The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

SOLAR SYSTEM INTERNETWORK (SSI) ARCHITECTURE

INFORMATIONAL REPORT

CCSDS 730.1-G-1

GREEN BOOK

July 2014

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CCSDS Secretariat
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E-mail: secretariat@mailman.ccsds.org

FOREWORD

In 1999, at the first Interoperability Plenary (IOP-1) meeting of national space flight agencies, an Interagency Operations Advisory Group (IOAG) was established to achieve cross support across the international space community and to expand the enabling levels of space communications and navigation interoperability. In response to increased agency interest in internetworked space communications architectures, the IOAG chartered a Space Internetworking Strategy Group (SISG) in 2007 "to reach international consensus on a recommended approach for transitioning the participating agencies towards a future 'network centric' era of space mission operations." In December 2008, the SISG submitted its preliminary *Operations Concept for a Solar System Internetwork (SSI)* (reference [1]) (hereafter referred to as the 'SSI Operations Concept') to the second IOP (IOP-2). The document provided a top-level definition of SSI operations, referencing elements, and services that were to be defined further in a separate SSI architecture document. IOP-2 directed that the IOAG finalize the SSI Operations Concept and then create a separate SSI Architecture document, both of which should be presented at IOP-3 in the late 2012–early 2013 timeframe. In 2010 the IOAG finalized the SSI Operations Concept and asked the CCSDS to create the SSI architectural definition. This Informational Report is intended to serve as that SSI architecture document.

Through the process of normal evolution, it is expected that expansion, deletion, or modification of this document may occur. This Report is therefore subject to CCSDS document management and change control procedures, which are defined in *Organization and Processes for the Consultative Committee for Space Data Systems* (CCSDS A02.1-Y-4). Current versions of CCSDS documents are maintained at the CCSDS Web site:

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EXECUTIVE SUMMARY

The SSI is an automated communication system for space ventures. Much as the terrestrial Internet enables communication among people and businesses without requiring a detailed understanding of network operations, the SSI supports communication among the engineers, scientists, and robotic devices operating in space ventures without requiring a detailed understanding of space communication operations.

SSI is not a revolution in space communications but rather an evolution of the familiar CCSDS communication standards on which most space communications are already based. In effect, SSI simply makes CCSDS links easier to use, so that they can be exercised in more complex configurations for more challenging flight missions.

Participation in the SSI is entirely voluntary and is expected to be incremental. An isolated flight mission will reduce cost and risk if it merely adopts the automated SSI communication protocols. Going further, collaborating missions can further reduce cost and risk by basing coordinated interoperation on the SSI protocol standards. Eventually that coordination can itself be automated, establishing a unified space communications fabric that new flight missions can utilize inexpensively with negligible impact on existing mission operations.

The SSI architecture is based on international standards and voluntary agreements, enabling extensive cross support among missions without restricting any organization's control over its own communication resources. Moreover, the SSI is engineered with features that prevent unauthorized resource utilization and protect the integrity and confidentiality of mission data as needed. SSI capability does require some investment: ground systems and flight assets must be provisioned with sufficient computing resources to enable successful operation of the SSI protocols, including network management. But the return on that investment includes support for enhanced functionality in space exploration missions, including Earth-orbiting, deep space, and relay-enabled missions:

- The handover of satellite data flow from one Earth station to the next is automated, ensuring continuous data flow between spacecraft and Mission Operations Centers (MOCs).
- High-speed spikes in spacecraft data download are automatically buffered for transmission over lower-speed (and less expensive) terrestrial network links.
- Data that are lost or corrupted in transit are automatically retransmitted, even over interplanetary distances and intermittent links. In particular, high-speed transmission disruptions due to severe weather are automatically handled.
- Multiple orbiters can easily and automatically forward data to and from multiple landed vehicles, honoring prioritization decisions made at the data source.
- Alternative data paths are available in the event of the failure of a given communication resource, increasing vehicle safety and total mission data return.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This document provides a top-level architecture of the Solar System Internetwork (SSI). It defines the features, elements, principles, and procedures of the SSI, consistent with the SSI Operations Concept (reference [1]) that was produced by the SISG and approved by the IOAG in 2010. The concepts defined in this architecture apply to all organizations and elements that participate in the SSI.

More detail is provided in other CCSDS documents, in particular, the forthcoming *Space Communications Cross Support—Architecture Requirements Document (SCCS-ARD*) (reference [2]).

1.2 RATIONALE

The CCSDS Space Internetworking Services-Delay-Tolerant Networking (SIS-DTN) Working Group developed this Informational Report in response to a request from the IOAG to define the architecture of the SSI that was described in the SSI Operations Concept (reference [1]). SSI implementation will be accomplished in three stages, as defined in this document.

1.3 BUSINESS CASE

A comprehensive argument for deployment of the SSI is beyond the scope of this document. The detailed discussion of this business case is presented in *Recommendations on a Strategy for Space Internetworking* (reference [3]), the final report of the IOAG's SISG. A representative excerpt, taken from section IV.B.4 of that report (specifically concerned with lunar mission operations), is reproduced here:

> …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.

Further details regarding the business case for the SSI can be found in section 8 of *Solar System Internetwork (SSI) Issue Investigation and Resolution* (reference [4]), also produced by the SISG.

1.4 DOCUMENT STRUCTURE AND CONTEXT

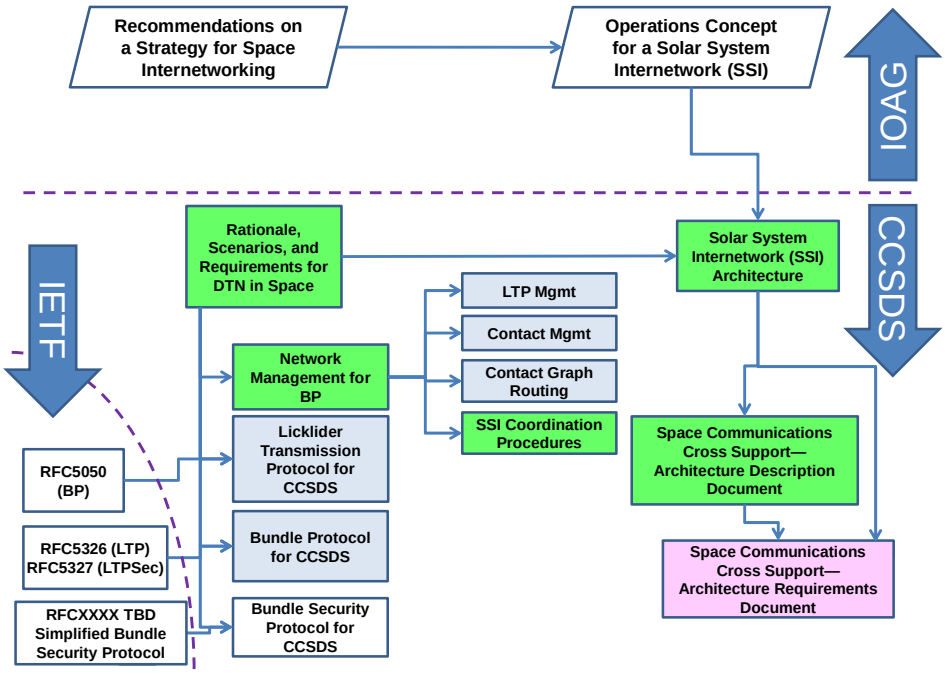
1.4.1 DOCUMENT STRUCTURE

This Informational Report is structured as follows:

- Section 1 contains introductory information explaining the purpose, scope, and rationale for the document; the business case for the SSI; the structure and context of the document; and the symbols used in the diagrams in this document. It also provides a list of references.
- Section 2 provides an overview of the SSI model and the multi-stage transition to the SSI. It includes a general explanation of the features of the SSI, how the SSI will benefit various types of users, and what is needed to provide SSI services.
- Sections 3, 4, and 5 detail the SSI transition stages: Mission Functionality, Internetwork Functionality, and Advanced Functionality, respectively. Each section contains an explanation of network operations for different mission scenarios in that stage of transition, including details on data flow, participating SSI elements and their functions, and network coordination. Each section lists the architectural principles that govern that transition stage and describes the operational procedures supported during that stage.
- Annex A provides a definition of terms that are italicized in the text.
- Annex B provides a definition of acronyms found in the text.
- Annex C summarizes concepts that are useful for understanding the SSI.
- Annex D provides a short list of informative references.

1.4.2 DOCUMENT CONTEXT

Figure 1-1 shows the relationships among the referenced IOAG documents, this document, and related current and future CCSDS documents. It should be noted that the Bundle Protocol (BP) and Licklider Transmission Protocol (LTP) Blue Books will standardize, within CCSDS, profiles of the BP and LTP specifications that are articulated in Internet Requests for Comments (RFCs) 5050 and 5326 (references [5] and [6]), respectively.

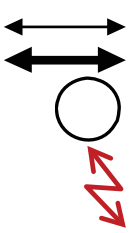


NOTE – Arrows between documents indicate that one document motivates and/or informs another.

Figure 1-1: Map of Referenced Documents

1.5 CONVENTIONS

The network operations diagrams in this document use the following notation:



Mission and/or engineering information flow
SSI automated data communications
SSI node
Radio Frequency (RF) or optical signal

The coordination diagrams in this document use the following notation:

Manual coordination (nonautomated)
Automated coordination

ASR Authority Schedule Request
CCP Composite Contact Plan
PCP Provider Contact Plan
PA Peering Agreement
NSA Network Service Agreement
USR User Schedule Request

The network operations and coordination diagrams in this document are neither prescriptive nor exhaustive; rather, they simply depict example SSI topologies and mission data coordination flows.

1.6 REFERENCES

The following documents are referenced in this Report. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Report are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS documents.

[1] *Operations Concept for a Solar System Internetwork (SSI)*. IOAG.T.RC.001.V1. Washington, DC: IOAG, 15 October 2010.

[2] *Space Communications Cross Support—Architecture Requirements Document*. Forthcoming.

