networking.' Other funding wanted to emphasize the ability of the protocols to combat disruptions and partitions in the network, prompting the term 'Disruption Tolerant Networking.'

DTN provides the services of an OSI layer-3 (network) protocol, though it may provide those services by using link, network, and/or transport protocols of the various parts of the end-to-end data path. As a layer-3 protocol, DTN contains its own naming semantics for endpoints and requires its own layer-3 routing protocol(s). While one can certainly run IP on both 'ends' of a path, where DTN was used in the middle, there is no implicit relationship between the two IP enclaves. That is, DTN is not intended to 'tunnel' IP packets across areas where IP would otherwise not function. While this is technically possible either via direct tunneling or via application layer gateways, it is generally a bad idea for a number of reasons. Thus we envision applications as choosing whether they will use end-to-end IP or end-to-end DTN at the time a data transfer is initiated. As mentioned above, DTN may make use of IP as an UNDERLYING layer on those parts of the end-to-end path supported by an IP infrastructure.

2. Bundling

In the terrestrial Internet, round trip times are relatively short and protocols can afford to engage in multiple exchanges to accomplish a particular task. An example of this is the File Transfer Protocol, where multiple round trips are required to open a TCP connection and obtain user and authentication information before data can be transferred. DTN encourages applications to engage in larger, more atomic operations in order to minimize end-to-end data exchanges. Thus a DTN file transfer application might obtain a user's identification and authentication information, information about files to be transferred, and error handling conditions, and package all of this information into a single data item to be transferred. To connote this process, the protocol data units exchanged by DTN are called *bundles* and the application process of forming the PDUs is termed *bundling*. The protocol specification for DTN is provided in RFC5050[4].

3. Custody Transfer

In the terrestrial Internet, data reliability is provided by the end systems, primarily using the TCP protocol. If data is lost or corrupted in the network, TCP will detect this and retransmit the data. To 'hold the gains that have been achieved', DTN supports a *custody transfer* mechanism for data reliability and retransmission. If a source marks data as requesting 'custodial delivery', DTN nodes along the path may (but are not required to) *take custody of* bundle. Taking custody of a bundle amounts to 'checkpointing' the bundle's progress. The node taking custody (the new custodian) becomes responsible for getting the bundle to its destination, retransmitting it if necessary. When a new custodian notifies the previous custodian that custody has been transferred, the old custodian is free to release the resources associated with ensuring delivery of the bundle.

Even if a bundle requests custodial delivery, all DTN nodes in the path are not required to take custody of it. This may be necessary for instance if a particular node does not have the resources to commit to ensuring the bundle will reach the destination. In these cases, nodes may accept bundles and attempt to forward them on in a 'best-effort' manner. If a downstream DTN node can take custody of the bundle, it notifies the bundle's current custodian, allowing the current custodian to release the bundle resources.

4. DTN as an Overlay Network

The DTN functionality does not have to be implemented at every node in the network. In these cases, DTN forms an *overlay network* on top of an existing network as is shown on the left of Figure 43. There DTN sits atop an IP network and uses the underlying IP routing and delivery mechanisms to transfer bundles between the Source and the Ground Station. To the IP network infrastructure (TCP/IP in the figure), DTN behaves like an application, opening connections between IP network nodes to transfer data. To applications, DTN appears like a network layer, where applications present DTN with data and metadata about the data's destination(s) and desired handling, and DTN delivers the data to the destination(s).

On the right side of Figure 43 DTN sits directly above the data link layer encapsulation. In this case DTN can more efficiently use the available resources and can take advantage of data-link-specific features.

B. Proposed Architecture for Space Internetworking

We propose that the Solar System Internetwork (SSI) will internetwork space communications in much the same way that terrestrial communications were internetworked using the TCP/IP suiteprotocols. Here ‘internetwork’ has a very specific meaning – to join together two or more subnetwork technologies and to provide a means of transferring data seamlessly end-to-end across the different subnetworks. Within a subnetwork, internetworked packets may be forwarded across multiple physical hops (the analogy would be between switched Ethernet and SLE).

The primary difference between the terrestrial Internet and the space internetwork proposed here is that the terrestrial Internet protocols have come to assume continuous, error-free, low-latency, end-to-end connectivity. In the space environment these assumptions do not necessarily hold due to scheduling and light-time delays and the difficulties of interplanetary communication.

Figure 44 shows the long-term “OV-1”-style vision for the architecture. In the figure, communications are possible (in principle) between any pair of devices that contain compatible communications hardware, are proximate enough to close the link between them, and are configured to communicate.

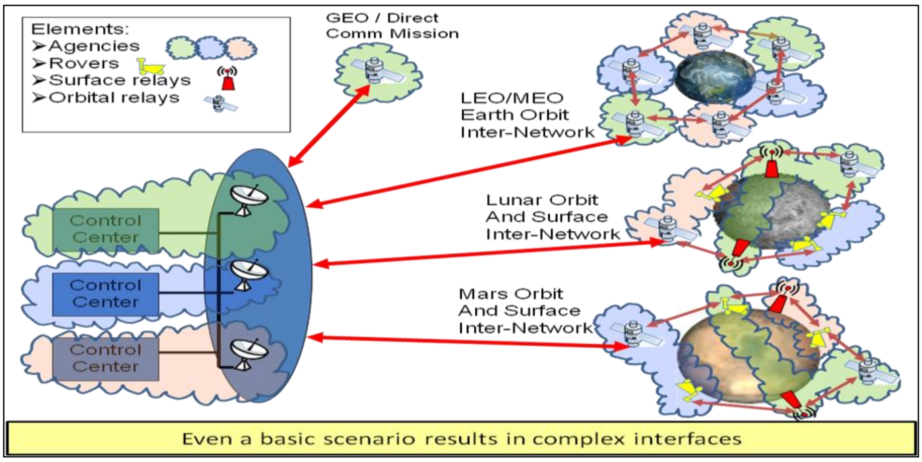


Figure 44: An interoperable interagency networked architecture for space communications

C. Overview of the Proposed Architecture

The proposed Space Internetworking Architecture for the SSI is:

- The internationally cross-supported set of physical layers (spectrum, modulation, coding) as described in the applicable CCSDS documents.
- The internationally cross-supported set of data links is: CCSDS TC[8], CCSDS TM[7], CCSDS AOS[1], and CCSDS Prox-1[3]. Profiles need to be developed to nail down enough parameters to achieve at least ‘least common denominator’ (LCD) interoperability on these link types. Standard

methods for negotiating higher levels of performance above that provided by the LCD standard are desired.

- Space packets are a supported data structure on the approved set of links, but are NOT routed. For each of the ‘standard’ data links, all nodes *must* be able to extract space packets from those links. A relay never has to examine the space packet header when deciding how to forward data to other spacecraft or the ground. Relays may examine the space packet header when deciding how to route data on board (traffic destined for the relay itself).
- Encapsulation packets are a supported data structure on links, but are NOT routed. For each of the ‘standard’ data links, all nodes *must* be able to extract encapsulation packets from those links.
- IP packets are a routable, supported data structure on links. To support the notion of ‘IP where it makes sense’ internationally standardized routing of IP packets SHOULD be a service that is offered in ‘connected’ environments and between connected environments where the environments are separated by reasonable delays from the perspective of the IP suite. IP packets are encapsulated according to the IP-over-CCSDS book for carriage on space data links. A profile may need to be developed to limit the set of options for such encapsulation.
- DTN bundles carried in one or more of (TBD) the approved encapsulation methods are an internationally cross-supported, routed data structure for all environments (regardless of connectivity / latency). Everybody supports bundles, and anybody who provides any relay services will relay bundles.
- Mechanisms must be developed to support link-layer (frame-based) commanding of remote elements past 1 hop from Earth. Tunneling frames over DTN and a standardized ‘hardware command generator’ application that receives DTN bundles and emits space packets containing hardware commands are two approaches that come to mind.
- While the plan would be to move towards terminating space data links at ground stations, CSTS (SLE) should remain, probably for a VERY long time and possibly forever, as an international cross-support point on the ground.[xxxvi]

D. Physical Layers

This includes spectrum, modulation, and coding. CCSDS needs to standardize the physical layers to the point of *ensured* interoperability, not just *potential* interoperability. Such standardization may require the development of ‘profiles’ to reduce the set of options for a particular profile to ensure interoperability. This is not the job of the SIS-DTN working group.

E. Data Link Layers

Whenever they can reasonably support mission communication requirements, missions will use one of the data link layer (ISO layer-2) protocols defined by CCSDS:

1. TC / TM (primarily for Earth-to-Space links)
2. AOS
3. Prox-1 (primarily for surface-to-orbit links)

Missions must refrain from implementing non-standard data links unless there is a compelling need to do so that overcomes the benefits of interoperability, cross-support, and infrastructure creation that using one of the standard data links provides. CCSDS needs to define profiles of these protocols to provide at least at a 'least common denominator' level of *ensured* interoperability. CCSDS needs to also be responsive to the evolving needs of missions so that the limited set of data link standards is not overly restrictive to future mission concepts.

The combination of a physical and a data link layer provides the basis for communication, and is required before interoperability at higher layers can even be considered.

F. Cross-Support Transfer Services (CSTS, SLE)

All agencies must support the transport of AOS and/or TC/TM frames via CSTS in and out of ground stations including at least the Space Link Extension – Return All Frames Service Specification [6] and the Space Link Extension – Forward CLTU Service Specification [5]

G. "Network" Layer (OSI layers 2.5--3) Data Structures

These data structures are the interoperability points of the proposed architecture. Note that not all network nodes must support all of the protocols described here.

1. CCSDS Space Packets *may* be used by those missions that want to use them as the primary 'above-link' data structure and to support packet-based emergency commanding. Space Packets have limited routing capabilities among nodes, but do not form a true OSI layer-3 protocol. Transport of Space Packets via CSTS will be supported for inter-agency cross-support on the ground.

2. CCSDS Encapsulation Packets must be supported on all space data links. Encapsulation packets become the standard layer 2.5 data structure for carriage of IP packets and DTN bundles. Encapsulation packets are not routed. Transport of Encapsulation Packets via CSTS will be supported for inter-agency cross-support on the ground.[xxxvii]

3. IP packets may be used, and when used on space links will be encapsulated within CCSDS Data Links according to the recommendations of the 'IP-over-CCSDS' specification. It may be that a profile of this specification needs to be developed in order to narrow down the options for such encapsulation. IP packets SHOULD be routable at relay nodes, provided that those relay points can in fact support IP traffic. That is, IP packets can only be forwarded by relays that can support multiple simultaneous links, and are not required to be forwarded across links with round-trip light times that exceed (10?)s. IP packets can be transferred inside IP-over-CCSDS-conformant encapsulation via SLE for inter-agency cross-support on the ground. IP packets can also be transported across DTN enabled links for those paths which have one-way light times exceeding that supported by the IP suite.

4. IP packets with appropriate security measures shall be a supported communication mechanism between agencies on the ground. Agency A is required to be able to accept IP

packets from Agency B (to support CSTS, e.g.), and to provide IP packets to Agency B. It is not a requirement that Agency A be able to forward packets (on the ground) from Agency B to Agency C. Such a capability is desirable but would likely be rarely used, as we expect there will be 'direct' connectivity among agencies via the Internet.

5. DTN Bundles are the main/preferred interoperability point and serve as the primary network (ISO layer 3) protocol in the Space Internetworking Architecture. DTN bundles are supported by all agencies, and are routed at space relays and on the ground. DTN bundles shall be carried inside [TBD CCSDS encapsulation method – Encap Packets?] when carried across space data links.

6. CSTS (SLE) must support transport of Space Packets, IP and Encapsulation packets in both directions (forward and return) on the ground for the foreseeable future [TBD exactly which services][xxxviii].

Note that because CCSDS Space Packets can be interspersed with encapsulation packets, *all* of the above network layer data structures may be mixed onto a particular data link and physical channel. Thus a particular mission might simultaneously use Space Packets for hardware commanding and some TT&C, IP as the primary high-rate telemetry packetization, and at the same time serve as an intermittent DTN relay for other spacecraft.

H. Applications

CCSDS shall develop a mechanism to support data-link-layer commanding 'at a distance' over DTN. That is, a mission operations center may wish to implement low-level commanding that is tied to the data link frame and that does not rely on the correct functioning of any higher protocol layers.

Three approaches immediately present themselves:

1. Tunneling data link layer frames over DTN. In this approach, a standardized DTN application resident on all relays would serve as a data link layer tunnel endpoint. Such an application would receive DTN bundles containing data link layer frames and probably some metadata, and would emit those frames 'as is' onto data links. This would allow mission control to use DTN to get a particular frame to the penultimate node in the path to a particular spacecraft, and to cause that node to emit a particular, pre-formatted (at mission control) data link layer frame to the destination spacecraft.
2. A standard 'hardware commanding' DTN application. Similar to the above, the standardized DTN application resident on all relays might, instead of receiving pre-formatted frames, receive bundles containing the information to construct such frames and emit them towards target spacecraft.

   An advantage of these first two methods is that presumably they facilitate placing the low-level command at the front of the data link layer frame, making it easier to detect with a correlator.

3. Hardware commanding based directly on encapsulated DTN bundles. Depending on the frame length and other tradeoffs, it may be possible to encode hardware commands directly in the headers of DTN bundles (such as by referencing particular DTN endpoint identifiers). The drawback of this approach is that it might not be guaranteed that a particular DTN bundle appear first in the frame, which would probably be a requirement for efficient low-layer detection.[xxxix]

CCSDS needs to standardize ONE approach. This work is probably within the scope of the CCSDS SIS-DTN working group.

Missions want to use only Space Packets directly in space links may do so, provided that they are only 1 data link layer hop from Earth (since space packets are not routed). If agencies want to implement private mechanisms to route space packets they may do so.

Missions may use only IP Packets provided that they operate in environments with continuous connectivity and relatively low delay (<10s round-trip light time) In these environments, IP packets are a supported network-layer data structure and can be routed by relays. This would allow missions such as NASA (Cx) to use IP in conjunction with an internationally cross-supported and routed space internetworking infrastructure. This will require *both* IP and DTN routing capabilities on near-earth (including Lunar) relays.

Applications that wish to do so may continue to use space packets to organize their data at the application level. The space packets will not be directly routable, but they can be grouped in some way and forwarded in DTN bundles. This would allow an agency to completely reuse an existing packet-based architecture by simply tunneling packets across the routed DTN infrastructure.

I. Summary

Figure 45 shows the communications options at each layer in the OSI protocol model. Here Space Packets and Encapsulation Packets are shown as a “layer 2.5” – above data link but below network.

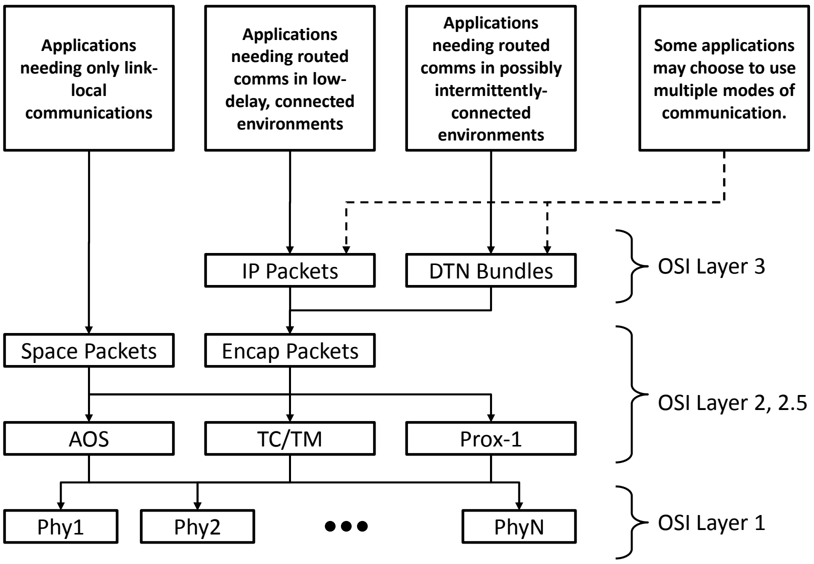


Figure 45: Stack diagram of communication options at each layer[xl]

J. Interoperability Points

As stated earlier, the goal of this effort is to define a set of protocols to form a ‘thin waist’ for space internetworking. The intent is to be able to support nodes from two different agencies on either side of an interoperability point. For interoperability to be meaningful, the nodes must provide interoperability up to a layer k in the OSI model such that they support end-to-end communications. Put another way, interoperability up to OSI layer k does no good if nodes do not have compatible protocols above layer k to support end-to-end communications. Similarly compatibility at OSI layer k is useless without compatibility at OSI layer $m<k$.

Figure 46 shows the interoperability points in the architecture.

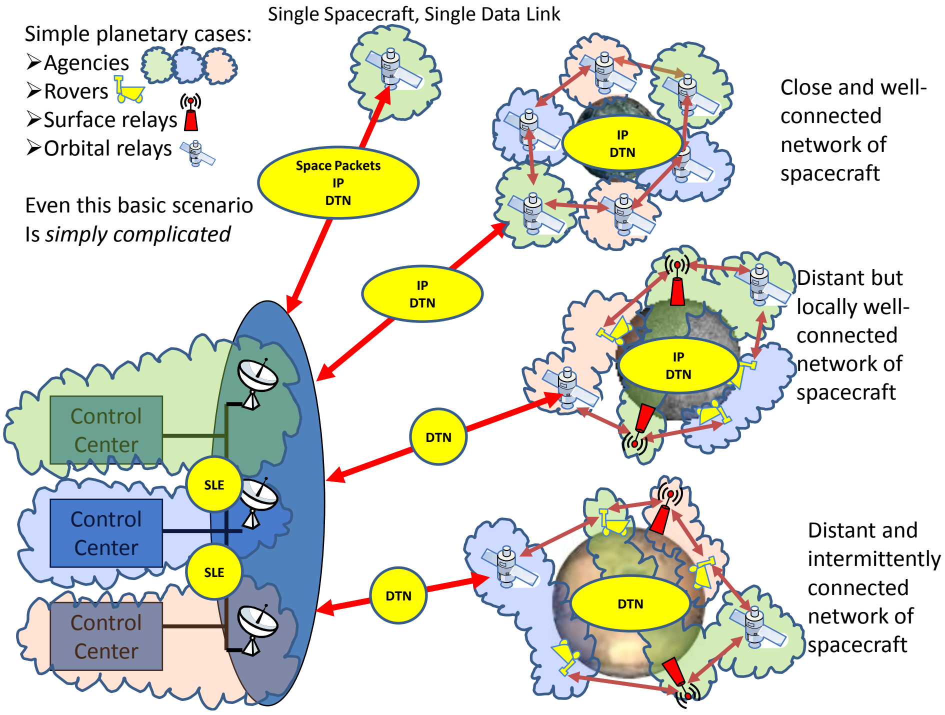


Figure 46: Interoperability points

"Interoperability" at any of the cross-support points in Figure 46 means the *combination* of compatible physical, data link and network layer protocols

K. Interplay Between Space Packets, IP Packets, and DTN Bundles

While the architecture allows for a mix of IP packets, CCSDS Space Packets, and DTN bundles on any particular link, each *end-to-end* communication will typically use *one* of these mechanisms as its network layer. Further, both ends of the communication will typically use the *same* network layer. That is, it is typically NOT the case that one end of a communication will use, say, DTN bundles and the other end will use IP packets.