[3] *Recommendations on a Strategy for Space Internetworking*. Errata/Clarification added. Report of the Interagency Operations Advisory Group Space Internetworking Strategy Group, IOAG.T.RC.002.V1. Washington, DC: IOAG, August 1, 2010.

[4] *Solar System Internetwork (SSI) Issue Investigation and Resolution*. IOAG.T.SP.001.V1. Washington, DC: IOAG, 1 August 2010.

[5] K. Scott and S. Burleigh. *Bundle Protocol Specification*. RFC 5050. Reston, Virginia: ISOC, November 2007.

[6] M. Ramadas, S. Burleigh, and S. Farrell. *Licklider Transmission Protocol—Specification*. RFC 5326. Reston, Virginia: ISOC, September 2008.

[7] *CCSDS File Delivery Protocol (CFDP)*. Issue 4. Recommendation for Space Data System Standards (Blue Book), CCSDS 727.0-B-4. Washington, D.C.: CCSDS, January 2007.

[8] *Asynchronous Message Service*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 735.1-B-1. Washington, D.C.: CCSDS, September 2011.

[9] *Space Communications Cross Support—Architecture Description Document*. Issue 1. Report Concerning Space Data System Standards (Green Book), CCSDS 901.0-G-1. Washington, D.C.: CCSDS, November 2013.

[10] *CCSDS Bundle Protocol Specification*. Issue 3. Draft Recommendation for Space Data System Standards (Red Book), CCSDS 734.2-R-3. Washington, D.C.: CCSDS, July 2014.

[11] S. Symington, et al. *Bundle Security Protocol Specification*. RFC 6257. Reston, Virginia: ISOC, May 2011.

[12] *Licklider Transmission Protocol (LTP) for CCSDS*. Issue 3. Draft Recommendation for Space Data System Standards (Red Book), CCSDS 734.1-R-3. Washington, D.C.: CCSDS, May 2014.

2 OVERVIEW

2.1 GENERAL

The SSI is a communication system for ventures into space. It is used to exchange information among participants in space mission activities, including:

- crewed and robotic space-faring vehicles, often carrying investigative instruments;
- planetary surface systems, with crew and/or instruments;
- ground antenna stations;
- centralized ground-based MOCs on Earth;
- science investigators at widely distributed laboratories on Earth.

The SSI operates in a manner that is in many ways similar to the operation of the terrestrial Internet. Like the terrestrial Internet, the SSI provides a network capability that connects various participants via a variety of lower-level capabilities, such as radio, wired, or optical communications devices. The network serves as a foundation for applications that provide higher-level capabilities such as reliable transfer of files and messages. Operation of the various capabilities is prescribed by protocol specifications. The relevant protocol specifications are published by the Internet Engineering Task Force (IETF) and the CCSDS.

Again, like the terrestrial Internet, the SSI interconnects multiple networks built on two types of networking architectures—the Internet architecture and the Delay-Tolerant Networking (DTN) architecture. These interconnected networks are termed *SSInets* in this document.

A discussion of additional terminology used in this document, which further defines concepts that were identified in the SSI Operations Concept (reference [1]), is contained in annex C.

It should be noted that the SSI architecture relies on the provision of terrestrial network paths—possibly augmented by security structures such as firewalls and Virtual Private Networks (VPNs)—and space data links that may be utilized by the SSI protocols.

2.2 TRANSITION

As of the time of publication of this document, nearly all space flight missions mounted by the national space agencies are characterized by a relatively simple communication model as shown in figure 2-1 and described below.

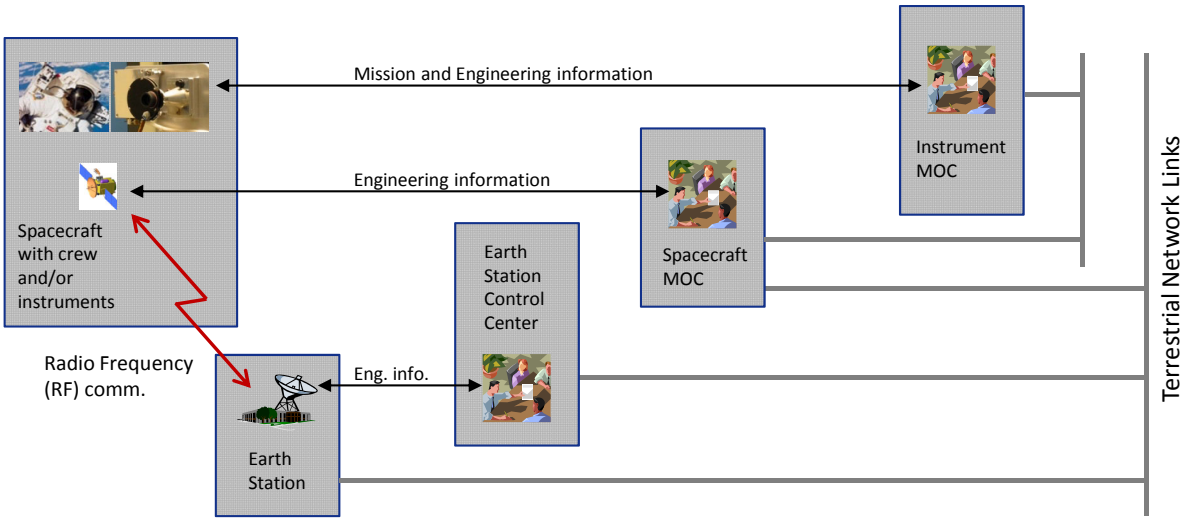


Figure 2-1: Simple Mission Communications Model

– The mission and its space communication services are managed entirely by a single space agency.

– The mission establishes a service agreement for space link communications services and schedules and manages the space link for those services using CCSDS Service Management and Space Link Extension protocols. The mission is responsible for the provisioning and utilization of the space link.

– The mission operates a single spacecraft which communicates with a single MOC.

– The spacecraft may have a human crew and/or one or more investigative instruments. The instruments on a spacecraft are often operated by geographically dispersed investigators on Earth who may be external to the space agency.

– The ‘downlink’ data from the spacecraft to the MOC typically take the form of mission-specific spacecraft telemetry encapsulated in CCSDS space packets that are encapsulated in CCSDS telemetry frames.

– The ‘uplink’ data from the MOC to the spacecraft typically take the form of mission-specific spacecraft commands, often encapsulated in CCSDS space packets and then encapsulated in CCSDS telecommand frames.

– The spacecraft communicates directly with one or more Earth stations (antenna complexes) which forward telemetry and telecommand frames (for example, using Space Link Extension [SLE]) between the Earth station and MOC during contact intervals throughout which the Earth station resources are dedicated to this mission.

– MOC staff and mission-specific procedures accomplish the delivery of science and instrument engineering data to investigators at their home institutions.

– Initiation and termination of contact between the spacecraft and an Earth station, and selection of the data to be communicated during the contact interval, are initiated by command on the spacecraft and by staff operations on the ground.

– Data that are not successfully received may be retransmitted in response to commands issued by mission operators.

However, recently published CCSDS standards are aimed at enabling a more powerful mission communication model to emerge over the next few decades. It is already possible to support mission operations scenarios such as the one shown in figure 2-2 below.

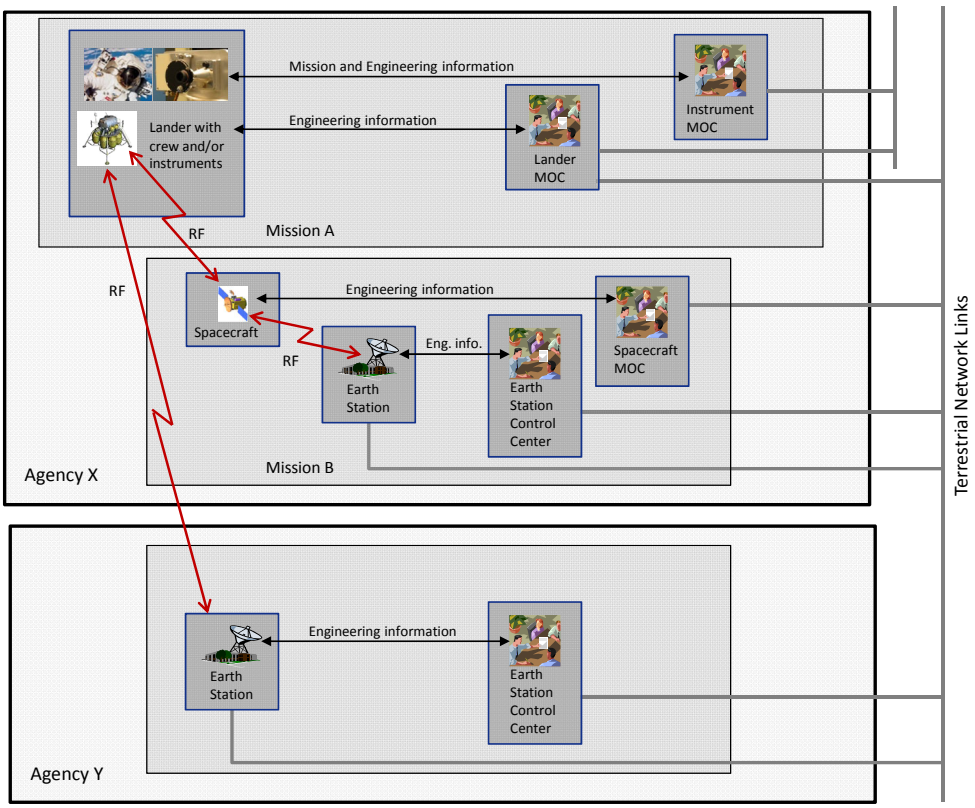


Figure 2-2: A More Complex Mission Operations Scenario

Currently, however, configurations such as these are always ad hoc and idiosyncratic. As these more complex scenarios become more common, standard protocols and procedures that enhance interoperability will become important as a means of controlling cost and risk.

A potential example of even more complex operations under this model is shown in figure 2-3.

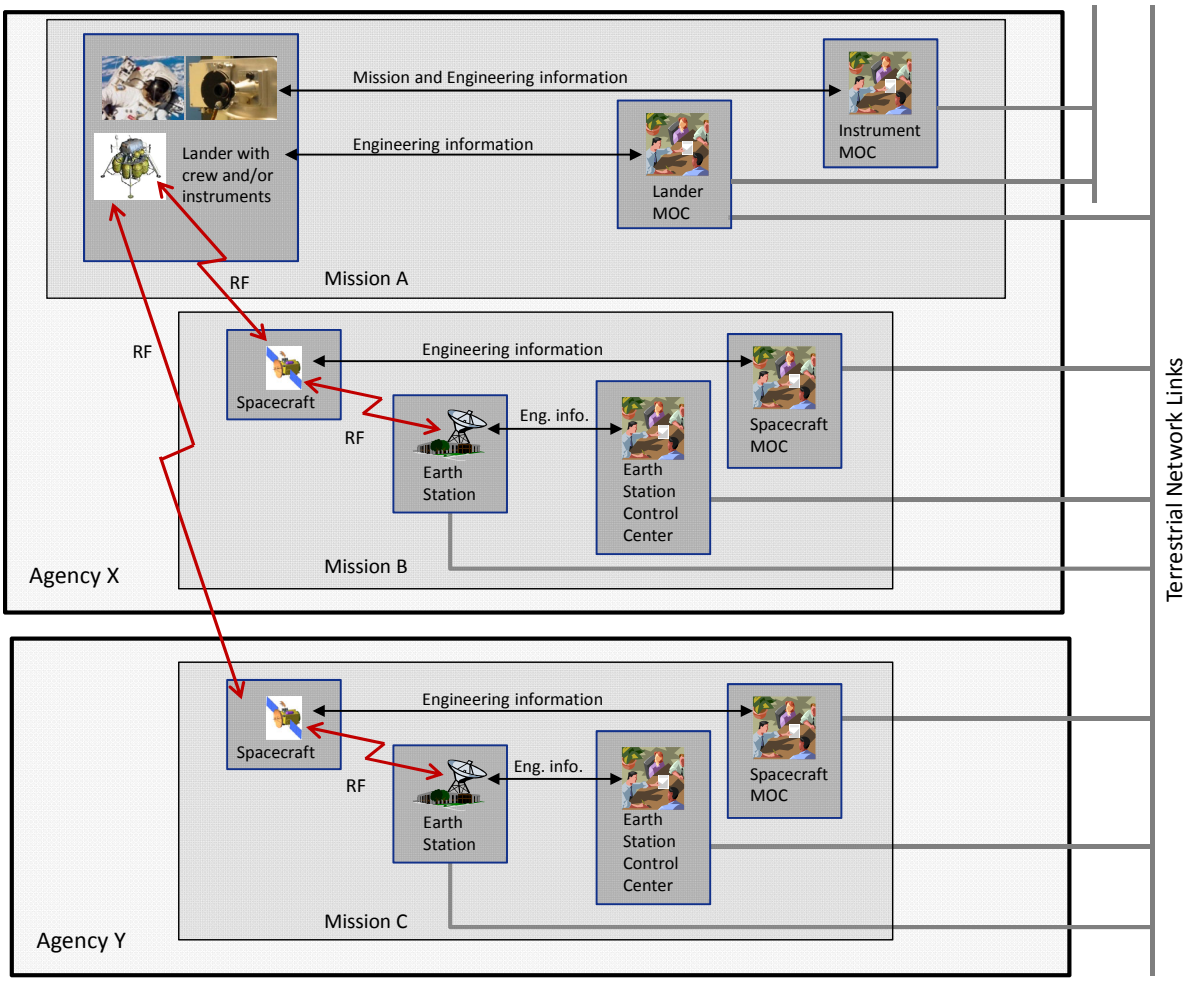


Figure 2-3: Emerging Complex Mission Communications Model

In the scenario depicted in figure 2-3:

– Missions may be jointly operated by multiple space agencies, with different elements of mission functionality managed by different MOCs.

– Space communications Earth station services may be provided by multiple space agencies.

– Missions may operate multiple spacecraft, which may autonomously collaborate on mission objectives. The set of spacecraft conducting a long-lived mission may change over time, as disabled spacecraft are decommissioned and new spacecraft are deployed.

– Data may be routinely relayed among spacecraft—even among spacecraft deployed for different missions, by different space agencies—on their paths to and from the MOCs. That is, not all data received by a spacecraft will necessarily be ‘uplink’, and not all data transmitted by a spacecraft will necessarily be ‘downlink’.

- Moreover, data may be relayed through different spacecraft at different times, introducing the possibility of multiple data paths between spacecraft and the MOCs.

- The data exchanged among spacecraft, MOCs, and investigators may be significantly more complex. For example, streaming video may be produced by crewed spacecraft. Files may be transferred, using the CCSDS File Delivery Protocol (CFDP) (reference [7]). Standard mission operations services messages may be published to multiple subscribers, in space and/or on Earth, using the CCSDS Asynchronous Message Service (AMS) (reference [8]).

The transition to this more powerful model may be thought of as occurring in three general stages, with the firm understanding that the transition from one stage to another will always be entirely at the discretion of each organization participating in the SSI (meaning that for the foreseeable future, organizations operating at different stages may be participating in the SSI concurrently). The SSI architecture, therefore, encompasses three broad grades of functionality to support participating organizations in their transition through these stages toward full deployment of the SSI. The three stages of transition are:

- **Stage 1 (Mission Functionality)—**introduction of the SSI protocols within MOCs and spacefaring vehicles to automate the mission data communications (command and telemetry) conducted within the simple mission communications model described in the first paragraphs of this section. The SSI architecture supports this stage by providing mission functionality (as described in section 3), which automates basic communication processes for individual space flight missions without requiring that Earth station service providers implement the SSI protocols.

- **Stage 2 (Internetwork Functionality)—**introduction of the SSI protocols into Earth station service providers to enable Network-Layer cross support. The SSI architecture supports this stage by providing internetwork functionality (as described in section 4), which enables the SSI protocols to operate across multiple space flight missions, possibly managed by different national space agencies (interagency cross support). The coordination of mission data communications is still manual at this stage.

- **Stage 3 (Advanced Functionality)—**automation of the coordination of mission data communications in the unified cross-support environment. The SSI architecture supports this stage by providing advanced functionality (as described in section 5), which provides automated support for the internetwork topologies, implementing a unified solar-system-wide communication network that can scale up to the complex space exploration programs of the future.

Organizations participating in the SSI may initially operate at any of the three stages, as long as they have implemented the functionality required in order to operate at all preceding stages: i.e., the stages are cumulative in functionality but need not be entered in sequence. Specifically, it is not necessary for an organization to participate in the SSI at Stage 1 for some period of time before beginning to participate at Stage 2, but participation at Stage 2 is only possible if all of the functionality required for participation at both Stage 1 and Stage 2 has been implemented. Likewise, it is not necessary for an organization to participate in the SSI at either Stage 1 or Stage 2 for a period of time before beginning to participate at

Stage 3, but participation at Stage 3 is possible only if all of the functionality required for participation at Stages 1, 2, and 3 has been implemented.

Space link data management is a critical precondition to successful operation of the SSI. For a comprehensive discussion of this topic, please refer to the *Space Communications Cross Support—Architecture Description Document* (SCCS-ADD) (reference [9]). Figure 2-4 below, excerpted from that document, offers an initial sense of the SSI architecture's reliance on this underlying cross-support architecture.[1]

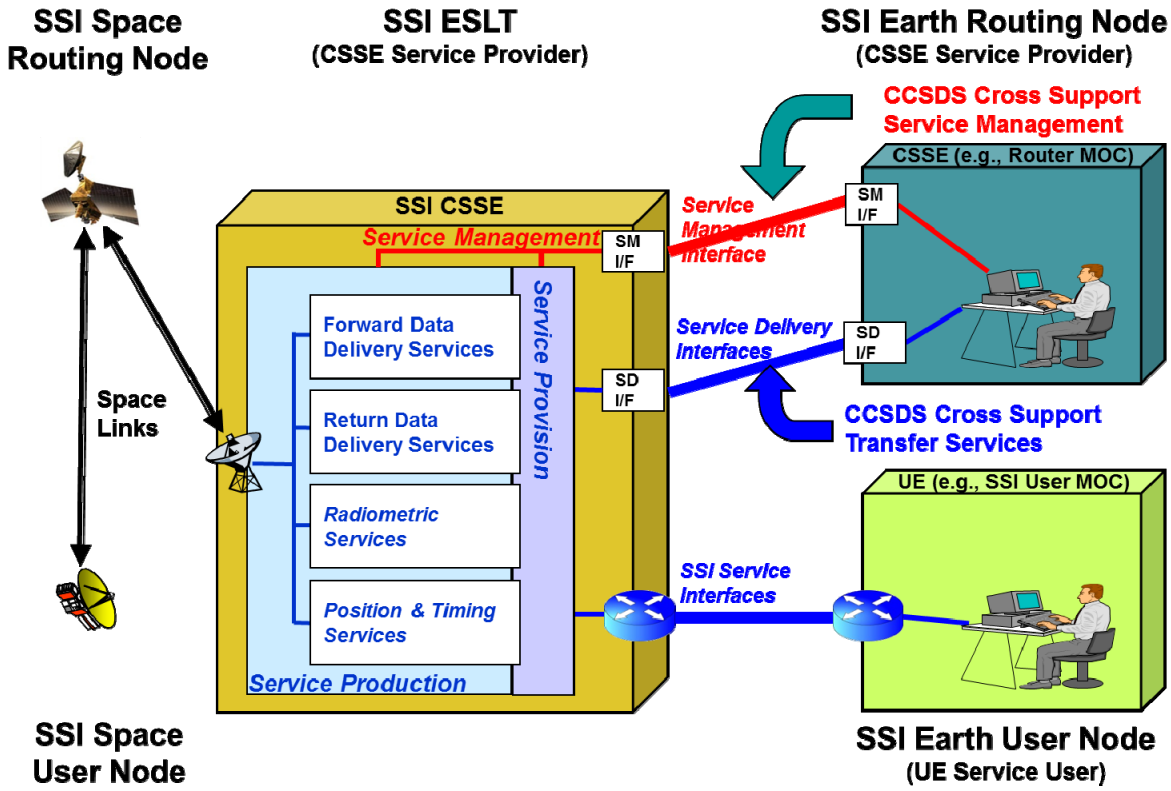


Figure 2-4: Cross-Support Service Provider Interfaces

Mechanisms and procedures for the management of terrestrial networks and space data links are already well established and are beyond the scope of SSI. Management of the networks assembled from those links, on the other hand, is within the scope of SSI; it comprises such functions as contact plan distribution and network node monitoring and reconfiguration, as described later in this document.