The choice of which network layer to use is constrained by the connectivity between the endpoints. Applications that need to communicate over a single data link layer hop may use any of the network layers described, including Space Packets whose 'scope' is a single data link layer hop. Applications that need to communicate across several data link layer hops but in a low-delay connected environment may choose to use IP, which is routed. An example might be human exploration of the moon supported by a robust relay infrastructure. Applications that might need to communicate across deep space, or where the end-to-end connectivity may be intermittent need to use DTN bundles. Table 2 shows the scopes of the various network layers allowed under the architecture.

Table 2: Scopes of the various data link layers.

Data Structure	Scope of Communications
Space Packets	Local to a particular data link. Can be used by applications that are guaranteed to be separated by one space link or by a limited number of hops because of their limited routing capabilities.
IP Packets	Local to a particular well-connected and low-delay network component. Can be used by applications that are separated by multiple network hops but that expect the network connectivity between them to be continuous and low latency.
DTN Bundles	Routed throughout the space internetwork. Can be used by applications regardless of latency or intermittent connectivity.

Thus while IP packets might be used in a circum-planetary network for “local” communications, any communications crossing deep space would typically use DTN bundles.

While it is possible to gateway between the various protocols, this is usually a brittle and unsatisfying solution at best. It is better for applications to use the network layer protocol suited to the communication environment.

L. Implications to Operations

Perhaps the largest change in transitioning to a networked infrastructure for space communications is not the technology that must be developed, tested, and inserted, but the cultural shift that must take place. To take full advantage of the proposed architecture, end systems will need to make use of multiple relays to increase data return. Those relay assets will in general be owned and controlled by other agencies. The whole routed infrastructure model relies on a rather free flow of information across agency boundaries to exchange routing information, which in this case includes scheduling information, resource constraints, and other factors that affect a node’s ability to communicate. This level of ‘shared governance’ of the infrastructure is a tremendous shift from the current tightly controlled model. As with technology insertion, it must be possible to transition to the shared governance model in a smooth and controlled manner.

Policy controls will be key to the transition to the shared governance model of operations. Agencies must maintain absolute control over their own assets while allowing other agencies to request access to resources, exchange control information, and eventually to flow data.

M. Routing

We distinguish here between two different operations, *forwarding* and *routing*. Forwarding is the act of receiving a datagram, making a decision about where to forward the datagram, and arranging for its transmission. Forwarding does not require any exchange of control information with other nodes in the network.

Routing is the act of exchanging the information necessary to automatically and autonomously create and maintain the information bases needed to forward traffic. Using a terrestrial analogy, forwarding can be achieved by static routes (all traffic to the network192.168.3.0/24 goes via next hop 192.168.2.16). Routing requires running a *routing protocol* among nodes.

To route in a DTN will require the construction of a DTN EID naming/addressing scheme and one or more routing protocols to exchange information about which EIDs are reachable by what paths. The construction of a naming scheme will be important because it will dictate the sizes of EIDs used (and hence the amount of data that must be transmitted with the routing protocol). The ability to *aggregate* addresses has allowed the Internet to grow to its current size while still keeping the forwarding tables in routers in the middle of the network manageable. This ability to express a multitude of addresses with a shorthand notation will probably be desirable for space internetworking.

N. DTN Capabilities

DTN is the best current candidate to be matured into a space internetworking protocol, but it does not necessarily meet all of the space internetworking requirements out-of-the-box.

The current DTN Bundle Protocol is specified in RFC5050, which defines the rules for formatting bundles for transmission between DTN nodes, and the requirements for processing and responding to administrative flags and messages.

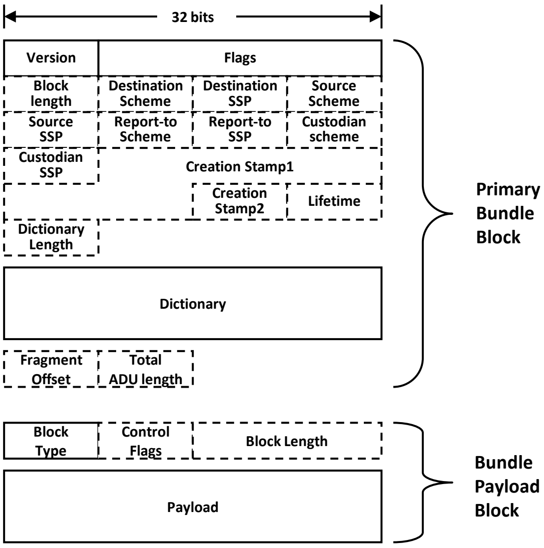


Figure 47: Bundle Protocol Blocks

The main features of the Bundle Protocol are:

- Flexible naming/addressing scheme.
- Reactive and proactive fragmentation. Depending on the DTN implementation, underlying network, and security policy, DTN bundles may be split if connectivity between DTN routers is unexpectedly terminated. This improves efficiency by allowing the transmitting node at the time connectivity is lost to discard that portion of the bundle that it knows was received and to transmit only the ‘last part’ at the next opportunity. In this case, both nodes form *bundle fragments* when connectivity is lost. The receiving node forms a fragment containing all the payload bytes it received correctly, and the transmitting node forms a fragment containing those payload bytes that it reasonably suspects were NOT received. The transmitting node then schedules the remaining fragment for routing. Bundle fragments are reconstructed at the destination into complete bundles. A DTN router may also decide to *proactively* fragment a bundle. This might be advisable if, for example, the router knows that the bundle cannot be transmitted during the scheduled connectivity opportunity.
- Time-to-live. Each bundle is assigned (by the source application) a ‘time-to-live’ that is meant to reflect the useful lifetime of the data. The time to live represents an actual time duration, not a network hop count, and is used to remove bundles from the system if they cannot be delivered in a timely manner.

- Custody Transfer. DTN implements reliable data delivery by means of in-network checkpointing of bundle progress called custody transfer.

- Per-Bundle Control Flags. Each bundle contains a set of flags that can trigger particular status reports about the bundle's progress. These include:

    - Request reporting of bundle reception.
    - Request reporting of custody acceptance.
    - Request reporting of bundle forwarding.
    - Request reporting of bundle delivery.
    - Request reporting of bundle deletion.

  These reports can be used to provide data accountability for bundles.

- Alternate 'Report-To' Addressing. The reports generated by a bundle may be directed to a different destination than the source. Reports may be directed towards destinations that are not generally reachable so that data accountability reports could be generated at nodes but would not be transmitted unless specific actions were taken to retrieve the records.

- Extensibility. DTN protocol data units are composed of a variable number of 'blocks'. Block types are identified by self-delimiting numerical values (SDNVs) so that expression is both efficient and highly extensible. Each block carries with it a set of flags identifying how nodes that do not understand the block should treat it (pass it unmodified, remove the block, discard the bundle, etc.). Thus additional capabilities such as "keep at most *N* of this type of cyclic telemetry value" can be implemented.

Using fragmentation and reassembly, DTN can easily implement CFDP Scenario 4 (reliable/unreliable end-to-end transfer via multiple waypoints in parallel) shown in Figure 48. A particular bundle containing the file to be transferred can be fragmented (proactively or reactively) at a network control center and the fragments forwarded over multiple paths to the destination. This is trivially extended to the case where there are multiple serial hops along one or the other of the paths.

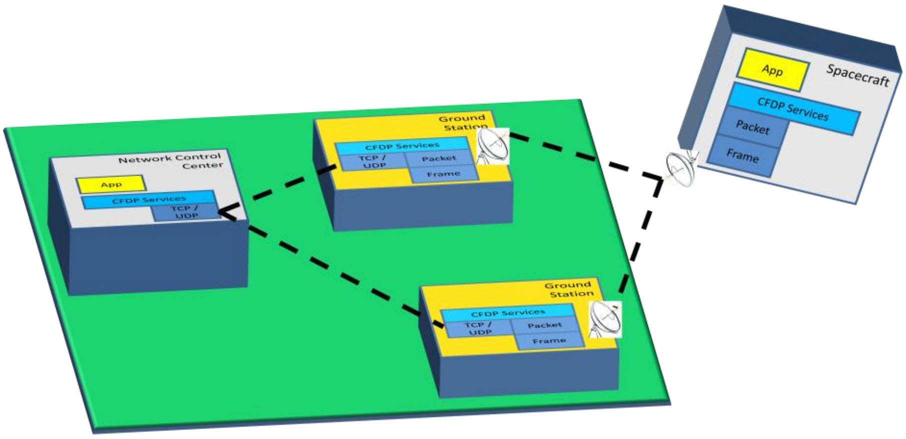


Figure 48: CFDP Scenario 4

O. Transition Path

There are a number of reasons that sudden and extensive changes to the space communications architecture should be avoided. Hardware development is timely and costly due to the harsh environment of space. Mission operations procedures that have been developed and honed through years of practice are comprehensive and trusted. Thus any plan to move to an internetworked architecture for space communications must include a transition path that grows from the current deployed and planned infrastructure with as few disruptions as possible.

P. Ground Infrastructure Transition to Networking

Networked architectures typically terminate data link layers where physical layers terminate. This is the case with Ethernet, for example, where the Ethernet frame terminates in the network card where the copper (or fiber) does. The current plans for space communication allow for space data links to be terminated not at ground stations but in mission operations centers. Under this approach, the physical link is terminated at the ground station but data link layer frames are essentially tunneled across the terrestrial Internet to mission operations centers using CCSDS Cross Support Transfer Services (CSTS), the follow-on to CCSDS Space Link Extension services (SLE). This allows an international cross-support point on the ground, where one agency can use CSTS to request access to, configure, and use another agency's ground station.

While the long-term vision for the architecture proposed here would terminate space links at ground stations and provide cross-support at the IP or DTN layers, continued support for Space Packets will require that CSTS (SLE) be maintained as an international cross-support point on the ground for as long as possible. Indeed, CSTS really consists of two parts, a data transfer part that could be obviated on moving to a truly networked infrastructure, and a service management part responsible for requesting access to, configuring, and using the remote resources. The service management functions will need to persist and become part of the new design.

Q. Application Transition to Networking

Fortunately a number of features can be used to provide a smooth transition:

1. As stated earlier, Space-Packet-based applications might continue to use Space Packets as their way of organizing application-layer data. If such applications never need to communicate more than one data link layer hop, they could continue to use Space packets indefinitely. If they envision eventually needed to communicate over multiple hops, applications could start by simply encapsulating Space Packets within DTN bundles. This might amount to nothing more than 'tunneling' the packets over DTN, allowing little or no change to the applications except possibly that their packets might be delayed in transit by more than just speed-of-light and processing delays (if the comm. subsystem is turned off, for instance).

2. Applications may run 'dual-stacked' for some period of time. Such applications could choose to use either Space Packets or DTN bundles when communicating, and could accept data from their peer applications using either format. An example of this is shown below, using CFDP as an example transition application.

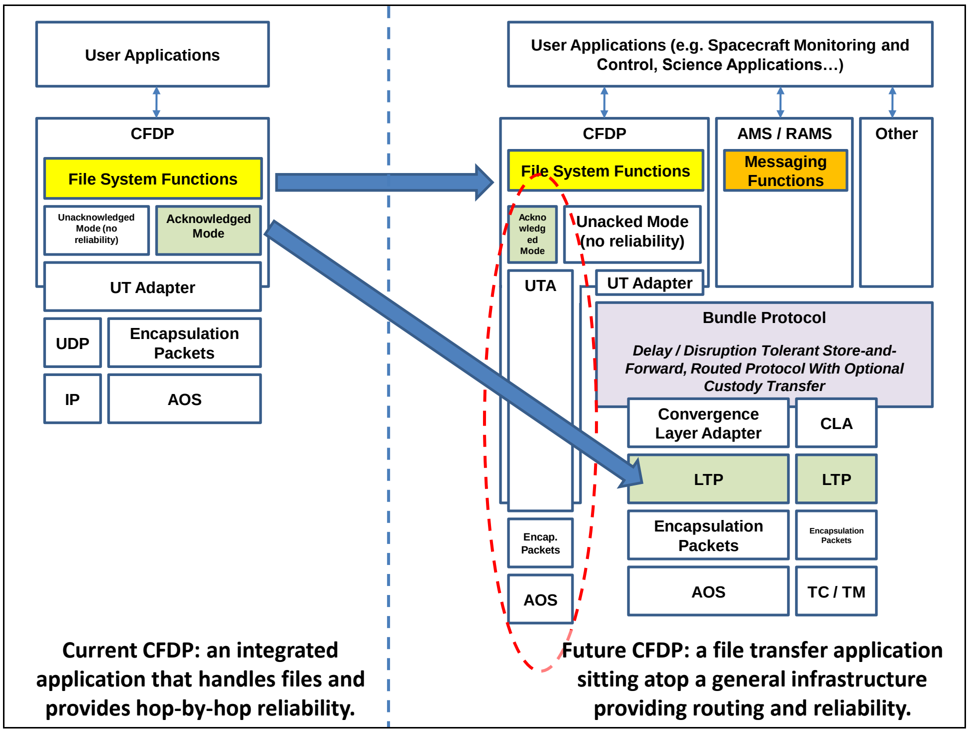
R. Application Transition Example: CFDP

Possibly the most successful example to date of protocol development/deployment above the data link layer is the CCSDS File Delivery Protocol (CFDP). CFDP is capable of multi-hop file transfers when no end-to-end path exists, using store-and-forward at the intermediate hops. The CFDP application itself is a prime candidate for migration to use DTN for two reasons:

1. CFDP already contains much DTN functionality. The 'application' (file transfer) portion of CFTP is designed to operate in long-delay and disrupted environments.

2. DTN can enhance the operation of CFDP by providing capabilities that CFDP lacks, most notably the ability to handle scenarios 4 and 5: multi-hop file delivery where parts of the file are sent along different paths to the destination. Currently CFDP store-and-forward overlay procedures require all parts of a file to follow the same path.

Figure 49 shows how CFDP could be migrated to use the DTN Bundle Protocol, including an intermediate stage that allows a CFDP implementations to communicate with both 'old' (non-DTN) and 'new' (DTN-based) implementations. This makes use of the layering internal to most CFDP implementations at the Underlying Transport Adaptor layer. Using this approach, CFDP implementations migrate from the configuration on the left to the one on the right. The part in the dotted oval on the right represents the 'forward migration' of the old architecture. Another feature of the configuration on the right is that it allows multiple applications to make use of features that are currently embedded within CFDP, such as the store-and-forward overlay and reliability.



Current CFDP: an integrated application that handles files and provides hop-by-hop reliability.

Future CFDP: a file transfer application sitting atop a general infrastructure providing routing and reliability.

Figure 49: CFDP Evolution Path

This represents a seamless growth path for CFDP as an application from the current implementation to one based on DTN bundles.

S. Profile Development and Protocol Interoperability

There is tension in protocol development between providing very few options, and thus increasing the chances of interoperability at the cost of flexibility, and providing lots of options, thus ensuring that a particular protocol is suited to a wide range of applications. To date, work within the CCSDS has skewed towards the latter of these. This is understandable, since most protocol development done above the packet layer in CCSDS has resulted in implementations used (and possibly reused) *within* agencies rather than *between* agencies. To be sure, there is always the intent that different implementations be interoperable, yet in order to satisfy all constituents, multiple options and operating modes seem to be unavoidable. Even the more complex data link layer protocols such as Proximity-1 have shown that non- or marginally-interoperable conformant implementations of the same specification are possible.

The profiles described above need to ‘nail down’ a small set of standard options / configurations to ensure at least a ‘least-common-denominator’ level of interoperability, and there need to be *as few profiles as possible* for a particular ‘layer’ in the space internetworking stack. This will almost surely mean that some missions will have to sacrifice performance in order to use and to contribute to a common infrastructure – there is no free lunch. The hope and belief is that improved efficiencies from being able to make use of a common infrastructure will eventually outweigh slight inefficiencies for particular missions. This will never happen unless missions conspire to make it happen, by cooperating to build the infrastructure that they can then use.

Future protocol development would do well to learn from this activity: build very simple layers with few options – and build more layers. Putting in the extra work up front to weed out extra options during protocol development, possibly by standardizing a 'base' protocol and a standard mechanism within the protocol to negotiate extended capabilities, should reduce the number of 'profiles' that need to be developed later.

T. Examples

1. Hardware Commanding Over the Network

Spacecraft often have mechanisms to respond to very low-level commands in case higher spacecraft functions are not available or are not operating correctly. Typically such low-level commands are encoded in the data link layer frames or in packets that are placed at a fixed offset from the frame synchronization marker so that command detection can be done with a hardware correlator. Thus the 'command interpretation' can happen within the radio, and thus can be used to perform very basic functions such as rebooting the C&DH.

Figure 50 shows a single data link layer frame, with hardware commands embedded either within the frame header itself (at offset *A*) or within the first packet (offset *B*).

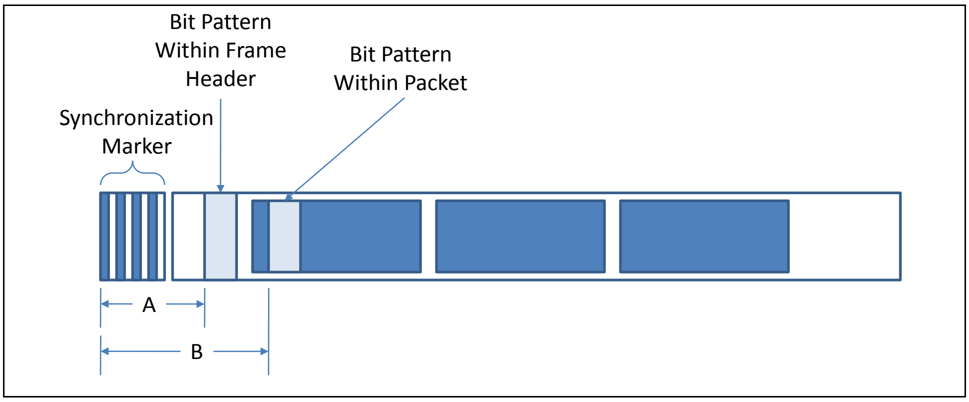


Figure 50: Hardware commands (light areas) at fixed offsets from frame synchronization marker.