[1] Acronyms that are used only in this figure or are called out later in this document: ESLT = Earth-space link terminal; CSSE = cross support service element; SM = service management; I/F = interface; SD = service delivery; UE = user element.

2.3 FEATURES

2.3.1 GLOBAL SUPPORT

The SSI architecture is based on international standards and voluntary agreements that enable the ground and space assets of all participating organizations to function as potential elements of mission cross support. Participation in the SSI can increase total mission data return while reducing the risk of critical data loss.

2.3.2 LOCAL CONTROL

At the same time, all participating organizations retain complete control of their flight and ground communication resources. Only those resources that have been explicitly offered as cross-support elements are made available through the SSI, and only to the degree explicitly authorized by the organizations that offer them.

2.3.3 RESOURCE PROTECTION

Rate control and congestion forecasting mechanisms built into the SSI architecture protect flight and ground assets from utilization beyond authorized levels. Mission data confidentiality, authentication, and integrity verification are enforced through the use of internationally standardized information security protocols and agreed-to configuration and operations models.

2.4 USING THE SSI

2.4.1 EARTH ORBITERS

SSI protocols automate data flow across multiple Link-Layer handovers as an Earth-orbiting satellite transits from one Earth station to the next, enabling continuous exchange of information between the spacecraft and its MOC. Also, the store-and-forward nature of SSI communications automatically matches high-rate data return spikes with continuous data delivery over lower-rate terrestrial infrastructure: data intermittently received at high rates are immediately automatically buffered in mass memory at the Earth station, while concurrent, continuous lower-rate transmission processes remove previously stored mass-memory contents and forward the buffered data to MOCs.

2.4.2 DEEP SPACE

SSI protocols automate the retransmission of lost or corrupt data, even over extremely long signal propagation delays and connectivity outages due to orbital movement. Recovery of lost data sent using frequency bands and/or link types that are affected by atmospheric distortion is automatic.

2.4.3 RELAY OPERATIONS

By standardizing the protocols for routing and data forwarding, SSI simplifies the utilization of multiple orbiters—even those operated by different space agencies—in the efficient transmission of mission data from landed planetary assets. Urgent data may be flagged for high-priority transmission at every point of transmission, rather than only at the original source.

2.5 PROVISIONING

The mission communications automation enabled by the SSI architecture relies on the provision of adequate computational resources, both in ground systems and in flight assets. It should be noted that this may require the deployment of additional routing, data forwarding, and network management computing equipment at Earth stations in Stages 2 and 3.

2.6 SERVICE ACCOUNTING

By agreeing to cross-support missions of each other's agencies, each partner agency can gain the benefits of shared resources and infrastructure. To monitor the use of resources, or possibly to charge for services in cases of inequity, organizations providing SSI transport service may want to track how much support their resources (e.g., space links, BP routers, ground stations) provide to their own and other organizations' missions. Accounting data can be collected to track the resources (e.g., space link bandwidth used, SSI router storage) used by different organizations or missions as identified by the SSI Endpoint Identifiers. Such information can then be used in inter-agency agreements and negotiations.

3 STAGE 1—MISSION FUNCTIONALITY

3.1 OVERVIEW

The mission functionality of SSI is the automation of the basic communication processes between vehicles and MOCs that might be performed for a single space flight mission. These processes include:

- the initiation and termination of transmissions;
- the selection of data for transmission according to priority designations declared by SSI users;
- the segmentation and reassembly of large data items for transmission in small increments;
- the retransmission of data that were lost or corrupted in transmission;
- the relaying of data from one entity to another via some other entity pre-selected by management.

By automatically retransmitting lost data and automating the integration of space link data flows from multiple antenna complexes, the automation implemented in Stage 1 can reduce cost and risk even in simple missions operating a single spacecraft.

Network-Layer cross support among missions is possible when the vehicles and MOCs of the missions involved all implement SSI mission functionality. However, the agreements governing such SSI cross support are ad hoc and privately negotiated rather than integrated into a unified SSI cross-support environment. Standard Link-Layer cross-support services and service management must be provided by the communications service providers.

3.2 NETWORK OPERATIONS

3.2.1 SIMPLE NETWORK OPERATIONS

3.2.1.1 General

In the simplest case (see figure 3-1), the SSI network configuration comprises just two SSI nodes: one at the spacecraft MOC and one onboard the spacecraft (serving both the spacecraft itself and also the spacecraft's crew and/or science instruments). Neither of these two nodes communicates with any node in any other SSInet.

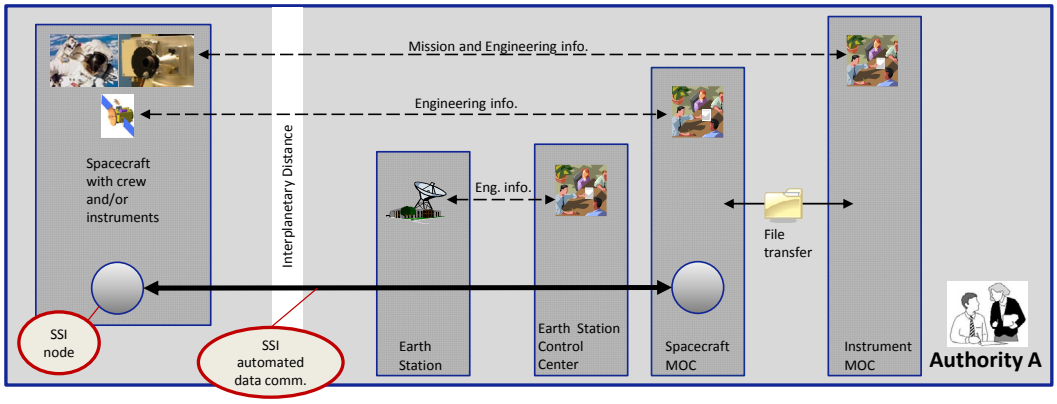


Figure 3-1: Minimal Network Configuration

The SSI data flow between these two nodes is established by requesting a space link session from the Earth station control center. Data are exchanged via the Earth station by Link-Layer mechanisms, which are nominally based on the CCSDS SLE service. (See reference [9] for more details.) The instrument MOC might be co-located with the spacecraft MOC, sharing access to the same SSI node, or data might be exchanged between the instrument and spacecraft MOCs by means of some other data-transfer mechanism, such as an Internet file transfer as shown. (It should be noted that in practice, even a simple flight mission is likely to use SLE in order to acquire Link-Layer services from multiple Earth stations to increase data return and reduce mission risk. These diagrams are conceptual, intended to illustrate communication relationships, rather than representative of actual mission configurations.)

The network configuration could be extended by configuring a separate SSI node for use by the instrument MOC, as shown in figure 3-2. This extension would enable the instrument MOC to operate on native instrument data flows securely routed through the node at the spacecraft MOC.

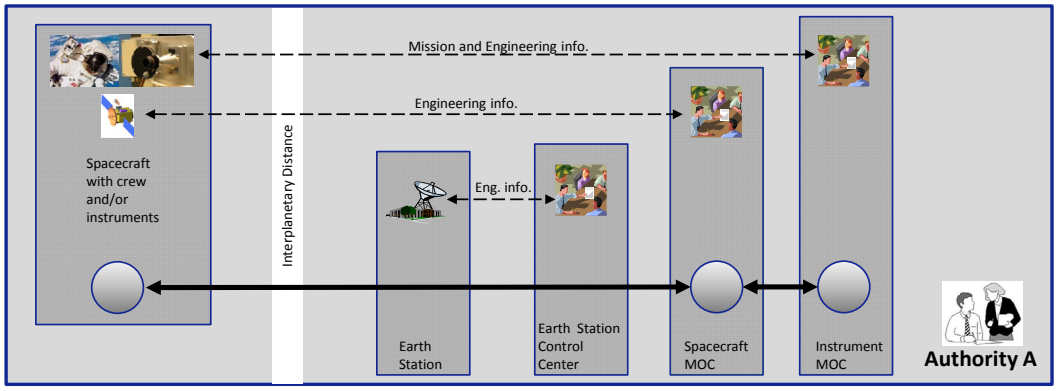


Figure 3-2: Adding Node for Instrument MOC

SSI mission functionality can even support missions entailing collaboration among multiple MOCs and vehicles—even if they are operated by different space agencies—so long as SSI

connectivity among the MOCs and/or among the vehicles can be privately coordinated among the participants. An example is the relay configuration shown in figure 3-3.

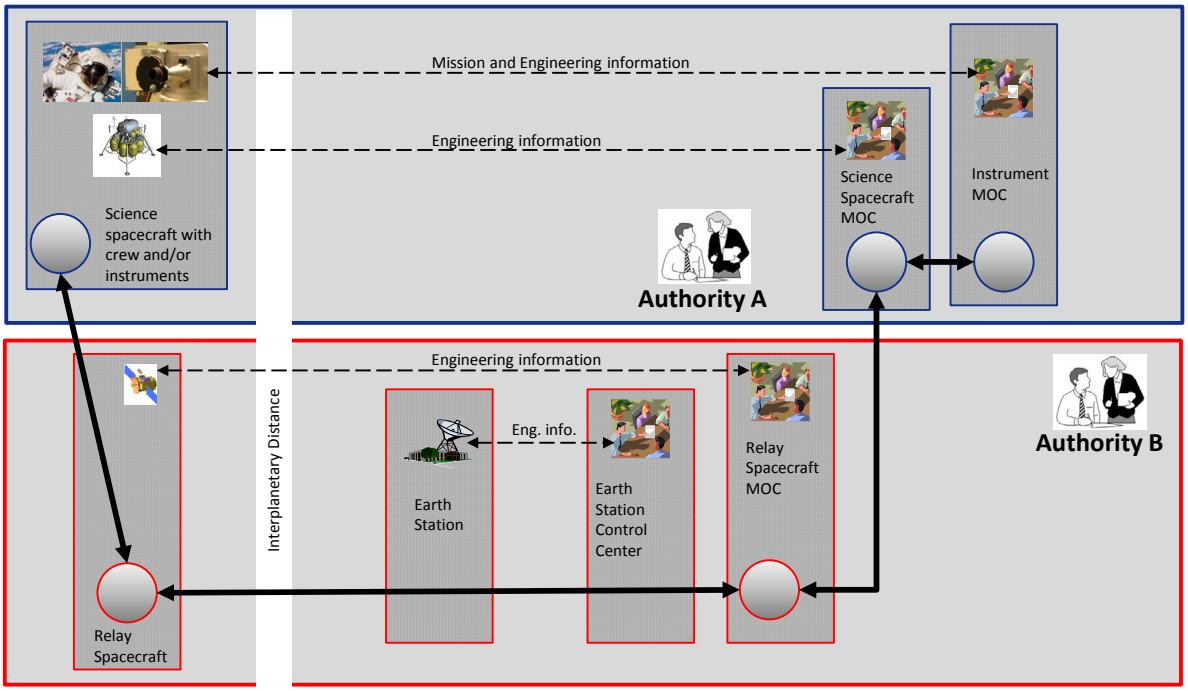


Figure 3-3: Interconnecting Multiple MOCs

In each of these configurations, all SSI data flow between the users, and the spacecraft traverses the spacecraft MOC, which is responsible for acquiring and managing the underlying space link services. The SSI supports these information flows as follows:

– mission and engineering information between the instrument MOC and the instrument (instrument commands and telemetry), where the instrument and spacecraft share access to a single SSI node;

– engineering information between the spacecraft MOC and the spacecraft (spacecraft commands and telemetry);

– engineering information, possibly including voice and video, between the crew and/or instrument and the MOC, again via the SSI node shared between the instrument and spacecraft.

3.2.1.2 Coordination of Mission Data Communications

In Stage 1 there is no formal structure for coordination of mission data communications. All procedures for coordination and provision of mission data communications are entirely private to the mission.

3.2.2 NETWORK COORDINATION ELEMENTS

3.2.2.1 Overview

The SSI network coordination elements involved in SSI mission functionality are described below.

3.2.2.2 Provider Node

Provider nodes are SSI nodes whose network protocol entities are configured to forward network *Protocol Data Units* (PDUs) received from other entities. Such nodes may act as user nodes when their application (e.g., network management) protocol entities send and receive data. Provider nodes may be located in space or on the surface of Earth or another planet, and may reside on spacecraft or in spacecraft MOCs (as in figure 3-2), in Earth/planetary Wide Area Networks (WANs), etc. In Stage 1 there are no provider nodes in Earth stations or Earth station control centers.

3.2.2.3 Provider Organization

A provider organization is responsible for administering one or more provider nodes, as designated by the corresponding authority for the node(s).

3.2.2.4 User Node

User nodes are SSI nodes whose network protocol entities are not configured to forward network PDUs received from other entities, but whose application protocol entities routinely send and receive data via the SSI. User nodes may be located in space or on the surface of Earth or another planet, and may reside on spacecraft or in MOCs (as shown in figure 3-2), in Science Operations Centers (SOCs), etc. In Stage 1 there are no user nodes in Earth stations.

3.2.2.5 User Organization

A user organization is responsible for administering one or more user nodes as designated by the corresponding authority for the node(s). As noted above, a provider node may act as a user node when its application (e.g., network management) protocol entities send and receive data; when a provider node is acting as a user node in this way, the corresponding organization responsible for administering that node acts as a user organization.

3.2.2.6 Authority

Every SSI node is assumed to be configured, managed, and operated by some single functionally autonomous organization, such as a space agency, space flight center,

commercial space flight operator, ground system network operator, or mission program, termed the node's *authority*. A node's authority may delegate node administration tasks to one or more subordinate organizations, but this delegation does not confer the role of node authority upon any delegate organization. The provider organization's authority serves as the SSI-Internet Service Provider (SSI-ISP) for the user organization.

3.2.2.7 User Schedule Request

A USR is a statement of SSI service needed by a user organization. The USR includes information regarding the time, rate (bandwidth), and type of requested service. In Stage 1 there is no formal standard for USRs; all coordination and provision of mission data communications is entirely internal to the mission.

3.2.2.8 Provider Contact Plan

A PCP is a schedule of planned SSI contacts between provider nodes administered by a provider organization, and user nodes administered by one or more user organizations. The PCP includes information regarding the start/end times and rate (bandwidth) of all planned contacts. In Stage 1 there is no formal standard for PCPs; all coordination and provision of mission data communications is entirely internal to the mission.

3.3 PRINCIPLES

The following principles pertain to Stage 1:

a) At this stage of SSI implementation, the coordination and provision of mission data communications is entirely internal to the mission.

b) Interagency SSI cross support may be provided, but the agreements governing such cross support are ad hoc and privately negotiated. Discussion of interagency cross support in SSI Stage 1 is beyond the scope of this document.

Inter-authority cross support of Link-Layer services will be employed by the spacecraft MOC to request, configure, and operate Link-Layer space communications from the MOC to the spacecraft.

3.4 PROCEDURES

3.4.1 INSTALLING AN SSI NODE

(For an explanation of the terminology used in this section, please see annex C.)

Each node requires a node number. Node numbers are assigned by the authority, from one or more ranges of node numbers allocated to that authority by the Space Assigned Number Authority (SANA).

Each node must be configured to run BP—that is, a 'Bundle Protocol Agent' (BPA) must be deployed at each node.

Wherever a BPA is deployed, mechanisms for BPA administration must be deployed as described in annex C. (Procedures for computing contact plans are assumed to be already in place, as they are generally a precondition to successful space flight operations.)

For each node on the surface of Earth, a *Convergence-Layer Adapter* (CLA) must be deployed underneath BP, enabling the node to communicate with other Earth-bound nodes via the Internet. Possible choices are the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) CLAs or potentially the LTP CLA running over underlying UDP/Internet Protocol (IP). Where the TCP and UDP CLAs are used, they must be configured to integrate correctly with the mission's IP network infrastructure.

For each node that either operates in space or else communicates with a node that operates in space, a CLA must be deployed underneath BP, enabling the node to communicate with nodes in space via CCSDS Link-Layer protocols. One possible choice is the LTP CLA, which performs reliable transmission over links that may have long signal propagation times and/or may be frequently unavailable.

NOTE – Multiple CLAs may be deployed for a single node, enabling the node to function as a gateway between different communication environments.

Wherever the LTP CLA is deployed, an LTP engine must also be deployed as part of the node.

Wherever an LTP engine is deployed, mechanisms for LTP engine administration must be deployed as described in annex C. In addition, one or more Link Service Adapters (LSAs) must be deployed underneath LTP, enabling the engine to communicate with topologically adjacent engines. Possible choices are (a) the UDP LSA, when the communicating engines both have Internet connectivity, and (b) the CCSDS Encapsulation Packets (EPs) LSA when communication between the two engines is possible only via a space link. Where the UDP LSA is used, it must be configured to integrate correctly with the mission's IP network infrastructure.

Wherever the EP LSA is used—in a flight system or in a ground node that communicates with a flight system—it must be integrated with the CCSDS packet transmission and reception functions of the local mission software. In particular, the node must be enabled to issue LTP segments autonomously and automatically, without explicit approval by any human administrative operator, whether the segments are destined for a node on Earth or in space.

As needed, one or more of the Bundle Security Protocol (BSP) security protocols may need to be deployed on various subsets of the nodes. BSP takes the form of bundle 'extension' blocks, so deployment of BSP does not entail the insertion of additional protocol layers at any nodes.

Wherever BSP is deployed, mechanisms for distributing BSP keys to SSI nodes must be deployed as described in annex C.

DTN applications, possibly supported by DTN application services as described annex C, must be deployed on those nodes from which SSI traffic is expected to originate and/or to which SSI traffic is expected to be directed. An unlimited number of DTN applications is possible.

3.4.2 REQUESTING SSI SERVICE

When a user organization wants to arrange for SSI services for its user node(s), the user organization submits a USR to the provider organization that will provide the services. At Stage 1 of SSI deployment, requesting SSI services is an informal, manual administrative procedure.

3.4.3 PUBLISHING SSI PROVIDER CONTACT PLANS

Given a set of USRs, a provider organization develops a PCP for the provider node(s) it administers, negotiating schedule adjustments with the user organization based upon the availability of those provider node(s) and bearing in mind any further direction from the provider organization's authority. The provider organization then distributes the PCP to user organizations so they may administer their user nodes(s) accordingly. At Stage 1 of SSI deployment, publication of the contact plan is an informal, manual administrative procedure.

3.4.4 ISSUING DATA FROM ONE NODE TO ANOTHER NODE

A *user* (a human or a cybernetic artifact that operates a vehicle or instrument) initiates operation of an application at the originating node. The application opens a 'source endpoint' and uses that endpoint to present an application PDU to BP for transmission. BP encapsulates the application data in a bundle and determines a route to the destination node based on the PCP; i.e., it decides which of the nodes with which the local node can physically exchange data (neighboring nodes) is the one that is most likely to forward the bundle to its final destination before the user-specified 'time to live' for this data bundle expires. BP then invokes the services of the underlying CLA to effect transmission of the bundle to that neighboring node.