The issue is that with the proposed architecture, data link layer frames are not routed and so hardware commands cannot propagate past a single data link layer hop. One solution to this is to provide a common, DTN-based application whose task is to process directives for sending data link layer hardware commands.

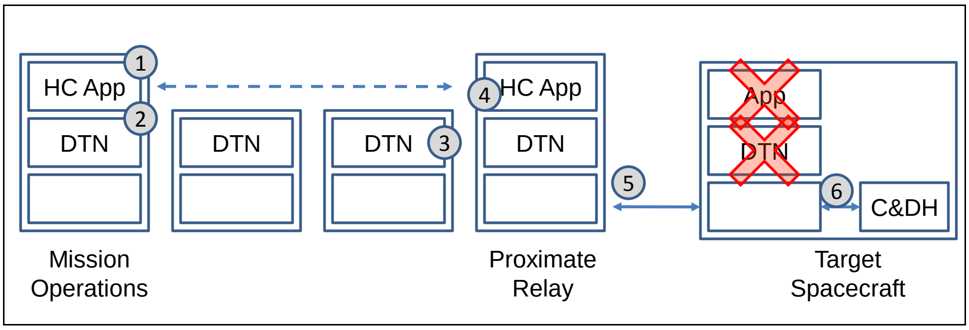


Figure 51: Hardware commanding application example.

Figure 51 shows how a DTN-based hardware command application might function. The same figure works with only slight variations for both the 'tunneled frame' and 'data-driven' hardware commanding mechanisms described above.

1. Hardware Commanding (HC) application generates the hardware command for the target spacecraft. This may be in the form of a pre-formatted data link layer frame for transmission to the spacecraft, or the information needed to generate such a frame at the Proximate Relay.
2. The HC application encapsulates the HC data (frame or information) in a DTN bundle.
3. The bundle is routed to the proximate relay. This requires all other relays in the path to function properly.
4. The HC application on the proximate relay consumes the bundle and generates the frame to transmit to the target spacecraft.
5. The hardware commanding frame is sent to the target spacecraft. We assume that neither the networking stack nor higher applications on the target spacecraft are functioning.
6. The hardware command is detected by the receiver and acted on by the target spacecraft.

U. Coexistence of Space Packets, IP Packets, and DTN Bundles

Figure 52 shows DTN bundles, IP packets, and Space Packets coexisting and being used to communicate both with a relay spacecraft and with a target spacecraft beyond. In the figure, AOS is used by one agency's Mission Operations to communicate with a Relay Spacecraft belong to a second agency. CSTS is used to obtain cross-support from a third agency's ground station. Space Packets encapsulated in AOS are used by Mission Operations to communicate directly with an application on the Relay Spacecraft. This is admittedly unlikely, but serves to illustrate that applications based on Space Packets can continue to be used and coexist with future IP- and DTN-based applications.

At the same time, IP packets and DTN Bundles for the Target Spacecraft are multiplexed into the AOS frames. The Relay Spacecraft routes the IP packets and DTN Bundles, deciding when and where to forward them based on information in the IP and Bundle headers. The Relay Spacecraft also uses a different data link layer (Prox-1) to communicate with the Target Spacecraft. An important and sometimes overlooked point in networking is that the layer-3 data structures (the IP packets and DTN

Bundles in this case) are *extracted* from the incoming framing and encapsulation, routed, and then *re-encapsulated and re-framed* for the outbound link.

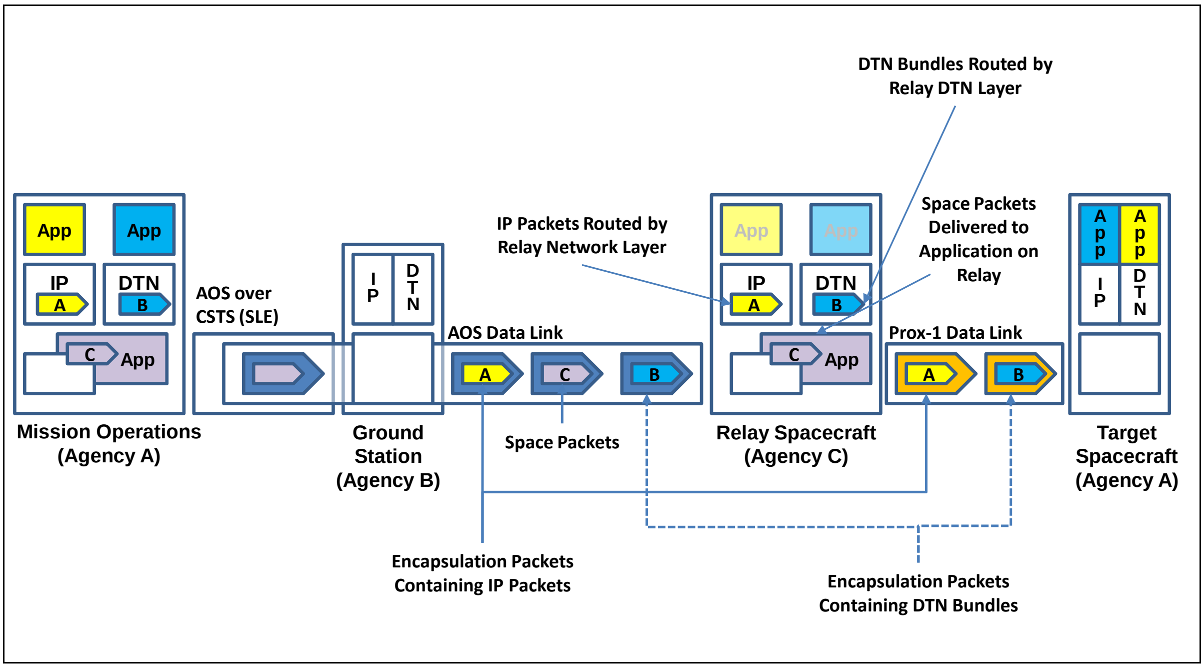


Figure 52: Example showing coexistence of Space Packets, IP Packets and DTN Bundles.

Figure 52 also illustrates a transition path for applications. Spacecraft may start out continuing to use Space Packets as their primary communications mechanism, as with the Relay Spacecraft in the figure. These spacecraft will not be able to take advantage of the Space Internetworking infrastructure as it is being built out, but could contribute to it by including IP and/or DTN capabilities. Over time, as networked applications are developed and proven, these applications can be deployed and used, first as experiments, then in parallel with Space Packet-based applications, and finally replacing them.

IX. Transition Strategy and Roadmap

The SSI is expected to develop as a confederation of independent, cooperative infrastructure assets voluntarily contributed by many agencies. It would:

- Be autonomously owned and operated by diverse space mission organizations
- Provide common, cross-supported network services for the benefit of all participants
- Include terrestrial assets such as ground stations, control facilities, ground data networks, etc.
- Include in-space assets such as data relay satellites, planetary surface communications networks, collaborative space mission elements, etc.

The SSI is expected to develop as a confederation of independent, cooperative infrastructure assets contributed by many agencies. Its development and operation would be based on:

- **Statements of Intent** from individual organizations to contribute infrastructure capabilities in order to support an internetworked data flow for individual missions. These would be subject to bilateral or multilateral cross support agreements
- **Standards:** An agreed set of common, extensible interoperability standards
- **Cross Support Services:** An agreed and published catalog of commonly provided cross-support services - in space and on Earth – that are offered by individual agencies
- **Management Processes:** An agreed set of cross-support service management processes, mechanisms and capabilities (in space and on Earth) that allow internetworked data flow to be invoked and configured
- **Governance mechanisms** to administer the necessary core internetworking management, coordination and operations functions that enable end-to-end internetworked data communications.

The SISG concludes that a “roadmap” along the lines of Figure 53 should be developed in greater detail than presented here, and agreed among the SSI participants in order to steer the upcoming transitional period towards deployment of the SSI. This is forward work after the architectural concept and definition phase is complete (but between IOP-2 and IOP-3 timeframes), and will allow the participating agencies to provide SSI building blocks which dovetail with each other in a way that best capitalizes on each agency’s ability to provide some portion of the SSI infrastructure.

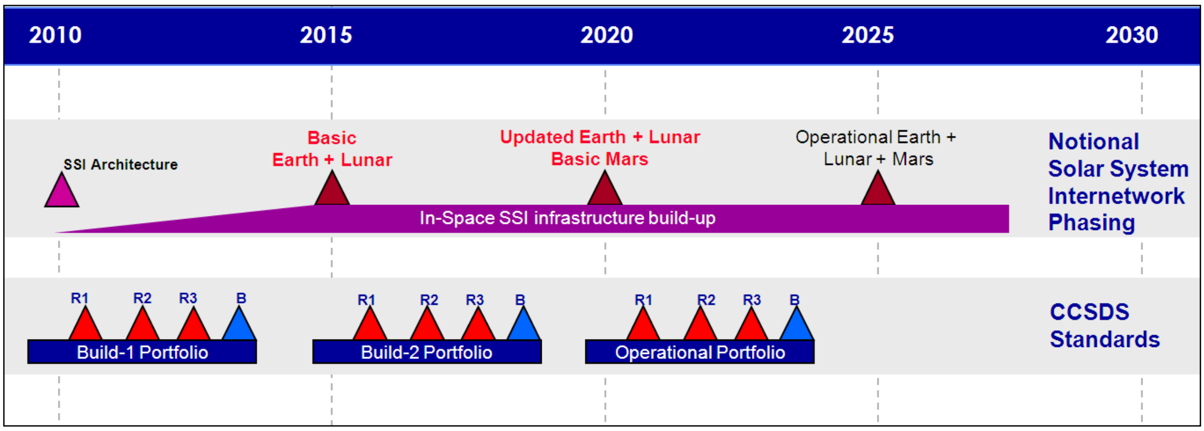


Figure 53: Candidate Roadmap for Solar System Internetwork Development

During this later phase, the IOAG should coordinate the execution of international flight tests and demonstrations of the new capabilities. The initial series of flight tests should build upon those proposed by the current NASA “Space DTN Development Project”, using deep space and ISS mission resources. Multiple organizations should be invited to join and participate in these campaigns.

Additionally, the IOAG should actively encourage individual missions to join the SSI confederation by indicating their willingness to contribute cross-support of space internetworking services. The IOAG should maintain an evolving catalog of such in-space mission deployments and the cross-support capabilities that they may offer, along with a corresponding catalog of available terrestrial cross-support.

Appendix A: The Reference Architecture for Space Communications (RASC)

A. Introduction

The purpose of this annex is to provide an executive summary of the Reference Architecture for Space Communications (RASC). This architecture is to be used as a common framework when space agencies present space communications systems and space communications scenarios.

B. Views

Since there are many aspects associated with space communications systems and scenarios, this reference architecture defines four Views to describe space communications systems and scenarios, each focusing on a different set of aspects associated with the space communications systems and scenarios.

The Views defined in this reference architecture are:

- The Physical View
- The Service View
- The Communications View
- The Enterprise View

C. Physical View

The Physical View is used to describe the physical configuration of space communications systems and scenarios and its physical characteristics.

Specifically, it describes:

- Physical elements used in space communications systems and scenarios
- Physical characteristics of the physical elements (including location, physical media for accessing)
- Topology and connectivity of the physical elements

Examples of physical elements are:

- Orbiting elements (Earth orbiter, Lunar orbiter, planet orbiter, etc)
- Landed elements (Lunar lander/rover, planet lander/rover, etc.)
- Ground elements (Ground station, control center, science facility, etc.)

D. Service View

The Service View is used to describe services (which are functions provided by some physical elements for other physical elements) and their functional characteristics.

Specifically, it describes:
- Services provided and used by space communications systems
- Functional characteristics of services
- Performance characteristics of services
- Methods and/or standards for using services
- Methods and/or standards for managing services

Examples of services are:
- Relaying services (frames, packets, files, etc.)
- Routing services (frames, packets, files, etc.)
- Store and forward services (frames, packets, files, etc.)
- Positioning and timing services (orbit determination, clock synchronization, etc.)
- Management services (services for managing provision of services)

E. Communications View

The Communications View is used to describe communications protocols and modulation/coding methods used between physical elements and their communicational characteristics.

Specifically, it describes:
- Communications protocols (including modulation/coding methods) used by space communications systems
- Parameter values of communications protocols

Examples of communications protocols are:
- Modulation methods (PM, BPSK, QPSK, etc.)
- Coding methods (BCH, convolutional, RS, Turbo, etc.)
- Data link protocols (TC, TM, AOS, Proximity-1, etc.)
- Network protocols (Space Packet, IP, etc.)
- Transport protocols (TCP, UDP, SCPS-TP, etc.)
- Application protocols (CFDP, AMS, etc.)

F. Enterprise View

The Enterprise View is used to describe the organizational structure associated with space communications systems and scenarios and its administrative characteristics.

Specifically, it describes:
- Organizations involved in space communications systems and scenarios
- Physical interfaces between organizations
- Administrative interfaces between organizations
- Documents exchanged between organizations.

Examples of organizations are:
- Space agencies
- Commercial service providers
- Science institutes

G. Example of a Space Communications Scenario

As an example, the space communications scenario for the cruise phase of a project called BepiColombo is described below using RASC.

BepiColombo is a joint ESA-JAXA project to explore Mercury. ESA develops a Mercury orbiter called the Mercury Planetary Orbiter (MPO) and JAXA develops another Mercury orbiter called the Mercury Magnetosphere Orbiter (MMO). These two spacecraft will be launched together by a single launcher. During the cruise to Mercury, MPO is the main spacecraft and MMO is operated as a payload of MPO. On arrival at Mercury, the two spacecraft will be separated from each other and start observations of Mercury independently.

Figure 54 shows the physical view of this project during the cruise phase. The two spacecraft are physically connected and they communicate with each other with a wired serial bus. During this phase, only MPO communicates with the earth using an RF link. On the ground, two ground stations are used: Cebreros in Spain as the primary station and Usuda in Japan as the secondary station. European Space Operations Centre (ESOC) in Germany is the control center for both spacecraft. Cebreros communicates directly with ESOC but Usuda communicates with ESOC through Sagamihara Space Operations Center (SSOC) in Japan. SSOC plays another role as the payload control center for MMO.

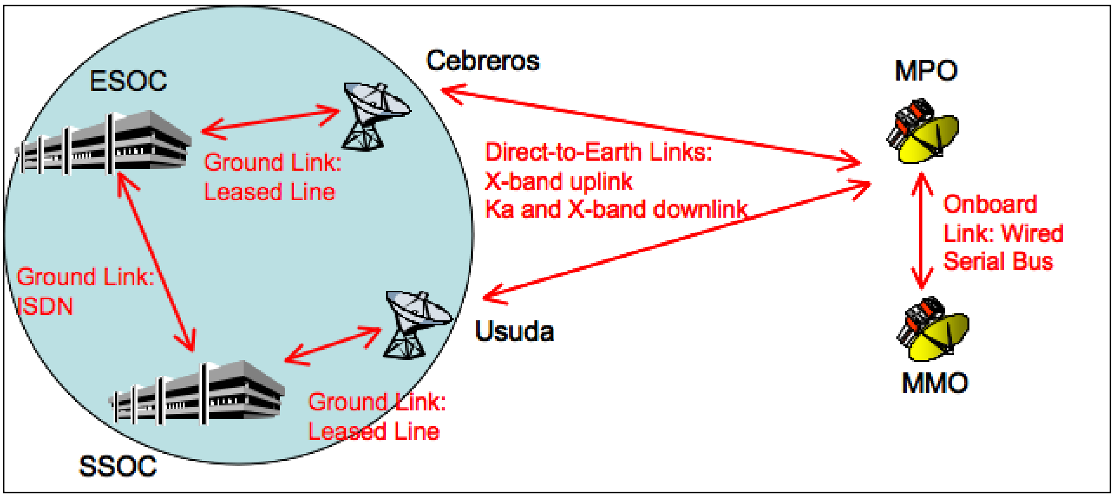


Figure 54: Scenario example: Physical view

There are three service views for this project depending on what elements provide services for what elements. Figure 55 is a case where MMO and its control center (SSOC) use services provided by MPO, Cebreros and ESOC. Although Cebreros relays frames, the concatenation of MPO-Cebreros-ESOC provides a packet relaying service between MMO and SSOC. Figure 56 is a case where MPO and its control center (ESOC) use services provided by Usuda and SSOC. Both Usuda and SSOC provide a frame relaying service between MPO and ESOC. Figure 57 shows a complicated case where MMO and SSOC use packet relaying services provided by MPO and ESOC but Usuda and SSOC also provide frame relaying services for MPO and ESOC.