Each node that receives a bundle whose destination endpoint resides on some other node functions in a similar way: after obtaining the bundle from its CLA, BP determines a route to the destination node and then invokes the services of the underlying CLA to effect transmission of the bundle to the selected neighboring node.

When a bundle arrives at the node on which the bundle's destination endpoint resides, BP delivers the encapsulated application data to the application that is waiting for that bundle at the destination endpoint. The application receives the data and operates on the received data for the benefit of the application's user.

3.4.5 SENDING A FILE FROM ONE NODE TO ANOTHER NODE

Sending a file is a special case of the general procedure for issuing data from one node to another. The application initiated at the source and destination nodes invokes a CCSDS-approved file transfer protocol, such as CFDP, which functions as the 'application' from the point of view of BP.

CFDP, for example, accomplishes this function as follows: At the source node, CFDP divides a source file into CFDP PDUs and presents each PDU to a BP 'UT-layer' adapter.[2] The BP UT-layer adapter presents each CFDP PDU to BP for transmission in a bundle; this adaptation is simplified by the convention that BP node numbers are used as CFDP entity numbers in the SSI. At the destination node, the BP UT layer receives the contents of received bundles, CFDP PDUs, and presents them to CFDP so that the file may be reassembled.

3.4.6 SENDING A BRIEF MESSAGE FROM ONE NODE TO A SET OF NODES

Sending a message is again a special case of the general procedure for issuing data from one node to another. The application initiated at the source and destination nodes invokes a CCSDS-approved message transmission mechanism such as AMS.

AMS, for example, accomplishes this function as follows: Copies of the message that are destined for subscribers that share access to a common SSI node are simply delivered via Internet transport protocols or via message queues, but the copy that is destined for all nonlocal subscribers is received by the node's Remote AMS (RAMS) gateway task. The RAMS gateway functions as an 'application' from the point of view of BP. It presents the message to BP for transmission in a bundle; this adaptation is simplified by the convention that BP node numbers are used as AMS continuum numbers in the SSI. At the destination node, the destination RAMS gateway receives the contents of received bundles (the AMS messages) and republishes them locally.

3.4.7 REPORTING ON THE OPERATIONAL STATE OF A NODE

Network Management Protocol (NMP) (or private ad-hoc) messages reporting on a node's operational state may be simply issued via BP to a destination node as described above, or may be published via AMS. This is a provider/user organization decision.

3.4.8 TROUBLESHOOTING NETWORK BEHAVIOR

Troubleshooting may be performed by provider/user organization personnel and/or by automated mechanisms. Anomalous network behavior is reported by NMP (or private ad-hoc) messages reporting on nodes' operational states. Problem diagnosis is aided by the aggregate processing statistics included in those messages. Remediation is accomplished by transmitting messages that modify the configuration of the affected node(s).

[2] 'UT' is 'unitdata transfer' (for details, see reference [7]).

3.4.9 MODIFYING THE CONFIGURATION OF A NODE

Node reconfiguration is the responsibility of the provider/user organization that administers the node. NMP and Key Distribution Protocol (KDP) (or private ad-hoc) messages directing a change in the configuration of a node are simply issued via BP to the destination node as described above.

3.4.10 SENDING AN EMERGENCY COMMAND

At times it may be necessary to send commands to a spacecraft or landed asset in space that cannot communicate directly with any Earth station and cannot receive bundles via the SSI. (For example, a landed asset may have insufficient power for direct-to-Earth communication and may not have an onboard SSI node, or its onboard SSI node may need to be restarted under mission operations control.) In this case, a delivery agent application must be deployed on an SSI node from which physical transmission to the target asset is possible. A message is sent via BP to the delivery agent application detailing the commands that are to be sent to the target asset and any ancillary information required for this purpose. Upon receipt of this message, the delivery agent application transmits the commands to the target asset. The SCCS-ADD (reference [9]) contains further discussion of this mechanism.

3.4.11 ESTIMATING THE TIME A BUNDLE WILL BE DELIVERED

User organization personnel may use the Bundle Delivery Time Estimation (BDTE) capability, in conjunction with the PCP and the aggregated network processing statistics issued via NMP, to obtain an estimate of the time at which a bundle of given size, transmitted from a given node at a given time, will arrive at its destination endpoint.

4 STAGE 2—INTERNETWORK FUNCTIONALITY

4.1 NETWORK OPERATIONS

4.1.1 SIMPLE NETWORK OPERATIONS

4.1.1.1 General

To utilize internetwork SSI functionality, a flight mission need not deploy any features of the SSI architecture beyond the features included in mission functionality. The transition to internetwork SSI functionality is entirely a matter of implementing within ground network service providers the same automation of basic communication processes that is implemented in vehicles and MOCs in Stage 1. For example, internetwork functionality enables the simple mission architecture shown in figure 3-2 to be modified as shown in figure 4-1, where an additional SSI node is established at the Earth station. Operating an SSI node at the Earth station enables co-location of the SSI node infrastructure with the rest of the SLE/Cross Support Transfer Service (CSTS) and space-link production equipment.

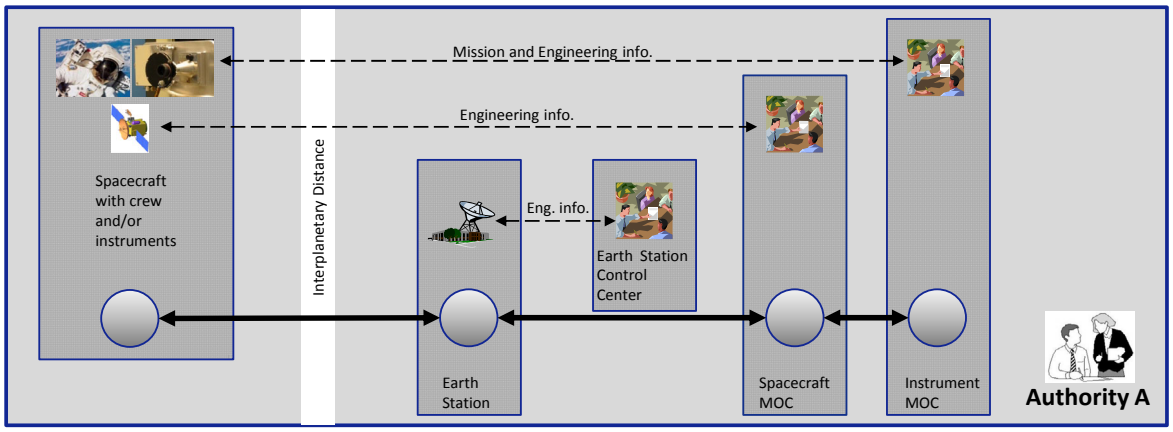


Figure 4-1: Adding a Node at an Earth Station

Operating an SSI node at the Earth station is especially useful for missions that return data from the spacecraft at rates in excess of the maximum terrestrial network data rate supported at the Earth station: each ‘spike’ of high-speed downlink is automatically buffered by the SSI protocols and gradually metered out at the network data rate over the quiet interval preceding the next downlink. This configuration may reduce the need to install expensive high-speed network lines to support high-rate science missions.

A natural extension of this topology would be one that encompasses multiple Earth station nodes (as shown in the example in figure 4-2).

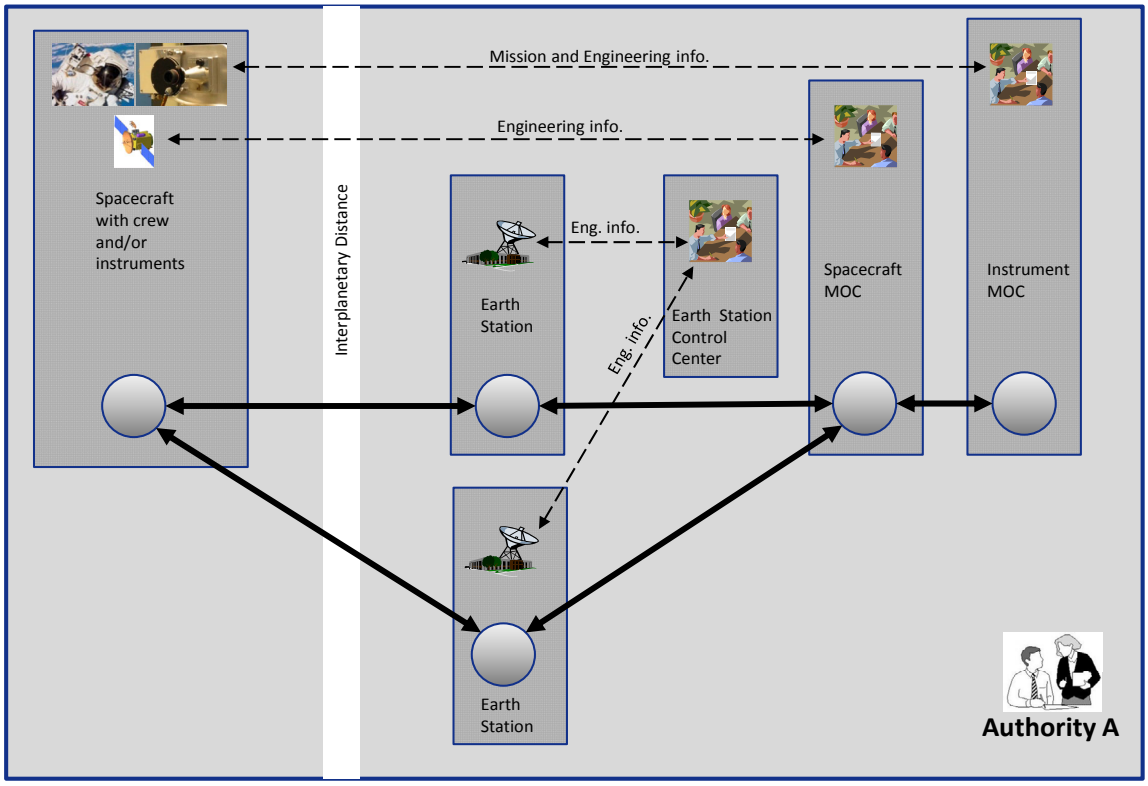


Figure 4-2: Mission Communications Architecture for a Mission Supported by Multiple Earth Stations

In all of these Stage 2 configurations the spacecraft MOC is still responsible for planning, scheduling, configuring, and managing the space links to its spacecraft. Once that link is established, SSI traffic can flow over it.