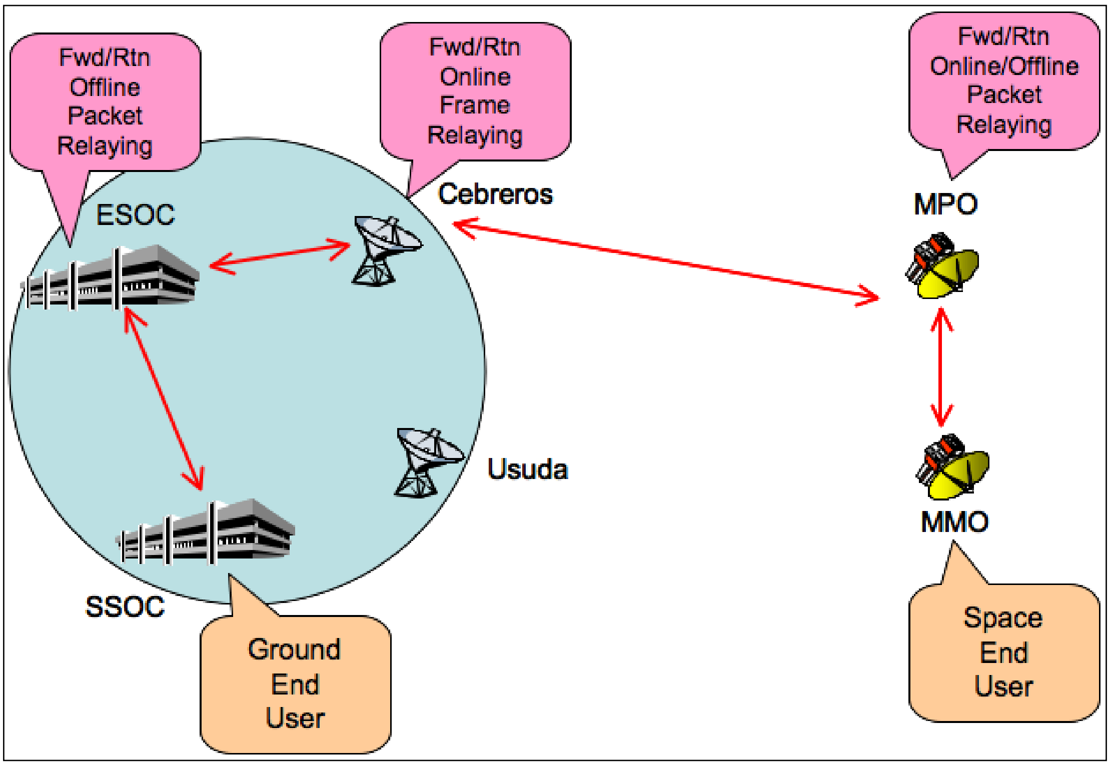


Figure 55: Scenario example: Service view 1

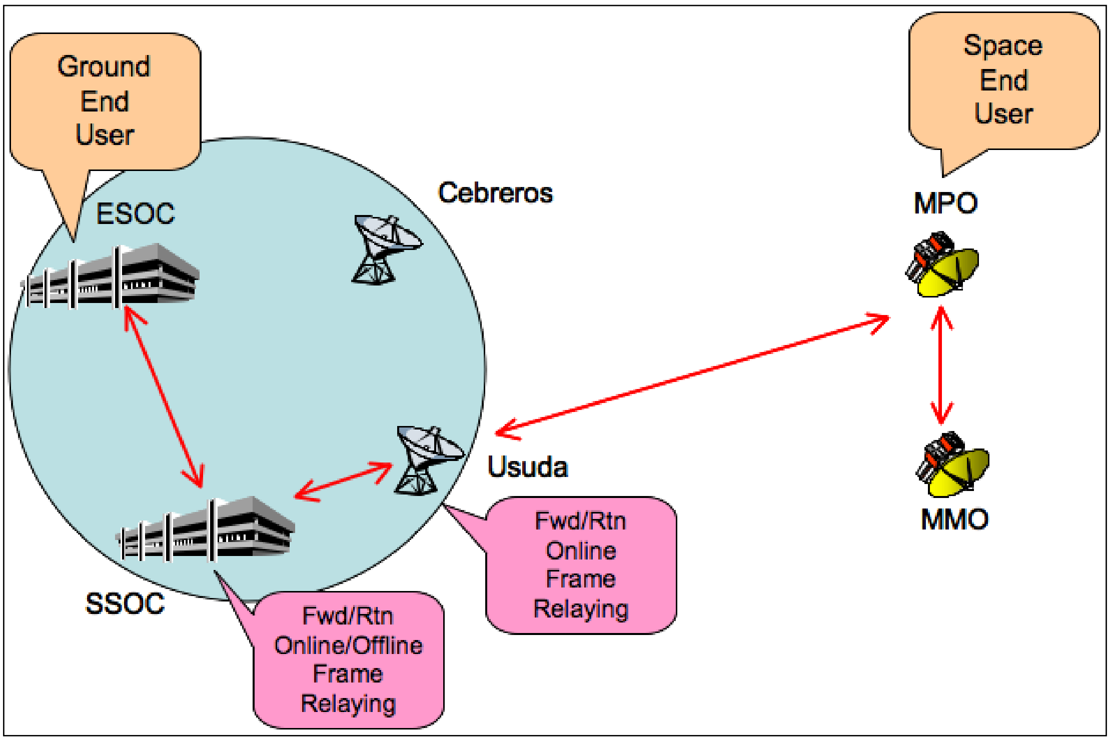


Figure 56: Scenario example: Service view 2

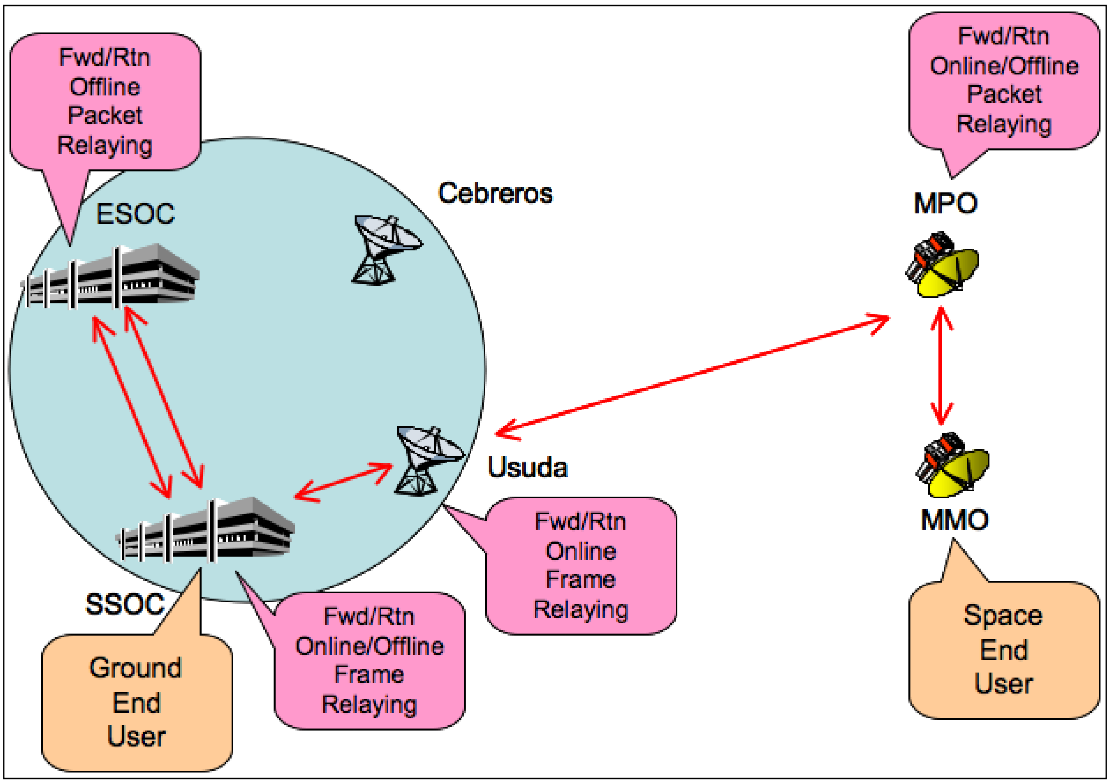


Figure 57: Scenario example: Service view 3

Figure 58 is the communications view, where the protocol stack used on each of the physical lines is shown. Figure 59 is a combined service/communications view, where the protocols used to support the service view of Figure 55 are shown.

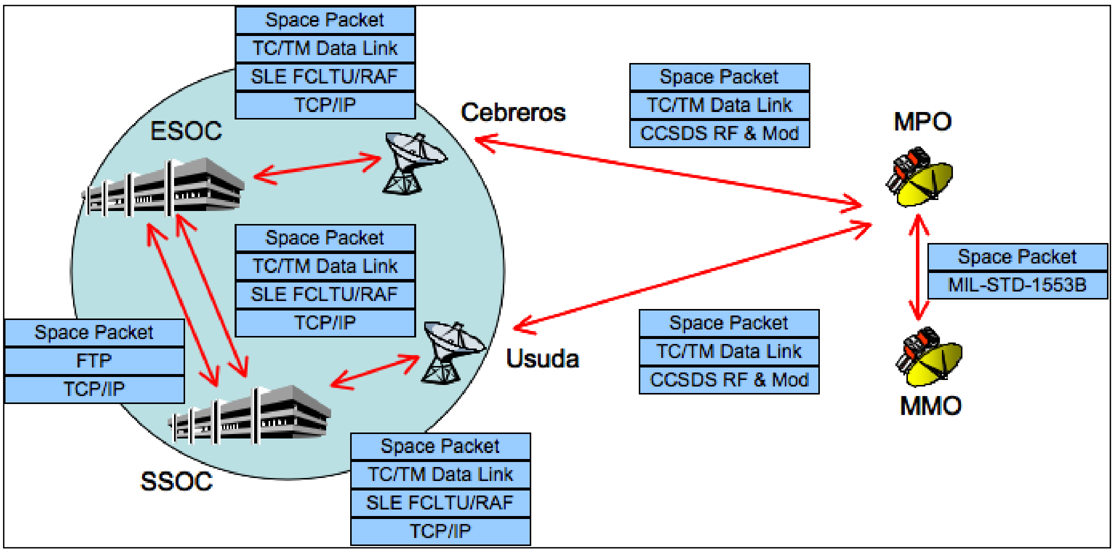


Figure 58: Scenario example: Communications view

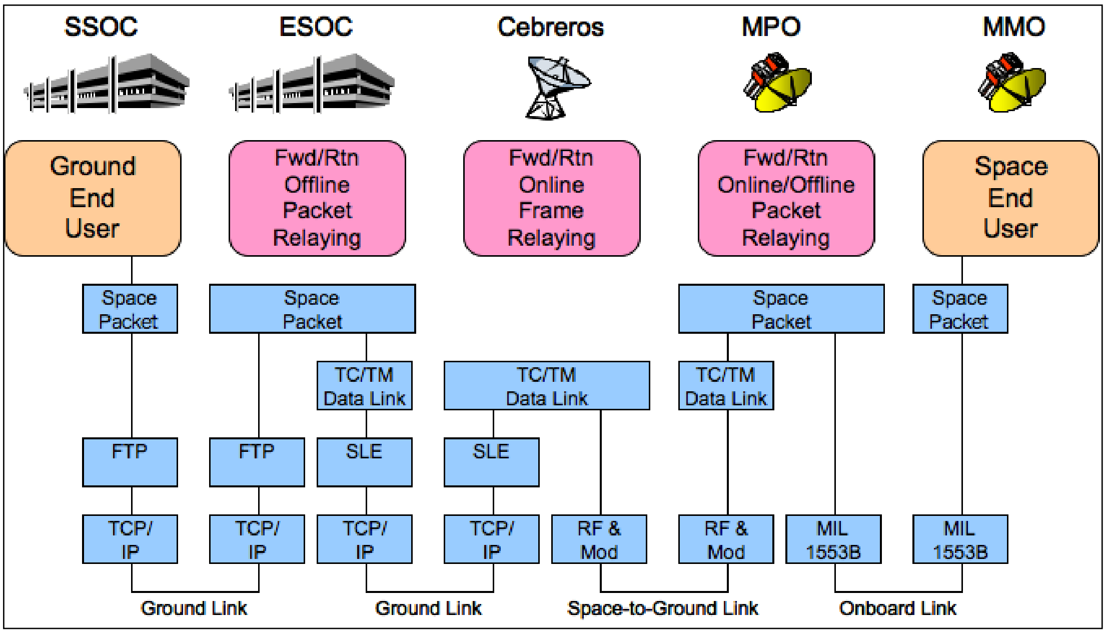


Figure 59: Scenario example: Service/Communications view

Figure 60is the enterprise view. It shows that MPO, Cebreros and ESOC belong to ESA and MMO, Usuda and SSOC belong to JAXA. There are two physical interfaces between ESA and JAXA, through which physical signals are exchanged with communications protocols: between MPO and MMO and between ESOC and SSOC. There is also one administrative interface between ESA and JAXA, through which documents are exchanged using e-mail, etc.

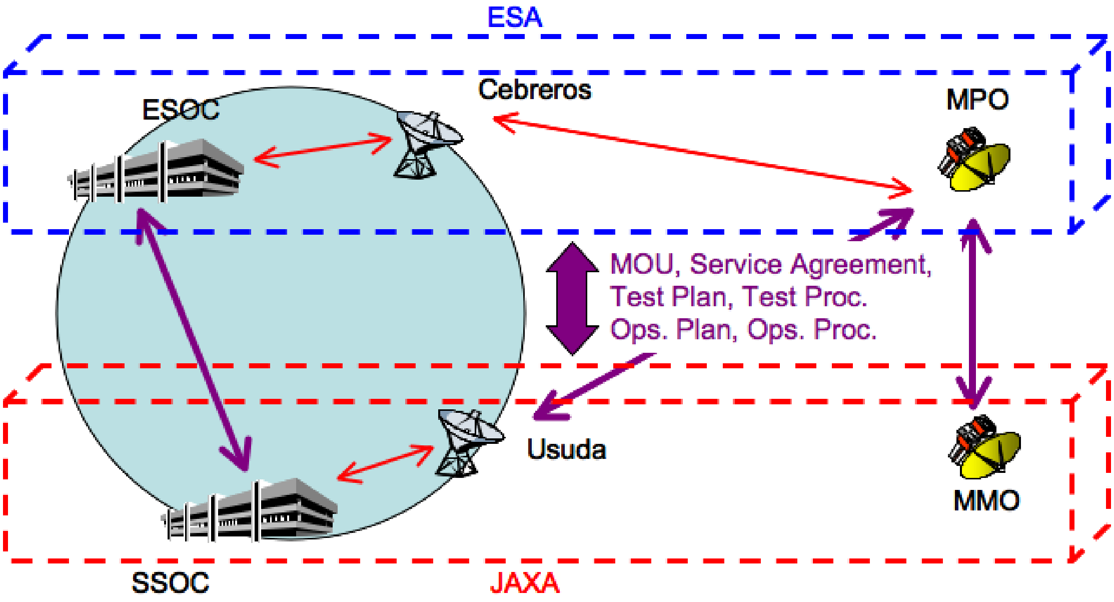


Figure 60: Scenario example: Enterprise view

Appendix B: Glossary

Cross Support	An agreement between two or more organizations to exploit the technical capability of interoperability for mutual advantage, such as one organization offering support services to another in order to enhance or enable some aspect of a space mission
Governance	Governance relates to decisions that define expectations, grant power, or verify performance. It consists either of a separate process or of a specific part of management or leadership processes. Governance relates to consistent management, cohesive policies, processes and decision-rights for a given area of responsibility. (From Wikipedia: http://en.wikipedia.org/wiki/Governance)
In-Space	Extraterrestrial. In this usage, in space communications includes earth-to-space, space-to-space, space to planetary surface, planetary surface-to-surface, etc.
Internetworking	Internetworking involves connecting two or more distinct computer networks or network segments together to form an internetwork (often shortened to internet), using devices which operate at layer 3 (Network layer) of the OSI Basic Reference Model (such as routers or layer 3 switches) to connect them together to allow traffic to flow back and forth between them. The layer 3 routing devices guide traffic on the correct path (among several different ones usually available) across the complete internetwork to their destination. (From Wikipedia) (From Wikipedia: http://en.wikipedia.org/wiki/Internetworking)
Interoperability	The technical capability of two or more systems or components to exchange information and to use the information that has been exchanged

Appendix C: List of Acronyms

AOS	Advanced Orbital Systems
BP	Bundle Protocol
CCSDS	Consultative Committee for Space Data Systems
CDMA	Code Division Multiple Access
CFDP	CCSDS File Delivery Protocol
CLTU	Command Link Transmission Unit
CMD	Command
CMD/TLM	Command /Telemetry
COP-1	Communications Operation Procedure - 1
CSTS	Cross Support Transfer Services
DFE	Direct From Earth
DSSS	Direct-Sequence Spread Spectrum
DTE	Direct To Earth
DTE	Data Terminal Equipment
DTN	Delay Tolerant Networking
EID	Endpoint IDentifier
EO	Earth Observation
ETE	End-to-end
EVA	Extra Vehicular Activity
GDS	Ground Data System
GE	Gateway Element
GEO	Geostationary Orbit
GMES	Global Monitoring for Environment and Security
IETF	Internet Engineering Task Force
IRTF	Internet Research Task Force
IOAG	Interagency Operations Advisory Group
IOP	Interoperability Plenary
IP	Internet Protocol
IRTF	Internet Research Task Force
ISO	International Standards Organization
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ITT	Invitation To Tender
LAN	Local Area Network
LEO	Low Earth Orbit
LSS	Lunar Surface Systems
LTP	Licklider Transmission Protocol
MMO	Mercury Magnetosphere Orbiter
MPO	Mercury Planetary Orbiter
MS	Mission Systems

NISN	NASA Integrated Services Network
OCA	Orbital Communications Adapter
OSI	Open Systems Interconnect
PDU	Protocol Data Unit
POTS	Plain Old Telephone System
RASC	Reference Architecture for Space Communications
RFC	Request For Comment
SFCG	Space Flight Coordination Group
SISG	Space Internetworking Strategy Group
SLE	Space Link Extension
SN	Space Network
SPR	Small Pressurized Rover
SSI	Solar System Internetwork
TBD	To Be Determined
TC	Telecommand
TCP/IP	Transmission Control Protocol / Internet Protocol
TDRSS	Tracking and Data Relay Satellite System
TLM	Telemetry
TM	Telemetry
UDD	User Defined Data
UT	Underlying Transport
UTA	Underlying Transport Adaptor
UTC	Universal Time Coordinated
VOIP	Voice Over Internet Protocol
XTCE	XML Telemetric and Command Exchange

Appendix D: References

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Appendix E: List of Findings and Recommendations

For convenience, this is a consolidated listing of all findings and recommendations from the text of the report.

Finding F-1: *In today's mission environment, network interoperability is limited to "best attempt" efforts to add SLE and cross support to ground stations, and very limited project-specific agreements for communications interoperability on the space segment. No communications interoperability for internetworking is agreed to other than taking advantage of the terrestrial internet for very limited ground interactions and unique ISS applications.*

Recommendation R-1: *There should be international agreement on how to do space-to-space interoperability and space-based infrastructure that supports space-to-space interoperability in a standard way.*

Recommendation R-2: *In-space internetworking should be fully verified as feasible in long delay mission environments.*

Recommendation R-3: *There should be international agreement on how to manage space-to-space or end-to-end interoperability.*

Recommendation R-4: *There should be interoperable services for timing, positioning, management, etc., in addition to services for relaying data.*

Finding F-2: *Lunar scenarios currently envisioned add new requirements that exceed the capabilities of current point-to-point links, such as visibility in craters and far-side operations; They also add new requirements for cross-support between international partners most likely involving routing through in-space assets.*

Recommendation R-5: *In support of envisioned Lunar collaborative missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

Finding F-3: *Mars missions in the 2025 timeframe will be increasing collaborative, and will be characterized by a local network infrastructure on Mars which locally uses routed IP protocols. Exact requirements are not stabilized, but it is clear that some form of interagency routed infrastructure based on IP and/or DTN will be required.*

Recommendation R-6: *In support of envisioned Mars collaborative missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

Recommendation R-7: *The cross-supported architecture for circa 2015 should include: cross-support services that cover CCSDS packet and CFDP-based file transfer across all elements in the end-to-end communications chain; Extension of the existing SLE services to include the transfer of files, transfer of packets, ancillary information such as radiometric tracking, link monitor data, navigation and accounting data; Inclusion in the cross-support services of a mechanism for low level commanding of a Mars asset utilizing a cross-supporting orbiter; an interoperable Network Time Service and a Navigation/Tracking Service; a naming and addressing scheme and a method for attaching metadata for data traversing cross-support infrastructure to avoid ambiguity and conflicts in, e.g., lander and orbiter addressing domains; A service management infrastructure for overall cross support.*

Finding F-4: *Near Earth missions are the most numerous missions, and the costs benefits of internetworking are therefore potentially large. Additionally the science benefits of such technologies as Sensor Webs are not achieveable in any other way.*

Recommendation R-8: *In support of envisioned Near Earth missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

Finding F-5: *There is a strong trend towards higher data rates on the space links which in turn calls for higher frequency bands offering higher bandwidth. Nonetheless, bandwidth efficient rather than power efficient modulation schemes will be needed.*

Finding F-6: *If the decoding process needed for a given coding scheme is less complex, such coding scheme is better suited for higher data rates and for the forward link as a low complexity decoder can be implemented as flight hardware.*

Finding F-7: *The transition to file based operations concepts enables the use of novel application layer error detection and correction techniques such as long erasure codes.*

Recommendation R-9: *In view of mostly file based operations, IOAG agencies should embark on developing novel coding techniques designed to error protect the end-to-end transfer of large size application data units.*

Finding F-8: *The dependency of missions on suitable space-borne relays is growing which in turn requires some form of routing capability. Such routing may initially be based on CCSDS Space Packets or other routable data structures such as IP packets or DTN bundles, which will then be carried by encapsulation packets. All these options require the CSTS services be upgraded to support packets.*

Finding F-9: *In general, a given Agency will invest into novel capabilities only if these capabilities respond to identified needs that can be derived from this agency's mission model, but not just for the sake of being able to provide cross support to another agency.*

Recommendation R-10: *In order to maximize the chances of being able to provide mutual cross support, the IOAG agencies should strive for agreeing on a common approach for Lunar and Martian missions whenever technically feasible.*

Recommendation R-11: *In support of envisioned Lunar, Mars and Near Earth missions, the IOAG agencies should embark on the development of an agreed-to cross-supportable internetworking architecture.*

Finding F-10: *Considering the well-established benefits from the ubiquitous terrestrial adoption of internetworking and <u>considering the plans for NASA's Constellation program[xli]</u> to further mature internetworking technology for space-borne applications, it is likely that the technology is ready for application to spaceflight missions, and it will bring benefits to those missions.*

Finding F-11: *Missions (programs and projects) are very conservative, and the burden of moving to a new technology must be driven by management, standards organizations, and infrastructure programs.*

Finding F-12: *The drive towards international cooperative missions, with increasing cost, increasing technical complexity, and increasing need to share data and assets, is in itself a driver towards space internetworking.*

Recommendation R-12: *The IOAG agencies should develop a consensus that space internetworking is an important new approach that the agencies are ready to move from concept to implementation. An international collaborative program should be instituted to prepare the technology for usage by missions (programs and projects).*

Finding F-13: *The IOAG should encourage the space agencies to extend their current ground-based cross support services into space via the build-up of re-usable in-space communications and navigation service infrastructure, with a view towards its becoming an enabling capability for new international space mission initiatives. Such infrastructure includes space-based data relays and planetary surface communications facilities that are united via their provision of common, interoperable services using CCSDS standards.*

Recommendation R-13: *The IOAG should ask the CCSDS to accelerate the creation of an overall Cross-Support Service Architecture that extends the current terrestrial services by defining the services offered by in-space infrastructure as well as their associated profiles of data communications and service management standards.*

Finding F-14: *Given that DTN is the only candidate protocol that is approaching the level of maturity required to handle the disconnection and delays inherent in space operations, future in-space cross support should be based on a DTN-routed architecture, interconnecting local "islands" of IP connectivity.*[xlii]

Recommendation R-14: *The SISG recommends that the IOAG/CCSDS should embark upon a program of DTN technology and standards development.*

Recommendation R-15: *Multiple access single-point to single-point modulation and coding techniques should be identified and codified as CCSDS standards for use in the near-Earth, Moon-to-Earth and Mars-to-Earth environments.*

Recommendation R-16: *Multiple access multiple-point to multiple-point modulation and coding techniques should be identified, adopted and codified as CCSDS standards for use between closely spaced in-space elements and for local planetary surface mesh communications.*

Recommendation R-17: *The CCSDS Encapsulation Packet should be adapted to provide a standard convergence layer to support end-to-end network connectivity required by the Internet Packet and DTN Bundle.*

Recommendation R-18: *Standards for multiple access data link establishment and management should be developed, adopted and codified within the CCSDS family of data link protocols.*

Recommendation R-19: *The CCSDS should identify, adopt and codify standards for structuring space communications infrastructure relay nodes to support native IP and native DTN services as well as providing bridging between DTN, IP and Space Packet at the network end-points.*

Recommendation R-20: *A common method for assigning and managing IP and DTN address spaces should be established for the Solar System Internetwork.*

Recommendation R-21: *A method for addressing and delivering CCSDS Space Packets should be established to ensure reverse support of Space Packet in the Solar System Internetwork.*

Recommendation R-22: *The CCSDS should identify and adopt a set of well defined router configuration and status parameters that must be exchanged between networks of space agencies providing cross-support as a node of the SSI.*

Recommendation R-23: *The IOAG should identify and adopt a set of well defined network routing behaviors that will be cross-supported in order to provide necessary end-to-end route management and execution between the nodes comprising the Solar System Internetwork (SSI).*

Recommendation R-24: *The IOAG should establish and coordinate a body responsible for management and administration of the cross-supported SSI name and address spaces.*

Recommendation R-25: *The CCSDS should identify and adopt a set of well defined approaches for defining, determining and exchanging communications capability and current/future availability information needed to build a distributed understanding of the "next best hop" component of the network route.*

Recommendation R-26: *The CCSDS should identify and adopt a set of well defined quality of service attributes and identifying parameters that must be exchanged and respected between networks of space agencies providing cross-support as a node of the SSI.*

Recommendation R-27: *The IOAG should identify and adopt a set of internetworking quality-of-service cross-support agreements to ensure that functional elements of various agencies acting as nodes of the SSI respect QoS attributes and provide QoS behaviors in a consistent manner.*

Recommendation R-28: *The IOAG should identify the appropriate level of command and control interoperability needed to support multinational joint operations of human and robotic assets.*

Recommendation R-29: *The CCSDS should identify and adopt a set of well-defined mechanisms for exchanging the definitions of command/control data sufficient to allow joint/collaborative command/control of a heterogeneous set of multinational assets*[xliii]

Recommendation R-30: *The CCSDS should identify and adopt a set of well-defined mechanisms (e.g., mediators/adaptors) to enable in-situ and remote interoperability between multinational human and robotic missions choosing to implement different, but approved, CCSDS standards. At a minimum, should include voice, video, data (health & safety, caution/warning, state and status), commands, and files).*

Recommendation R-31: ***Recommendation****: The CCSDS should identify and adopt a set of well-defined mechanisms and standards which will allow systems to interoperably define and enforce the rights and privileges that one asset has on another.*[xliv]

Finding F-15: *A specification for the Space Internetworking Architecture must be developed as the basis for future bilateral agreements between cooperating space agencies.*

Recommendation R-32: *The IOAG should direct the CCSDS to develop the Space Internetworking Architecture document as a Recommended Practice or Recommended Standard, and the IOAG strike an agreement among the IOAG agencies that the specification will be the basis for bilateral agreements between cooperating agencies.*

Recommendation R-33: *The IOAG or a designated sub-team should study the potential need for additional governance mechanisms which should be agreed to between the IOAG agencies for cases where operational concepts for internetworking drive common operational needs (allocation of common addresses, routing* *operations, etc.) and for situations where multilateral agreements (versus bilateral agreements) may be most effective.*

Appendix F: Ongoing Projects in Internetworking within the IOAG agencies

ESA

ESA DTN / IP Testbed Implementation and Evaluation

- Project Coordinator: HAI S.A. (Hellenic Aerospace Industries)
- Technical/Scientific Leader: Vassilis Tsaoussidis, Democritus, University of Thrace
- Schedule:
    - Testbed Requirements Phase Jan 09
    - Design Engineering Phase Jan 10
    - Validation and Assessment Phase Mar 10

In-orbit and Ground tests to compare CCSDS and IP based protocols

- Project Coordinator: University of Wuerzburg, Germany
- Schedule:
    - Final Report Feb 09

ESA Ground Segment Data System Architecture to support CFDP, DTN, IP

- ITT to be issued soon
- Schedule:
    - KO: Feb 09 End: April 10

Security in DTN

- To be confirmed. Potential ITT issued during Q4 2009

Space internetworking

- ITT to be issued Q1 2009 1 year duration

Study on Disruptive Tolerant Networks (DTN) integration with satellite networks

- Study by Telecoms Department to be initiated in 2009 18 months duration

RASTA Test bed

- Generic test-bed with existing CCSDS protocol stacks and already used for
- CFDP prototyping and reference.
- Will be made generally available for all related network prototyping.

NASA

NASA Space DTN Readiness Project

- Wide variety of flight and ground demonstrations intended to elevate DTN technology readiness level to TRL9 by 2011.
- Deep Impact Flight Demo – October 2008 (COMPLETED)
- TDRSS DTN Demo – 4Q FY09
- Bioserve DTN-on-ISS demo
    - 1st flight demo – 3Q FY09
    - 2nd flight demo – 4Q FY10
    - Bioserve final results – 4Q FY11
- Various Return On Investment (ROI) experiments: 2009-2011

OMNI (Operating Missions as Nodes on the Internet) Project

- CANDOS experiment completed January 2003 on Shuttle flight STS-117

Constellation Program (CxP)

- The NASA Constellation Program is a major agency-wide program to replace Shuttle access to ISS and also conduct manned missions to the Moon and beyond.
- The CxP is developing space internetworking not as a development project, but as a fully operation capability for all program spacecraft and facilities.
- The CxP is intending to develop international partner capabilities which will require interentworking, and they plan to do that with extensive use of CCSDS recommended standards and practices.
- Internetworking capabilities are developed in phases and block builds which are too complex and extensive to be listed here.

Appendix G: The Scenario Template Table

Scenario Template Instantiations

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Trajectory Type	LEO			
Frequency Band DFE	S-band	S-band	S-band	S-band
Frequency Band DTE	S and/or X for TT&C, X for payload data return link	S and/or X for TT&C, X for payload data return link	S and/or X for TT&C, X for payload data return link	S and/or X for TT&C, X or Ka for payload data return link
Frequency Band In Space Link	S or Ka-band (26 GHz) or optical (848 nm) for payload data to GEO relay	S or Ka-band (26 GHz) or optical (848 nm) for payload data to GEO relay	Ka-band (26 GHz) or optical (848 nm) for payload data to GEO relay	Ka-band (26 GHz) or optical (848 nm) for payload data to GEO relay
Frequency Band Relay – Earth Link	27.5 – 30.0 GHz fwd 18.1 – 20.2 GHz rtn	27.5 – 30.0 GHz fwd 18.1 – 20.2 GHz rtn	27.5 – 30.0 GHz fwd 18.1 – 20.2 GHz rtn	27.5 – 30.0 GHz fwd 18.1 – 20.2 GHz rtn
Modulation Scheme DFE	Remnant carrier w/ subcarrier for TT&C	Remnant carrier w/ or w/o subcarrier for TT&C	Remnant carrier w/ or w/o subcarrier for TT&C	Remnant carrier w/ or w/o subcarrier for TT&C
Modulation Scheme DTE	Remnant carrier w/ and w/o subcarrier or QPSK for TT&C, suppressed carrier (QPSK and 8PSK) for high rate payload data	Remnant carrier w/ and w/o subcarrier or QPSK for TT&C, suppressed carrier (QPSK and 8PSK) for high rate payload data	Remnant carrier w/ and w/o subcarrier or QPSK for TT&C, suppressed carrier (8PSK – 16APSK VCM) for high rate payload data	Remnant carrier w/ and w/o subcarrier or QPSK for TT&C, suppressed carrier (8PSK – 16 APSK VCM) for high rate payload data

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Modulation Scheme In Space Link	QPSK	QPSK	8PSK – 16APSK VCM	8PSK – 16APSK VCM
Modulation Scheme Relay – Earth Link	QPSK	QPSK	8PSK – 16APSK VCM	8PSK – 16APSK VCM
Coding DFE	BCH	BCH	BCH	BCH
Coding DTE	concatenated for TT&C, none or (255,239) RS for payload data	concatenated for TT&C, none or (255,239) RS for payload data	concatenated for TT&C, (255,239) RS or LDPC or long erasure codes for payload data	concatenated for TT&C, (255,239) RS or LDPC or long erasure codes for payload data
Coding In Space Link	none or (255,239) RS for payload data	none or (255,239) RS for payload data	(255,239) RS or LDPC or long erasure codes for payload data	(255,239) RS or LDPC or long erasure codes for payload data
Coding Relay – Earth Link	none or (255,239) RS for payload data	none or (255,239) RS for payload data	(255,239) RS or LDPC or long erasure codes for payload data	(255,239) RS or LDPC or long erasure codes for payload data
Forward Symbol Rates	Forward link max. 20ks/s	Forward link max. 100ks/s[1]	Forward link max. 100ks/s	Forward link max. 100ks/s
Return Symbol Rates	TT&C return link up to 1 Ms/s, payload return link some 200 Mb/s	TT&C return link up to 1 Ms/s, payload return link some 200 Mb/s	TT&C return link up to 1 Ms/s, payload return link some 400 Mb/s	TT&C return link up to 1 Ms/s, payload return link some 600 Mb/s
Forward Space Link Protocol(s)	Conventional packet TC	Conventional packet TC	Conventional packet TC, file transfer (reliable CFDP)	Conventional packet TC, file transfer (reliable CFDP)

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[1] At rates in this order the latency in particular when not closing the loop at the termination point of the space link, but in the control center COP-1 most likely will not be feasible and other means outside the scope of conventional packet TC will have to be used to achieve reliability.

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Return Space Link Protocol(s)	Conventional packet TM for HK, AOS framing for payload data return link	Conventional packet TM for HK, AOS framing for payload data return link, file transfer (CFDP)	Conventional packet TM for HK AOS framing for payload data return link, file transfer (CFDP)	Conventional packet TM for HK, AOS framing for payload data return link, file transfer (CFDP)
Navigation Technologies	Auto-track angles, one- or two-way Doppler, tone/code ranging, GPS, DORIS, special-to-type payload data products	Auto-track angles, one- or two-way Doppler, tone/code and CCSDS PN ranging (transparent), GPS, DORIS, GALILEO, special-to-type payload data products	Auto-track angles, one- or two-way Doppler, tone/code and CCSDS PN ranging (transparent), GPS, DORIS, GALILEO, special-to-type payload data products	Auto-track angles, one- or two-way Doppler, tone/code and CCSDS PN ranging (transparent), GPS, DORIS, GALILEO, special-to-type payload data products
No. of constituent networks	1 plus terrestrial networks	1 plus terrestrial networks	2 plus terrestrial networks	2 plus terrestrial networks
Types of constituent networks: Earth-based tracking network, Space-based local network, Surface local network, Terrestrial network	Earth-based tracking network: CNES, NASA GN, ESTRACK Space-based local network NASA SN, Artemis Terrestrial networks	Earth-based tracking network: CNES, NASA GN, ESTRACK Space-based local network NASA SN, ESA DRS Terrestrial networks	Earth-based tracking network: CNES, NASA GN, ESTRACK Space-based local network NASA SN, ESA DRS Terrestrial networks	Earth-based tracking network: CNES, NASA GN, ESTRACK Space-based local network NASA SN, ESA DRS Terrestrial networks
No. of alternate paths: Diversity of end-to-end paths	DTE Via GEO relay	DTE Via GEO relay	DTE Via GEO relay	DTE Via GEO relay

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Relay Technology	GEO Relay with S/Ka-band or optical in-orbit link and Ka-band to Earth link	GEO Relay with S/Ka-band or optical in-orbit link and Ka-band to Earth link	GEO Relay with Ka-band or optical in-orbit link and Ka-band to Earth link	GEO Relay with Ka-band or optical in-orbit link and Ka-band to Earth link
Persistency of end-to-end connectivity	Episodic or Persistent, depending on the relay network	Episodic or Persistent, depending on the relay network	Episodic or Persistent, depending on the relay network	Episodic or Persistent, depending on the relay network
Existence of in-space network	GEO DRS	GEO DRS	GEO DRS	GEO DRS
Grades of Services - QoS	No explicit end-to-end QoS	No explicit end-to-end QoS	No explicit end-to-end QoS, except where ensured by file transfer mechanism	No explicit end-to-end QoS, except where ensured by file transfer mechanism
Latency of end-to-end data delivery	Medium latency (max orbital period plus ground comms) Low latency with complete GEO relay network	Medium latency (max orbital period plus ground comms) Low latency with complete GEO relay network	Medium latency (max orbital period plus ground comms) Low latency with complete GEO relay network	Medium latency (max orbital period plus ground comms) Low latency with complete GEO relay network
Reliability of end-to-end data delivery	95% - 98%	95% - 98%	100%, except in case of catastrophic failures	100%, except in case of catastrophic failures
Aggregate throughput of the in-space network	Up to 450 Mb/s	Up to 450 Mb/s	Up to 600Mb/s	Up to 600 Mb/s
Connectivity topology with Earth: DTE, trunk line	DTE	DTE	DTE	DTE

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Methods of data staging by in-space network: bent-pipe or store-& forward	Bent pipe	Bent pipe	Bent pipe	Bent pipe
Modes of end-to-end data transfer: stream mode, file mode, messaging	Stream mode	Stream mode File mode	Stream mode File mode	Stream mode File mode
Heterogeneity of the space internetwork: data link layer	CCSDS (for space-Earth link & in-space link)	CCSDS (for space-Earth link & in-space link)	CCSDS (for space-Earth link & in-space link)	CCSDS (for space-Earth link & in-space link)
Heterogeneity of the space internetwork: physical layer	RF Optical (in-space link only)	RF Optical (in-space link only)	RF Optical (in-space link only)	RF Optical (in-space link only)
Cooperating agencies for in-space network	JAXA and ESA	JAXA and ESA	JAXA and ESA	?
Cooperating agencies for Earth-based tracking network	CNES, JAXA and ESA	CNES, JAXA and ESA	JAXA and ESA	?
Nature of space relay satellite: dedicated, piggy-back, primary / secondary / extended mission	Dedicated relay satellite(s)	Dedicated relay satellite(s)	Dedicated relay satellite(s)	Dedicated relay satellite(s)

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Nature of surface relay: dedicated, shared, fixed, mobile, …	N/A	N/A	N/A	N/A
Terrestrial Cross Support Interfaces (TT&C only)	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management
Terrestrial Cross Support Services (TT&C only)[2]	SLE RAF, RCF, ROCF, CLTU; Radiometric Data (TDM) delivery, ad-hoc (mostly manual) service management (incl. ODM transfer); ad-hoc navigation	SLE transitioning to network layer (i.e. packet services FSP and RSP, Space Link Monitor Data, Radiometric Data delivery, Automated Bilateral or CCSDS Service Management	X-support FSP, RSP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management	X-support FSP, RSP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management
In Space Cross Support Interfaces	Spacecraft - Relay	Spacecraft – Relay	Spacecraft – Relay	Spacecraft – Relay
In Space Cross Support Services	Bent pipe	Bent pipe	Bent pipe	Bent pipe

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[2] Note: Due to the very high rate payload data return link, it is assumed that this interface will not be part of cross support arrangements. The payload data will be pre-processed at the termination point of the return link (e.g. transcribed to storage media that will then be mailed. This also applies to the termination point of the relay satellite payload data return link.