Many configurations beyond the ones shown here are possible. For example, there might be direct SSI connectivity between the instrument MOC and the Earth station(s); i.e., there might be no need for traffic between the instrument MOC and an Earth station to be routed through the spacecraft MOC. Alternatively, an SSI node might be established at the Earth station control center and that node might or might not be topologically interposed between the MOCs and the Earth stations.

An important variant on the architecture for a mission supported by multiple Earth stations is one in which all of the Earth stations can acquire downlink data from the spacecraft but only a subset of those stations have the ability to uplink data to the spacecraft, as shown in figure 4-3. The SSI protocols automatically can convey data reliably in both directions through this topology using asymmetric routing rules:

– The spacecraft MOC will establish space-link services with one or more Earth stations.

– Data that must be sent to the spacecraft by an Earth station that has only a payload data link can simply be forwarded to the MOC.

– The MOC will in turn forward the data to whichever Earth station will have a bidirectional Telemetry, Tracking, and Command (TT&C) link to the spacecraft at its next communication opportunity, for upload during that contact.

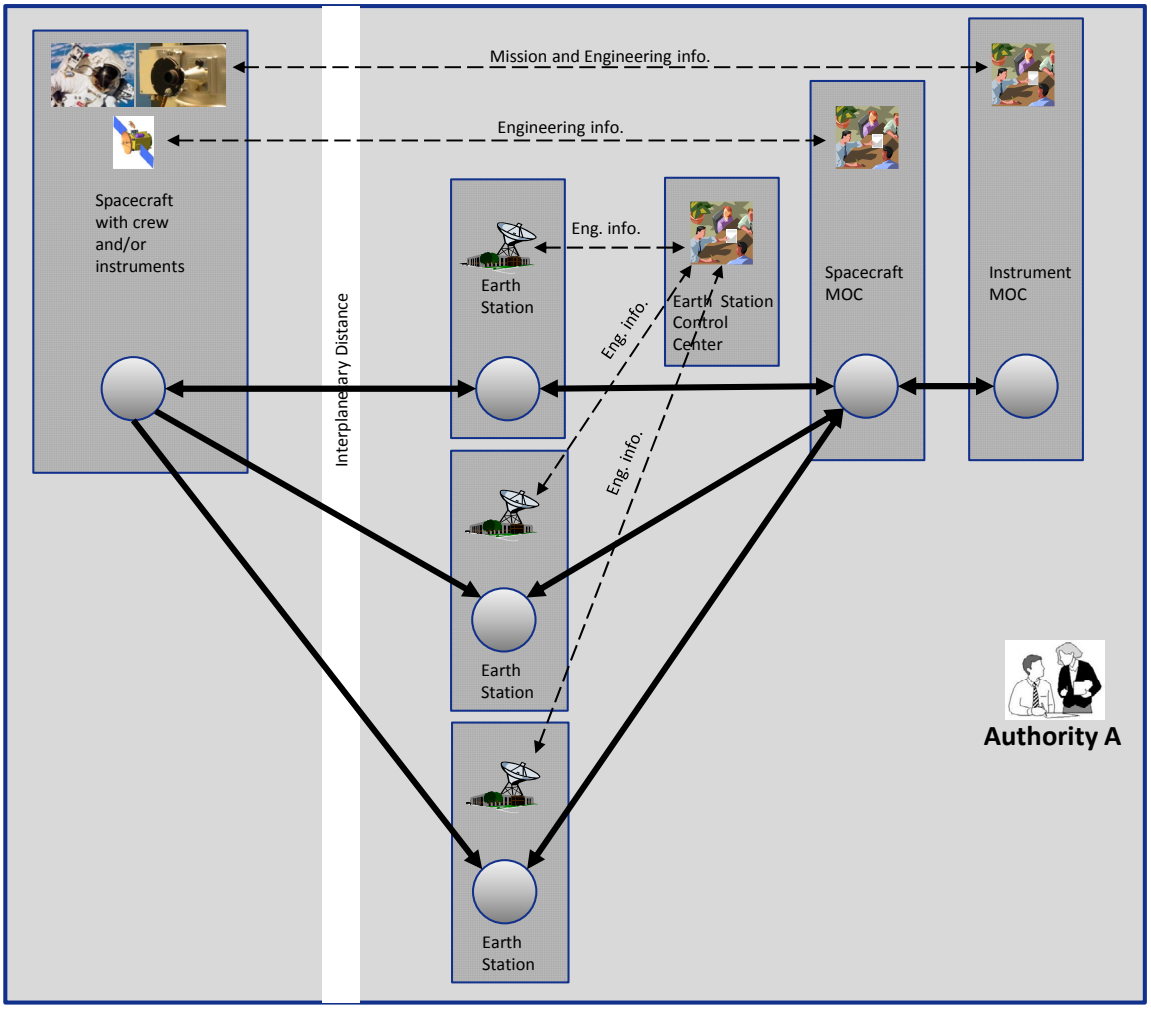


Figure 4-3: Asymmetric Routing through Multiple Earth Stations

4.1.1.2 Coordination of Mission Data Communications

Figure 4-4 depicts the coordination of data flow for a mission supported by multiple Earth stations as shown the examples depicted in figures 4-2 and 4-3. Data flow coordination for other Stage 2 simple network operations scenarios would be similar, involving additional user and provider organizations under a single authority.

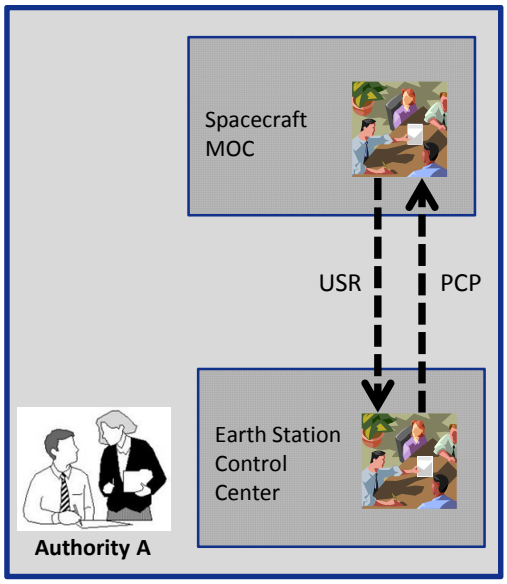


Figure 4-4: Coordination of Mission Data Communications for a Mission Supported by Multiple Earth Stations

4.1.2 RELAY MISSIONS

4.1.2.1 General

The basic SSInet may alternatively be augmented in a different way to support the general relay-supported mission pattern shown in the example in figure 4-5.

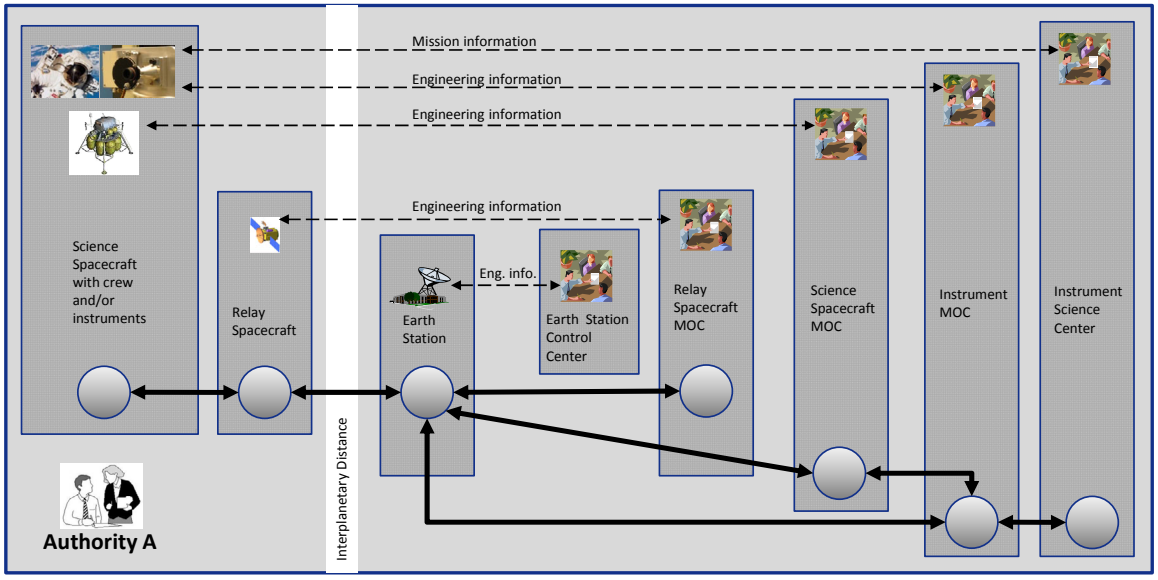


Figure 4-5: Mission Communications Architecture for Relay-Supported Mission

In the scenario depicted in figure 4-6, the basic SSInet has been extended to include nodes for:

- a science spacecraft, possibly on a planetary surface;
- the science spacecraft MOC;
- a science data end-user site, which is distinct from the instrument MOC.

This configuration supports these additional information flows:

- science spacecraft engineering information (science spacecraft commands and telemetry) between the science spacecraft and the science spacecraft MOC;
- science spacecraft instrument science information, flowing between the science spacecraft's instrument(s) and the corresponding science data end-user site(s).

It should be noted that the relay spacecraft in this example may not necessarily be a dedicated relay; it might instead be a science spacecraft that also functions as a relay. Furthermore, this example shows direct SSI automated data communications between the instrument MOC and the Earth station control center—an operating model that today's missions do not adopt but that the SSI architecture could support.