Mission Type	Earth Observation Missions (excluding geostationary satellites)			
	Today	2015	2020	2025
Cross Support Network Topology Complexity[3]	Low	Low	Low to medium	Low to medium
Security Requirements	Ground communications and payload data confidentiality (some missions)	Ground communications and payload data confidentiality	Ground communications; TC integrity and possibly authentication, confidentiality of all return link data	Ground communications; TC integrity and possibly authentication, confidentiality of all return link data
Cross Support Needs	Ground Coverage extension, mission safety	Ground Coverage extension, mission safety	Ground Coverage extension, mission safety, (near) real time payload data acquisition and distribution	Ground Coverage extension, mission safety, (near) real time payload data acquisition and distribution

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[3] Taking into account the data relay return link the complexity might be considered medium, however, it is assumed her that the payload data rate requires special measures in any case and enhanced routing capabilities will not help.

Mission Type	Lunar Missions			
	Today	2015	2020	2025
Trajectory Type	Moon Orbiter or Lander			
Frequency Band DFE	S and X	S and X	S and Ka (23 GHz)	S and Ka (23 GHz)
Frequency Band DTE	S and X	S, X and Ka (26 GHz)	S and Ka (26 GHz)	Ka (26 and 38/40 GHz)
Frequency Band In Space Link	N/A	N/A	VHF or S for moon relay	S for moon relay
Frequency Band Relay – Earth Link	N/A	N/A	Ka 37/40 GHz for moon relay trunk line, S for contingency	Ka 37/40 GHz for moon relay trunk line, S for contingency
Modulation Scheme DFE	Remnant carrier w/ subcarrier	Remnant carrier w/ subcarrier and w/o subcarrier, BPSK,QPSK, DSSS[4]	BPSK,QPSK, DSSS	BPSK,QPSK, DSSS
Modulation Scheme DTE	Remnant carrier w/ and w/o subcarrier for TT&C, suppressed carrier (QPSK) for high rate payload data	Remnant carrier w/ and w/o subcarrier for TT&C, suppressed carrier (GMSK) for high rate payload data	BPSK,QPSK, DSSS	BPSK,QPSK, DSSS
Modulation Scheme In Space Link	N/A	N/A	remnant carrier w/o subcarrier for the moon relay, DSSS (S-band)	remnant carrier w/o subcarrier for the moon relay, DSSS (S-band)

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[4] Attribute values with yellow background color reflect the input provided by a single agency and therefore it might be difficult to obtain cross support commensurate with such attribute values.

Mission Type	Lunar Missions			
	Today	2015	2020	2025
Modulation Scheme Relay – Earth Link	N/A	N/A	BPSK, QPSK, DSSS	BPSK, QPSK, DSSS
Coding DFE	BCH	BCH or LDPC	LDPC	LDPC
Coding DTE	Concatenated	Concatenated, turbo, LDPC	Turbo or LDPC, long erasure codes for payload data	Turbo or LDPC, long erasure codes for payload data
Coding In Space Link	N/A	N/A	Convolutional, LDPC	Convolutional, LDPC
Coding Relay – Earth Link	N/A	N/A	LDPC	LDPC
Forward Symbol Rates	Up to. 4ks/s	Up to 1 Mb/s	Up to 100 Mb/s	Up to 100 Mb/s
Return Symbol Rates	TT&C return link few ks/s, payload return link up to 10 Mb/s	Up to 150 Mb/s	Up to 250 Mb/s	Up to 250 Mb/s
Forward Space Link Protocol(s)	Conventional packet TC	Conventional packet TC, AOS, encapsulation service	Conventional packet TC (including low level emergency commanding), AOS, modified CFDP and AMS over DTN	Conventional packet TC (including low level emergency commanding),, AOS, modified CFDP and AMS over DTN
Return Space Link Protocol(s)	Conventional packet TM, AOS framing for payload data	Conventional packet TM, AOS framing	Conventional packet TM, AOS framing, AMS and modified CFDP over DTN	Conventional packet TM, AMS and modified CFDP over DTN
Navigation Technologies	Doppler, tone/code ranging	Doppler, tone/code and SNIP PN ranging	Doppler, SNIP PN ranging	Doppler, SNIP PN ranging

Mission Type	Lunar Missions			
	Today	2015	2020	2025
No. of constituent networks	CNSA ESA: 2 plus terrestrial networks JAXA NASA: 2 plus terrestrial networks ISRO NASA: 2 plus terrestrial networks	?	?	?
Types of constituent networks: Earth-based tracking network, Space-based local network, Surface local network, Terrestrial network	Earth-based tracking network: CNSA, DSN, ESTRACK, ISRO, JAXA Terrestrial networks	NASA SN Earth-based tracking network: CNSA, DSN, ESTRACK, ISRO, JAXA Terrestrial networks	NASA SN NASA and other moon relays Earth-based tracking network: CNSA, DSN, ESTRACK, ISRO, JAXA Terrestrial networks	NASA SN NASA and other moon relays Earth-based tracking network: CNSA, DSN, ESTRACK, ISRO, JAXA Terrestrial networks
No. of alternate paths: Diversity of end-to-end paths	N/A (DTE/DFE)	DTE/DFE Possibly surface to surface relay	DTE/DFE or moon relay network Possibly surface to surface relay	Fully networked
Relay Technology	N/A	N/A	Moon relay network for landed assets and science orbiters	Bent pipe and store and forward
Persistency of end-to-end connectivity	Episodic, non-persistent	Episodic, non-persistent	Highly persistent	Persistent
Existence of in-space network	N/A	N/A	Moon orbiting relay network	yes
Grades of Services - QoS	No explicit end-to-end QoS	No explicit end-to-end QoS	Explicit end-to-end QoS	Explicit end-to-end QoS

Mission Type	Lunar Missions			
	Today	2015	2020	2025
Latency of end-to-end data delivery	Low to medium	Low to medium	low	low
Reliability of end-to-end data delivery	95% - 98%	95% - 98%	100%, except in case of a catastrophic failure	100%, except in case of a catastrophic failure
Aggregate throughput of the in-space network	N/A	N/A	100 Mb/s	500 Mb/s
Connectivity topology with Earth: DTE, trunk line	DTE/DFE	DTE/DFE	DTE/DFE Trunk line	Trunk line
Methods of data staging by in-space network: bent-pipe or store-& forward	N/A	N/A	Bent pipe Store-&-forward	Bent pipe Store-&-forward
Modes of end-to-end data transfer: stream mode, file mode, messaging	Stream mode	Stream mode File mode	Stream mode File mode Messaging mode for inter-Moon comm	Stream mode File mode Messaging mode for inter-Moon comm
Heterogeneity of the space internetwork: data link layer	N/A	N/A	CCSDS (for space-Earth link & proximity link), CDMA DSSS	CCSDS (for space-Earth link & proximity link), CDMA DSSS
Heterogeneity of the space internetwork: physical layer	RF only	RF only	RF Possibly optical for space-Earth link	RF Possibly optical for space-Earth link

Mission Type	Lunar Missions			
	Today	2015	2020	2025
Cooperating agencies for in-space network	N/A	N/A	?	?
Cooperating agencies for Earth-based tracking network	CNSA and ESA JAXA and NASA ISRO and NASA	NASA and ESA RKO and CNSA	NASA and ESA	NASA and ESA
Nature of space relay satellite: dedicated, piggy-back, primary / secondary / extended mission	N/A	N/A	dedicated	dedicated
Nature of surface relay: dedicated, shared, fixed, mobile, …	None	N/A	Fixed, shared	Fixed, dedicated
Terrestrial Cross Support Interfaces	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management
Terrestrial Cross Support Services	SLE RAF, RCF, CLTU; ad-hoc (mostly manual) service management; ad-hoc navigation	CSTS RAF/FCLTU, FSP, RSP, IP, Space Link Monitor Data, Radiometric Data, Automated Bilateral or CCSDS Service Management	File or AMS over IP or DTN bundle, IP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management	File or AMS over IP or DTN bundle, IP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management

Mission Type	Lunar Missions			
	Today	2015	2020	2025
In Space Cross Support Interfaces	None	None	Moon lander – Moon Relay, Moon orbiter – Moon Relay, on surface lander - lander	Vehicle to moon network
In Space Cross Support Services	None	N/A	Space Packet relay (enabling low level emergency commanding), DTN bundle	Space Packet relay (enabling low level emergency commanding), DTN bundle
Cross Support Network Topology Complexity	N/A	Low	Medium	High
Security Requirements	Hardly any except at the level of ground communications	TM confidentiality	TC integrity, TM confidentiality, human rated	TC integrity, TM confidentiality
Cross Support Needs	Ground Coverage extension, mission safety	Ground and moon coverage extension, mission safety	Ground and moon coverage extension, mission safety	Ground and moon coverage extension, mission safety

Mission Type	DTE/DFE Science Missions			
	Today	2015	2020	2025
Trajectory Type	Highly elliptic EO, Lagrange Point, interplanetary			
Frequency Band DFE	S or X	S or X	X	X
Frequency Band DTE	S and/or X	S (?), X and Ka	X and Ka	X and Ka
Frequency Band In Space Link	N/A	N/A	N/A	N/A
Frequency Band Relay – Earth Link	N/A	N/A	N/A	N/A
Modulation Scheme DFE	Remnant carrier w/ subcarrier	Remnant carrier w/ and w/o subcarrier,	Remnant carrier w/ subcarrier and w/o subcarrier, suppressed carrier (BPSK)	Remnant carrier w/ subcarrier and w/o subcarrier, suppressed carrier (BPSK)
Modulation Scheme DTE	Remnant carrier w/ and w/o subcarrier	Remnant carrier w/ and w/o subcarrier, GMSK	Remnant carrier w/ and w/o subcarrier, GMSK	Remnant carrier w/ and w/o subcarrier, GMSK
Modulation Scheme In Space Link	N/A	N/A	N/A	N/A
Modulation Scheme Relay – Earth Link	N/A	N/A	N/A	N/A
Coding DFE	BCH	BCH	BCH, TBD coding scheme for high rate forward link	BCH, TBD coding scheme for high rate forward link

Mission Type	DTE/DFE Science Missions			
	Today	2015	2020	2025
Coding DTE	concatenated	Concatenated, turbo	Concatenated, turbo, LDPC	LDPC, long erasure codes
Coding In Space Link	N/A	N/A	N/A	N/A
Coding Relay – Earth Link	N/A	N/A	N/A	N/A
Forward Symbol Rates	Up to 4ks/s	Up to 4ks/s w/ subcarrier Up to 256 ks/s w/o subcarrier	Up to 4ks/s w/ subcarrier Up to 256 ks/s w/o subcarrier Up to 1 Ms/s with suppressed carrier	Up to 4ks/s w/ subcarrier Up to 256 ks/s w/o subcarrier Up to 1 Ms/s with suppressed carrier
Return Symbol Rates	S: up to 1 Ms/s X: up to 10 Ms/s	S: up to 2 Ms/s X: up to 10 Ms/s Ka: 1 Ms/s	S: up to 2 Ms/s X: up to 10 Ms/s Ka: ?	S: up to 2 Ms/s X: up to 10 Ms/s Ka: ?
Forward Space Link Protocol(s)	Conventional packet TC	Conventional packet TC (including low level emergency commanding) CFDP	Conventional packet TC (including low level emergency commanding) CFDP	Conventional packet TC (including low level emergency commanding) CFDP
Return Space Link Protocol(s)	Conventional packet TM AOS space data link	Conventional packet TM AOS space data link CFDP	Conventional packet TM AOS space data link CFDP	Conventional packet TM AOS space data link CFDP
Navigation Technologies	Auto-track angles, Doppler, tone/code and proprietary PN ranging, ΔDOR	Auto-track angles, Doppler, tone/code and CCSDS PN ranging, ΔDOR, SBI	Auto-track angles, Doppler, tone/code and CCSDS PN ranging, ΔDOR, SBI	Auto-track angles, Doppler, tone/code and CCSDS PN ranging, ΔDOR, SBI

Mission Type	DTE/DFE Science Missions			
	Today	2015	2020	2025
No. of constituent networks	1 to x plus terrestrial networks	1 to x plus terrestrial networks	1 to x plus terrestrial networks	1 to x plus terrestrial networks
Types of constituent networks: Earth-based tracking network, Space-based local network, Surface local network, Terrestrial network	Earth-based tracking networks Terrestrial networks	Earth-based tracking networks Terrestrial networks	Earth-based tracking networks Terrestrial networks	Earth-based tracking networks Terrestrial networks
No. of alternate paths: Diversity of end-to-end paths	Typically one, but more than one tracking network may be in view at a given time	Typically one, but more than one tracking network may be in view at a given time	Typically one, but more than one tracking network may be in view at a given time	Typically one, but more than one tracking network may be in view at a given time
Relay Technology	N/A	N/A	N/A	N/A
Persistency of end-to-end connectivity	Typically non-persistent	Typically non-persistent	Typically non-persistent	Typically non-persistent
Existence of in-space network	N/A	N/A	N/A	N/A
Grades of Services - QoS	No explicit end-to-end QoS	No explicit end-to-end QoS	Explicit end-to-end QoS	Explicit end-to-end QoS
Latency of end-to-end data delivery	Medium to high latency	Medium to high latency	Medium to high latency	Medium to high latency
Reliability of end-to-end data delivery	95% - 98%	95% - 98%	100%, except in case of a catastrophic failure	100%, except in case of a catastrophic failure

Mission Type	DTE/DFE Science Missions			
	Today	2015	2020	2025
Aggregate throughput of the in-space network	N/A	N/A	N/A	N/A
Connectivity topology with Earth: DTE, trunk line	DTE/DFE	DTE/DFE	DTE/DFE	DTE/DFE
Methods of data staging by in-space network: bent-pipe or store-& forward	N/A	N/A	N/A	N/A
Modes of end-to-end data transfer: stream mode, file mode, messaging	Stream mode	Stream mode File mode	Stream mode File mode	Stream mode File mode
Heterogeneity of the space internetwork: data link layer	N/A	N/A	N/A	N/A
Heterogeneity of the space internetwork: physical layer	N/A	N/A	N/A	N/A
Cooperating agencies for in-space network	N/A	N/A	N/A	N/A
Cooperating agencies for Earth-based tracking network	Many to many	Many to many	Many to many	Many to many

Mission Type	DTE/DFE Science Missions			
	Today	2015	2020	2025
Nature of space relay satellite: dedicated, piggy-back, primary / secondary / extended mission	N/A	N/A	N/A	N/A
Nature of surface relay: dedicated, shared, fixed, mobile, …	N/A	N/A	N/A	N/A
Terrestrial Cross Support Interfaces	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; NAV-NAV; Service Management – Service Management
Terrestrial Cross Support Services	SLE RAF, RCF, CLTU; ad-hoc (mostly manual) service management; ad-hoc navigation	X-support FSP, RSP, Space Link Monitor Data, Radiometric Data (TDM), Automated Bilateral or CCSDS Service Management (including ODM transfer)	X-support FSP, RSP, CFDP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management	X-support FSP, RSP, CFDP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management
In Space Cross Support Interfaces	N/A	N/A	N/A	N/A
In Space Cross Support Services	N/A	N/A	N/A	N/A

Mission Type	DTE/DFE Science Missions			
	Today	2015	2020	2025
Cross Support Network Topology Complexity	Very low	Low	Low	Low
Security Requirements	Hardly any except at the level of ground communications	Ground communications	TC integrity, TM confidentiality	TC integrity, TM confidentiality
Cross Support Needs	Ground Coverage extension, mission safety	Ground Coverage extension, mission safety	Ground Coverage extension, mission safety	Ground Coverage extension, mission safety

Mission Type	Mars Missions			
	Today	2015	2020	2025
Trajectory Type	Mars Orbiters with science and data relay payload, Landed Assets, Dedicated Data Relay Orbiters			
Frequency Band DFE	(S), X	X, Ka for radio science	X, Ka for radio science	X, Ka
Frequency Band DTE	(S), X	X, Ka for radio science	X, Ka	X, Ka
Frequency Band In Space Link	UHF	UHF	UHF, X, optical	UHF, X, optical
Frequency Band Relay – Earth Link	X	X	X and Ka	X and Ka
Modulation Scheme DFE	Remnant carrier w/ subcarrier	Remnant carrier w/ subcarrier	Remnant carrier w/ and w/o subcarrier	Remnant carrier w/ and w/o subcarrier, suppressed carrier (BPSK)
Modulation Scheme DTE	Remnant carrier w/ and w/o subcarrier	Remnant carrier w/ and w/o subcarrier, GMSK	Remnant carrier w/ and w/o subcarrier, GMSK, 16APSK	Remnant carrier w/ and w/o subcarrier, GMSK, 16APSK
Modulation Scheme In Space Link	Remnant carrier w/o subcarrier	Remnant carrier w/o subcarrier	Remnant carrier w/o subcarrier	Remnant carrier w/o subcarrier
Modulation Scheme Relay – Earth Link	Remnant carrier w/ and w/o subcarrier	Remnant carrier w/ and w/o subcarrier, GMSK	Remnant carrier w/ and w/o subcarrier, GMSK, 16APSK	Remnant carrier w/ and w/o subcarrier, GMSK, 16APSK
Coding DFE	BCH	BCH	BCH, TBD advanced coding for higher rate uplink, long erasure codes	BCH, LDPC, long erasure codes

Mission Type	Mars Missions			
	Today	2015	2020	2025
Coding DTE	Concatenated, turbo	Concatenated, turbo, LDPC	Turbo, LDPC, long erasure codes	Turbo, LDPC, long erasure codes
Coding In Space Link	convolutional	convolutional	convolutional	convolutional
Coding Relay – Earth Link	Concatenated, turbo	Concatenated, turbo, LDPC	Turbo, LDPC	Turbo, LDPC, long erasure codes
Forward Symbol Rates	Up to 4ks/s	Up to 4 ks/s w/ subcarrier Up to 256 ks/s w/o subcarrier	Up to 4 ks/s w/ subcarrier Up to 256 ks/s w/o subcarrier	Up to 4 ks/s w/ subcarrier Up to 256 ks/s w/o subcarrier
Return Symbol Rates	Up to 6 Ms/s (max 4 Ms/s via relay)	Up to 6 Ms/s (max 4 Ms/s via relay)	Up to 12 Ms/s (max 4 Ms/s via relay)	Up to 12 Ms/s (max 4 Ms/s via relay)
Forward Space Link Protocol(s)	Conventional packet TC, Prox-1 for relay link	Conventional packet TC, unacknowledged CFDP Prox-1 for relay link	Conventional packet TC (including low level emergency commanding), Prox-1/2 for relay link with packet service, Reliable e2e CFDP (extended procedures)	Conventional packet TC as backup (including low level emergency commanding), modified reliable CFDP over DTN-BP and LTP
Return Space Link Protocol(s)	Conventional packet TM or AOS, unacknowledged CFDP, Prox-1 for relay link	Conventional packet TM or AOS, unacknowledged CFDP, Prox-1 for relay link	Conventional packet TM or AOS framing, reliable e2e CFDP (extended procedures) Prox-1/2 for relay link with packet service	Conventional packet TM as backup AOS framing for return link, modified reliable CFDP over DTN-BP and LTP

Mission Type	Mars Missions			
	Today	2015	2020	2025
Navigation Technologies	Doppler, tone/code ranging, ΔDOR, Prox-1 Doppler and ranging	Tone/code and CCSDS PN ranging, ΔDOR (with Ka DOR tones), Prox-1 Doppler and ranging, Single Beam Interferometry	Tone/code and PN ranging, ΔDOR (with Ka DOR tones), Prox-1/2 Doppler and ranging, Single Beam Interferometry	Tone/code and PN ranging, ΔDOR (with Ka DOR tones), Ka/Ka tracking data types, Prox-1/2 Doppler and ranging, Single Beam Interferometry
No. of constituent networks	3 plus terrestrial networks	NASA-ESA: 3 plus terrestrial networks RKO/CNSA: 1 plus terrestrial networks	NASA-ESA: 3 plus terrestrial networks	
Types of constituent networks: Earth-based tracking network, Space-based local network, Surface local network, Terrestrial network	Earth-based tracking network: DSN and ESTRACK Space-based local network: Mars “Network”; Terrestrial networks	Earth-based tracking network: DSN, ESTRACK, RKO network, CNSA network Space-based local networks: Mars “Network”; Phobos Grount Network Terrestrial networks	Earth-based tracking network: DSN, ESTRACK Space-based local networks: Mars “Network” Terrestrial networks	?

Mission Type	Mars Missions			
	Today	2015	2020	2025
No. of alternate paths: Diversity of end-to-end paths	Rover – Ody – DSN - MOC Rover – MEX – ESTRACK - MOC	Rover/lander – MRO – DSN - MOC Rover/lander – Scout'13 – DSN – MOC Phobos Lander – Phobos Orbiter – CNSA tracking network – RKO MOC	Rover – MRO – DSN - MOC Rover – MSO – DSN – MOC	
Relay Technology	UHF Prox-1; limited relay availability as pointing requirements on orbiter for science and relay operation are conflicting	UHF Prox-1; limited relay availability as pointing requirements on orbiter for science and relay operation are conflicting	Prox-1 and Prox-2 over X-band and/or optical; dedicated relays available	Prox-1 and Prox-2 over X-band and/or optical; dedicated relays available
Persistency of end-to-end connectivity	Episodic, non-persistent	Episodic, non-persistent	Episodic, non-persistent	?
Existence of in-space network	Mars "Network"	Mars "Network"; Phobos Grount "Network"	Mars "Network"	?
Grades of Services - QoS	No explicit end-to-end QoS	No explicit end-to-end QoS	Explicit end-to-end QoS	?
Latency of end-to-end data delivery	High latency	High latency	High latency	?
Reliability of end-to-end data delivery	95% - 98%	95% - 98%	100%, except in case of a catastrophic failure	100%, except in case of a catastrophic failure

Mission Type	Mars Missions			
	Today	2015	2020	2025
Aggregate throughput of the in-space network				
Connectivity topology with Earth: DTE, trunk line	DTE: rover – Earth DTE: science orbiter - Earth Trunk line: none	DTE: rover/Lander – Earth DTE: science orbiter - Earth Trunk line: none	DTE: rover/Lander – Earth DTE: science orbiter - Earth Trunk line: none	
Methods of data staging by in-space network: bent-pipe or store-& forward	Store-&-forward	Store-&-forward	Store-&-forward	
Modes of end-to-end data transfer: stream mode, file mode, messaging	Stream mode File mode	Stream mode File mode	Stream mode File mode Messaging mode for inter-Mars comm	
Heterogeneity of the space internetwork: data link layer	CCSDS (for space-Earth link & proximity link)	CCSDS (for space-Earth link & proximity link)	CCSDS (for space-Earth link & proximity link)	
Heterogeneity of the space internetwork: physical layer	RF only	RF only	RF Possible optical for space-Earth link	RF Possible optical for space-Earth link
Cooperating agencies for in-space network	NASA and ESA	NASA and ESA RKO and CNSA	NASA and ESA	

Mission Type	Mars Missions			
	Today	2015	2020	2025
Cooperating agencies for Earth-based tracking network	NASA and ESA RKO and ESA	NASA and ESA RKO and CNSA	NASA and ESA	
Nature of space relay satellite: dedicated, piggy-back, primary / secondary / extended mission	Piggy-back relay radio to science orviter	Piggy-back relay radio to science orbiter	Piggy-back relay radio to science orbiter	Piggy-back relay radio to science orbiter Dedicated relay satellite
Nature of surface relay: dedicated, shared, fixed, mobile, …	None	None	None	None
Terrestrial Cross Support Interfaces (TT&C only)	Spacecraft – Station; Station – MOC; Lander MOC-Relay MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; Lander MOC-Relay MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; Lander MOC-Relay MOC; NAV-NAV; Service Management – Service Management	Spacecraft – Station; Station – MOC; Lander MOC-Relay MOC; NAV-NAV; Service Management – Service Management
Terrestrial Cross Support Services (TT&C only)	SLE RAF, RCF, CLTU; ad-hoc (mostly manual) service management; ad-hoc navigation; ad hoc relay data file exchange; ad-hoc ancillary data file exchange	X-support FSP, RSP, Space Link Monitor Data, Radiometric Data, Automated Bilateral Service Management; standard interface for relay data file exchange	X-support FSP, RSP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management; end-to-end services via relay	X-support FSP, RSP, Space Link Monitor Data, Radiometric Data, CCSDS Service Management; end-to-end services via relay
In Space Cross Support Interfaces	Spacecraft - Relay	Spacecraft – Relay	Spacecraft – Relay; possibly Relay - Relay	Spacecraft – Relay; possibly Relay – Relay

Mission Type	Mars Missions			
	Today	2015	2020	2025
In Space Cross Support Services	User Defined Data Delivery; Open Loop Recording; Doppler and Time Tag Ranging	Space Packet Delivery; Open Loop Recording, Doppler and Time Tag Ranging Data delivery in standard file format	Space Packet Delivery; CFDP way point; Open Loop Recording, Doppler and Time Tag Ranging Data delivery in standard file format	Space Packet Delivery; simplified CFDP over DTN-BP and LDP; Open Loop Recording, Doppler and Time Tag Ranging Data delivery in standard file format
Cross Support Network Topology Complexity	Low	Low	Medium	Medium
Security Requirements	Hardly any except at the level of ground communications	Payload data confidentiality	TC integrity, confidentiality of all return link data	TC integrity, confidentiality of all return link data
Cross Support Needs	Ground Coverage extension, mission safety; extension data volume for landed assets	Ground Coverage extension, mission safety; extension data volume for landed assets	Ground Coverage extension, mission safety; extension data volume for landed assets	Ground Coverage extension, mission safety; extension data volume for landed assets

Appendix H: Errata/Clarifications

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[i] Some of these services, for example bidirectional space packets and cross-supported CFDP, may be obviated by the network-layer services the SISG has identified in phase-2 of its activities. For example, if CFDP is run over an internetwork service, then the cross-support requirement is for the internetwork service (layer) and not for the application layer (file transfer, for CFDP).

[ii] The Proximity-1 services are defined (possibly not in a clean way as a service), but are not or are only partially implemented by the existing radios.

[iii] Even though there are fewer lunar missions projected now than when this document was written, there is still a strong case for Earth-orbiting missions and Mars missions that will require network-centric operations.

[iv] As in the stated above in (iii), even though the Constellation Program is in flux, there is still a strong case for Earth-orbiting and Mars missions that will require network-centric operations.

[v] The SISG confirms that the CCSDS Encapsulation Packet shall serve as the standard convergence layer for access to CCSDS link layer protocols (packet TM/TC, AOS, Prox-1) to support the bi-directional transfer of IP packets and DTN Bundles.

As regards on-ground cross-support services required in support of this standard convergence layer, the SISG has now come to the conclusion that no cross-support at packet level is required. Exposed services that support multiplexing and demultiplexing at frame level provide the functionality needed.

Figure 61 (below) illustrates a cross-support scenario, where a DTN enabled User MOC needs to communicate with the User Spacecraft via a relay orbiter that is conventionally operated, e.g. using Space Packets on the basis of the ECSS Packet Utilization Standard (PUS) with a file transfer (FT) capability on top. The User MOC uses CFDP over the DTN Bundle Protocol (BP) for communication with the lander.

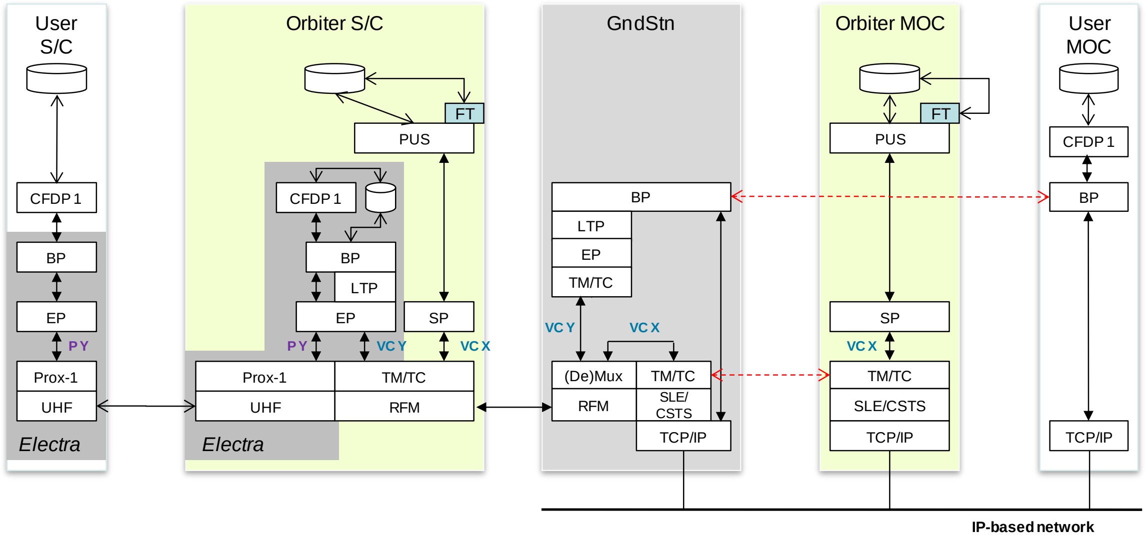


Figure 61: Scenario example: Enterprise view

Space Packets are shown in Figure 61 to travel in TC/TM frames, but AOS frames could be used as well. The ground station interface in the return direction can be based on the existing SLE RCF service, which supports both TM and AOS frames and allows the selection of a desired Virtual Channel. For the forward link, the SISG recommends that CCSDS defines an equivalent frame service (F-Frame). Today, the F-CLTU service would be used, which however supports neither a synchronous forward link as needed for AOS framing nor multiplexing of frames streams originating from different sources. The F-Frame service will provide both capabilities.

DTN Bundles travel directly on top of TCP between the User MOC and the Ground Station. At the Station, for the forward link the Bundles are wrapped into LTP segments which in turn are embedded into Encapsulation Packets. These Packets are then put into the frame type used on the given space link and then multiplexed with the frames originating from the Orbiter MOC. For frames received from the space link, the inverse process is applied.

[vi] It has been recognized that the document referred to in the text of this report as “SLE service management” does not provide the full set of required functions. The CCSDS is evolving a next-generation cross-support service management recommendation called Space Communication Cross Support Service Management that will provide the required services, and the SISG anticipates that it will be widely deployed.

[vii] In fact, due to the cross-support provided by SLE (CSTS), the ground station(s) in this example may belong to any agency.

[viii] As stated in (vi) above, it has been recognized that the document referred to in the text of this report as “SLE service management” does not provide the full set of required functions. The CCSDS is evolving a next-generation cross-support service management recommendation called Space Communication Cross Support Service Management that will provide the required services, and the SISG anticipates that it will be widely deployed.

[ix] Here "packet delivery services" refers to the internetworking layer in the SSI (IP packets or DTN bundles) not space packets. Even though the infrastructure may use packet delivery services, the mission operations may use file-based operations built on top of the packet services.

[x] For landed elements, missions are moving away from DTE/DFE communications for reasons of mass, power, cost and volume of science data return.

[xi] While this approach appears simple, the various ad hoc proprietary interfaces and scheduling considerations make it difficult.

[xii] The data exchanged at Cross support point 1 typically also includes metadata related to the operations of the foreign agencies' assets (e.g., UHF radio). This requires that the supporting Agency's control center inspect the file and metadata before uploading to the relay for execution.

[xiii] As part of its Phase 2 activities, the SISG has determined that an internetworked approach where the network provides an optionally-reliable datagram delivery service to applications is best. Under this design, the applications are hosted only at the 'edges' of the network, and since no requirement has been identified for one agency to communicate directly with (command/control) another agency's asset, cross-supported application-layer protocols like CFDP should not be necessary. The same holds true for a cross-supported CCSDS packet service. Recovery from error conditions where the networking capability is (temporarily) not functional on a network 'edge' is supported by a delivery agent on the next-to-last node that interacts directly with the edge node below the network layer.

[xiv] This bullet statement should be replaced by "Inclusion of a Time Synchronization service local to the Mars networking environment and the SSI as a whole."

[xv] Since this document was first published, the SISG has developed a notion of a standardized 'last-hop commanding/first-hop telemetry' application that would be responsible for providing this capability. Implementing this functionality as a specialized application allows it to fit into the overall architecture more cleanly.

[xvi] As stated above, since this document was first published, the SISG has developed a notion of a standardized 'last-hop commanding/first-hop telemetry' application that would be responsible for providing this capability. Implementing this functionality as a specialized application allows it to fit into the overall architecture more cleanly.

[xvii] Loose time synchronization throughout the network is required by the bundle protocol.

[xviii] Number 2) should be replaced with numbers 2) and 3) and Figure 28 should also be replaced, as follows:

> 2) Tracking/Navigation Service: The availability of the proximity links offers certain radiometric data types for navigating the user Mars spacecraft. This includes the Doppler/range data on the proximity RF link between an approach spacecraft and the relay orbiter for precision approach navigation that complement the radio metric data (Doppler, range and DDOR obtained from the DTE/DFE RF link of the approach spacecraft) in support of Mars Orbit Insertion.

3) Open-loop Recording Service: During the Entry, Descent, and Landing (EDL) phase, the RF link between the lander and a relay spacecraft could be operated as envisaged in the Proximity-1 standard as to obtain lander telemetry and radio metric observables. However, as any interaction with the lander during this critical phase is not feasible due to the two-way light time between Earth and Mars, in general the focus is on collecting as much information as possible for forensic purposes in case of a non-nominal landing. To that end, the relay spacecraft performs an open-loop recording (aka canister mode) of the proximity link signal emitted by the lander. Offline processing of the recorded spectrum permits calculation of the 1-way Doppler, detection of the beacon tones, if implemented by the lander, or even reconstruction of the telemetry. Figure 28 gives a description of the Tracking/Navigation and Open-loop Recording services.

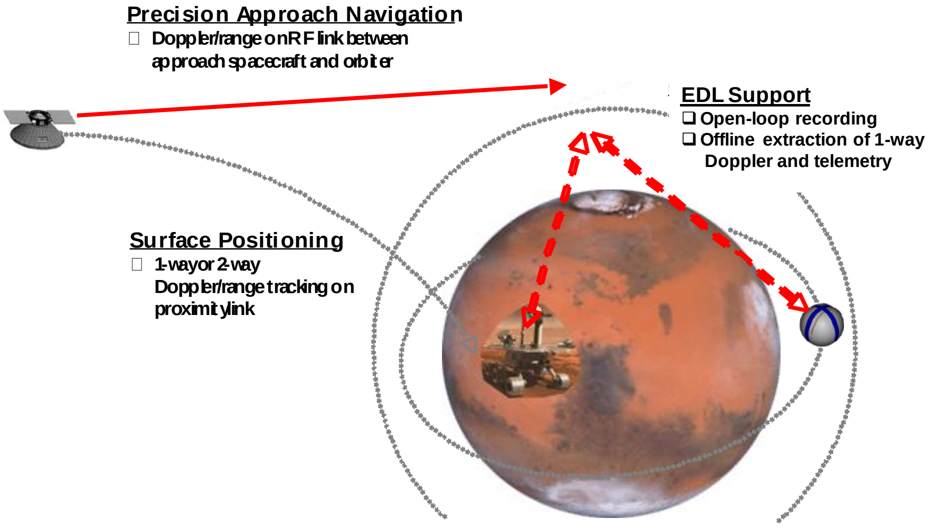


Figure 28: Tracking/Navigation service local to Mars networking environment

[xix] Replace ‘interoperate’ with ‘coexist.’

[xx] As noted earlier, the SISG has determined that a last-hop commanding/first-hop telemetry application can support these services. Such an application could then use DTN for delivery up to the penultimate node.

[xxi] As in the stated above, even though the Constellation Program is in flux, there is still a strong case for Earth-orbiting and Mars missions that will require network-centric operations.

[xxii] Although NASA’s Constellation program is in flux, numerous other projects involving international coordination and cross-support in space (e.g. METERON, DTN onboard ISS) are underway. The SISG believes that these will serve to mature the technology to the point that it will be ready for application to other missions.

[xxiii] Ignore the following sentence, "In the ISO/OSI standard seven layer communications model, the bundle is on top of the transfer layer and can be considered as a 'container' suitable for the transport of any payload data."

[xxiv] See Errata/Clarification (v).

[xxv] Text should read:

'Consequently, the in-space cross support infrastructure will need to be based on a dual-platform of internetworking technology according to the characteristics of the end-to-end environment:

- Local regions of IP or DTN-based communications in places where the IP suite works well (e.g., inside spacecraft, close to Earth, within the cislunar system, on and proximate to other Solar System bodies)
- DTN-based communications to operate effectively over paths where IP cannot (e.g. across very long delays and/or possible disruptions)

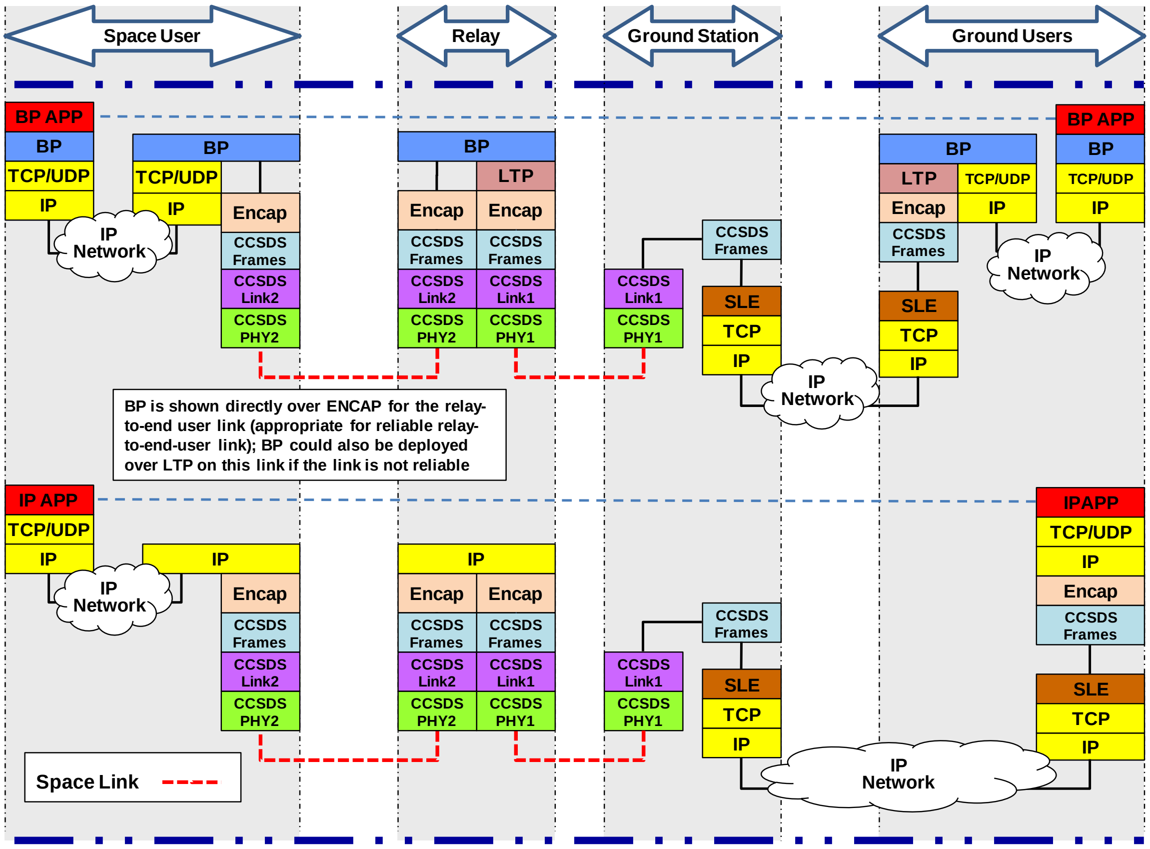
NOTE -- While it is possible to tunnel IP over BP, thus using BP to 'bridge' islands of local IP connectivity, doing so would require great caution to ensure that the IP applications could tolerate any effects (e.g. delays) incurred by the BP bridge.'

[xxvi] Finding F-14 should read, 'Given that DTN is the only candidate protocol that is approaching the level of maturity required to handle the disconnection and delays inherent in space operations, future in-space cross support should be based on a DTN-routed architecture that provides communication in environments where IP cannot.'

[xxvii] Ignore Figure 37. To understand how the BP fits into space operations, refer to Figure 38 (quadrants 2b and 3) in the text, the new version of Figure 41 provided in Errata (xxix) and the new figures that replace Figure 42 in Errata (xxx).

[xxviii] The SISG concluded that the CSP as an end-to-end service only needs to be supported on the end nodes, i.e., on the 'edges' of the network. As a consequence, there is no need for a CSTS packet service, as tunneling of transfer frames is already supported and Space Packets can travel within these frames. In cases where Space Packets need to be supported on the 'last hop', this will be achieved by means of the Last Hop Delivery Agent. Refer to Errata/clarification (v), as well.

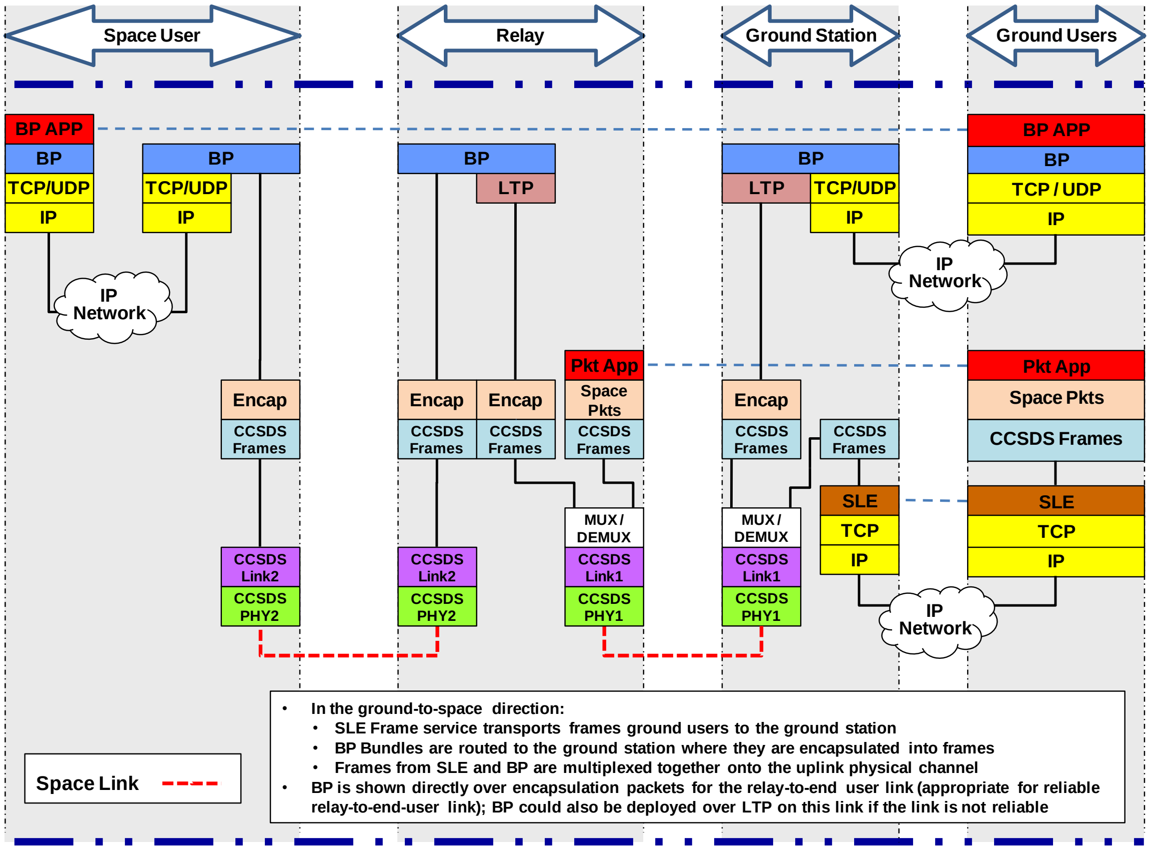
[xxix] Replace Figure 41 with the figure below. Figure 41 in the original text does not explicitly show the use of the CCSDS Encapsulation Protocol or CCSDS Framing. The diagram below shows those and is also stylistically consistent with the updated diagrams for Figure 42 in Errata (xxx). The new Figure 41 below does NOT show multiplexing of BP bundles/IP Packets together with 'traditional' packet command/telemetry at the ground station, as do the updated Figures 42a and 42b in Errata (xxx). While such multiplexing is possible, it overly complicates the figure.



BP is shown directly over ENCAP for the relay-to-end user link (appropriate for reliable relay-to-end-user link); BP could also be deployed over LTP on this link if the link is not reliable

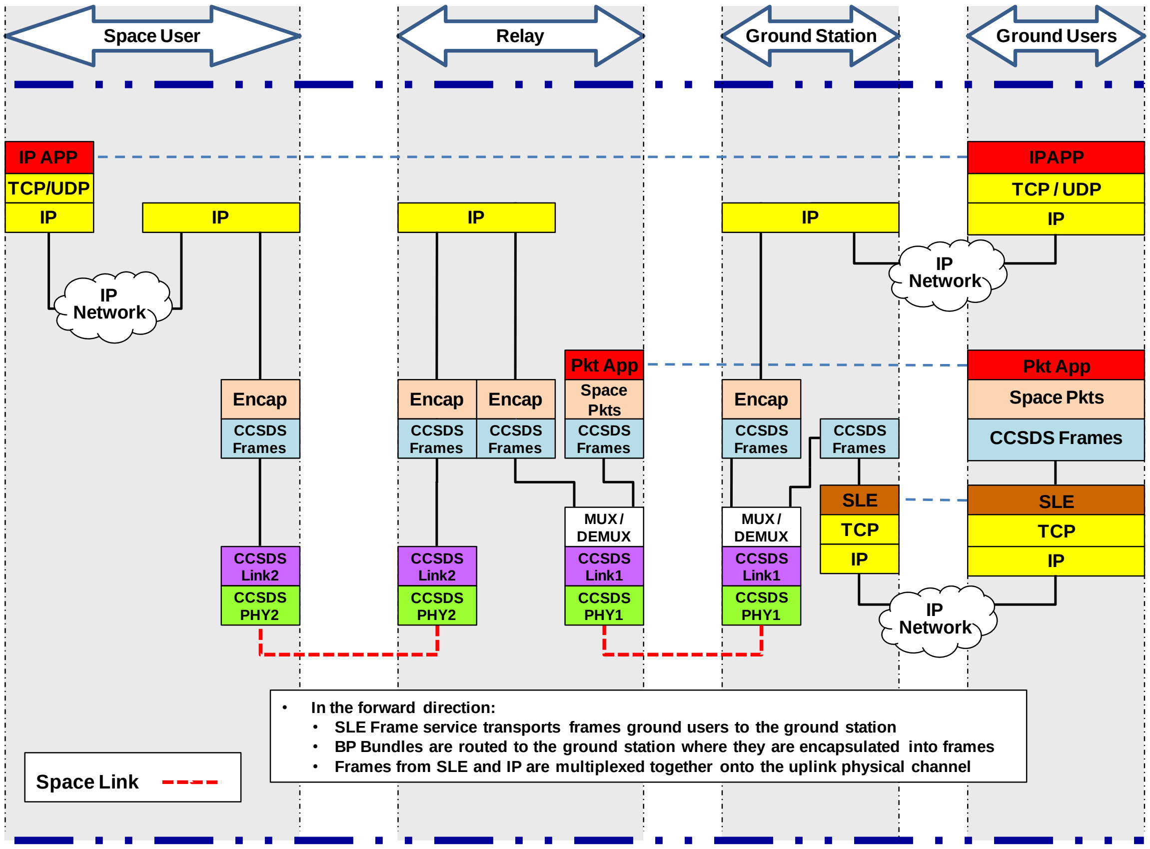
Figure 41: Phase-1 Deployment of IP and DTN

[xxx] Replace Figure 42 with the figures below (Figures 42a and 42b). Figure 42a shows the Phase-2 DTN deployment coexisting with traditional CCSDS Packet communications. In the top part of the figure, Bundle Protocol-Based applications communicate by routing bundles through the network. At the ground station, bundles are received from the ground and are encapsulated into CCSDS Encapsulation Packets, which are then put into frames and multiplexed together with other frames (e.g., from packet-based applications) onto the physical uplink channel. The bundles are extracted in the relay and forwarded according to the BP routing table. The figure assumes a reliable relay-to-space-user link, so that bundles can be encapsulated directly into Encapsulation packets without using LTP. The bottom part of the figure shows a traditional packet-based application using SLE to communicate with the ground station. Here (again considering the forward direction) the frames that are formed by the ground user are extracted from the SLE tunnel and multiplexed onto the space link.



- In the ground-to-space direction:
  - SLE Frame service transports frames ground users to the ground station
  - BP Bundles are routed to the ground station where they are encapsulated into frames
  - Frames from SLE and BP are multiplexed together onto the uplink physical channel
- BP is shown directly over encapsulation packets for the relay-to-end user link (appropriate for reliable relay-to-end-user link); BP could also be deployed over LTP on this link if the link is not reliable

Figure 42a: Phase-2 DTN deployment coexisting with traditional CCSDS Packet communications



- In the forward direction:
  - SLE Frame service transports frames ground users to the ground station
  - BP Bundles are routed to the ground station where they are encapsulated into frames
  - Frames from SLE and IP are multiplexed together onto the uplink physical channel

Figure 42b: Phase-2 IP deployment coexisting with traditional CCSDS Packet communications

Figure 42b shows the Phase-2 IP deployment coexisting with traditional CCSDS Packet communications. It is similar to Figure 42a, except that IP packets are always carried in CCSDS encapsulation packets and do not use LTP.

Any number of frame streams could be multiplexed together at the ground station. These streams could be a mix of BP bundles, IP packets, and traditional space packets delivered to the ground station via SLE.

[xxxi] XTCE covers most of this requirement; what is missing is a common set of rules for naming elements.

[xxxii] The SISG has developed an SSI Operations Concept that outlines the process for coordinating the assets contributed by the different agencies. This process is cooperative and voluntary; no enforcement of rights and privileges is currently defined.

[xxxiii] The SISG has not identified any need for multiple access data link protocol.

[xxxiv] The mechanisms to encapsulate IP packets in CCSDS encapsulations packets are already defined; new protocol IDs will need to be defined to support DTN bundles and LTP segments.

[xxxv] The SISG has identified the need for these different protocols to coexist, but the need for a gateway function between these protocols has not been established.

[xxxvi] The intent of this statement is to ensure that simple missions that do not use internetworking can continue using the current CSTS.

[xxxvii] Refer to Errata/Clarification statement (v).

[xxxviii] Refer to Errata/Clarification statement (v).

[xxxix] In working further on this topic, the SISG has come up with a solution that is described in the Errata/Clarification (v). None of the three approaches outlined here apply.

[xl] Figure 45 should be replaced by:

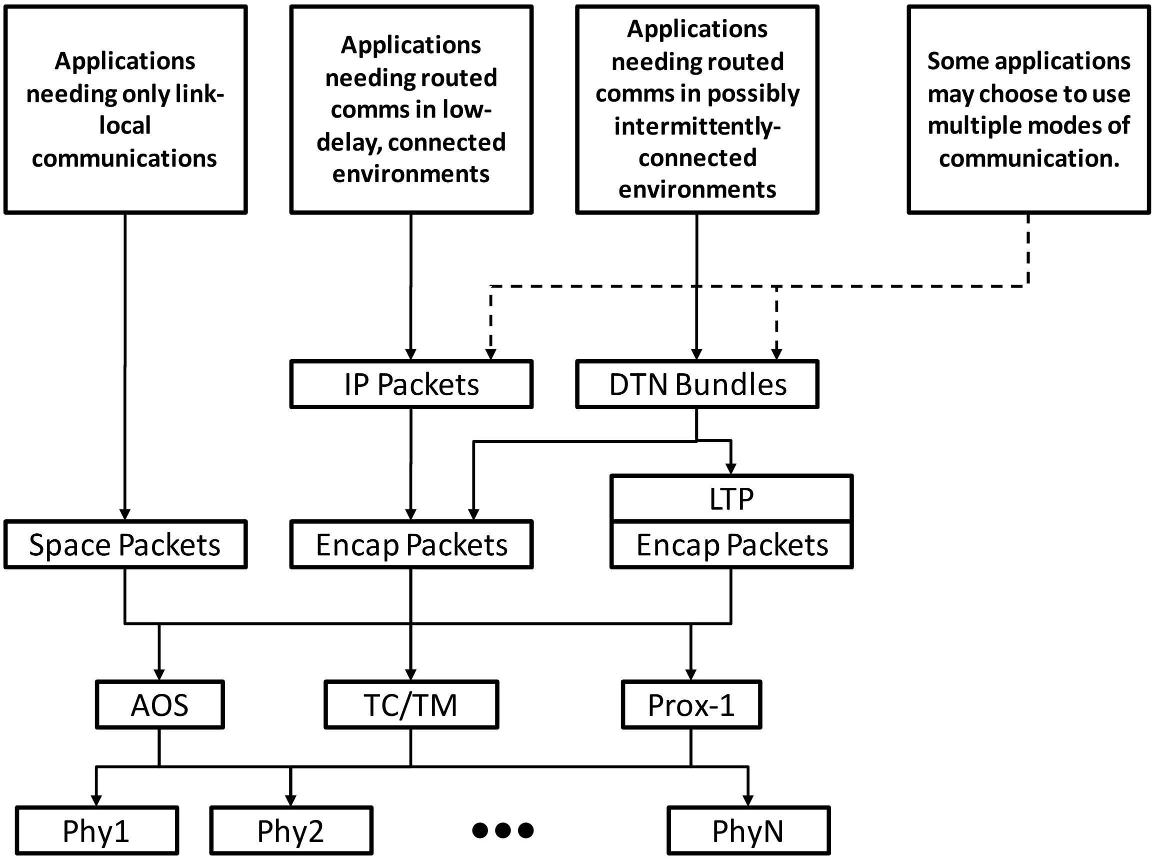


Figure 45: Stack diagram of communication options at each layer

[xli] Although NASA's Constellation program is in flux, numerous other projects involving international coordination and cross-support in space (e.g. METERON, DTN onboard ISS) are underway. The SISG believes that these will serve to mature the technology to the point that it will be ready for application to other missions.

[xlii] Finding F-14 should read, 'Given that DTN is the only candidate protocol that is approaching the level of maturity required to handle the disconnection and delays inherent in space operations, future in-space cross support should be based on a DTN-routed architecture that provides communication in environments where IP cannot.'

[xliii] XTCE covers most of this requirement; what is missing is a common set of rules for naming elements.

[xliv] The SISG has developed an SSI Operations Concept that outlines the process for coordinating the assets contributed by the different agencies. This process is cooperative and voluntary; no enforcement of rights and privileges is currently defined.