This relay-supported configuration could also be augmented to include multiple science spacecraft, multiple relay spacecraft, and/or multiple Earth stations, all operating in the closed network topology of a single mission.

4.1.2.2 Coordination of Mission Data Communications

Figure 4-6 depicts the coordination of mission data communications for the relay example shown in figure 4-5. It should be noted that the relay spacecraft acts as a provider node for the science spacecraft, and as a user node of the Earth station.

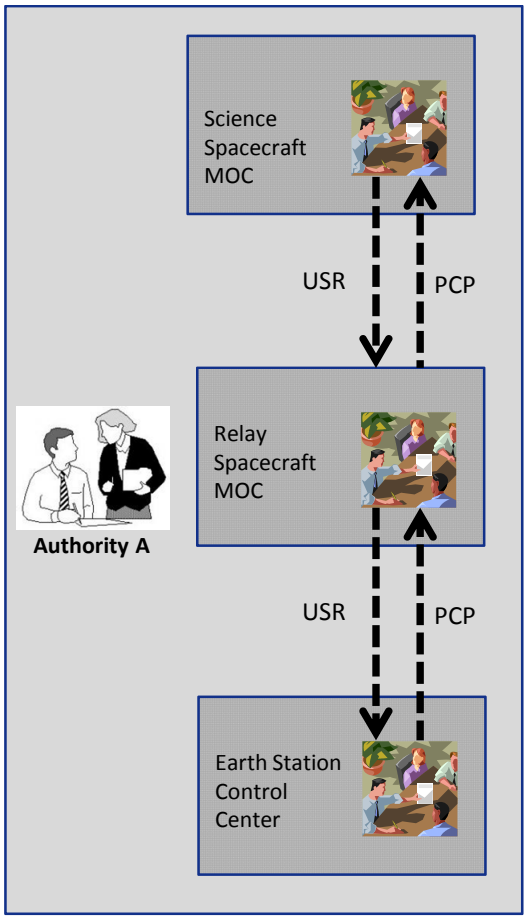


Figure 4-6: Coordination of Mission Data Communications for a Relay Mission

4.1.3 CROSS-SUPPORTED MISSIONS

4.1.3.1 General

Implementing SSI architectural features within ground network service providers introduces the possibility of offering SSI network service that is cross supported among multiple providers. Figure 4-7 is a simple illustration.

In this example, a second *subSSInet*, configured, managed, and operated by a second authority, has been added to the basic communications architecture depicted in figure 4-1.

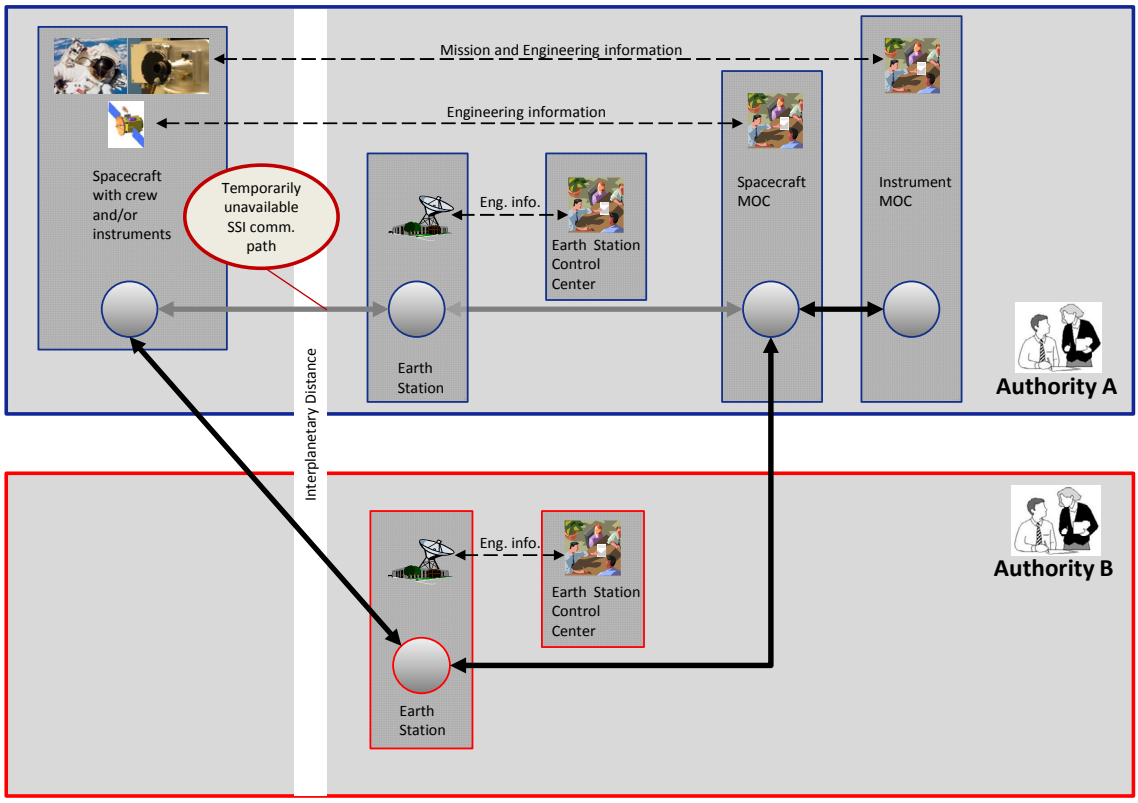


Figure 4-7: Cross-Supported Adaptation of Simple Mission Architecture

This expanded SSInet enables information to flow between Authority A's spacecraft (and instrument) and MOC(s) even when Authority A's Earth station is unavailable for this purpose (gray arrows indicate the temporarily unavailable SSI communications path within Authority A). Authority A has made arrangements (via an NSA) with Authority B for an Authority B provider organization to provide service to Authority A's user node. As shown, information is conveyed in bundles forwarded from Authority A's mission control center and/or SOC to Authority B's Earth station control center, and from there to Authority B's Earth station, and then onward to Authority A's spacecraft.

Ad-hoc protocols for network management and key distribution, while arguably serviceable in Stage 1 SSI operations, are not appropriate for the potentially cross-supported operations of Stage 2. NMP and KDP must be formally standardized at this point.

4.1.3.2 Coordination of Mission Data Communications

Given the implementation of SSI architectural features within ground network service providers, NSAs between authorities enable the coordination of mission data communications to extend across authority boundaries. Figure 4-8 depicts the mission coordination for the example shown in figure 4-7.

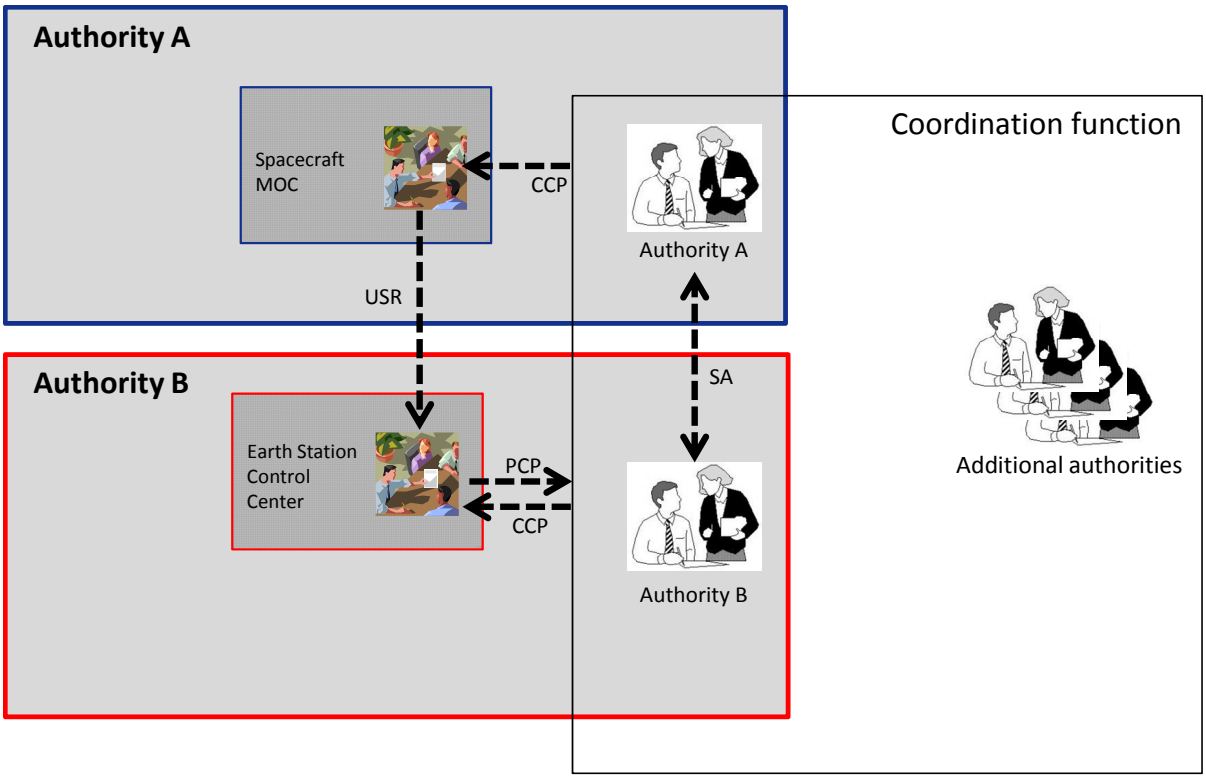


Figure 4-8: Coordination of Mission Data Communications in a Simple Cross-Support Mission

4.1.4 RELAY MISSIONS

4.1.4.1 General

By analogy to the simple relay mission topology shown earlier (in figure 4-5), an example for a cross-supported relay mission is shown in figure 4-9. In this scenario, Authority A has an NSA with Authority B that allows the Authority B Earth station and relay spacecraft to provide service to the Authority A mission.

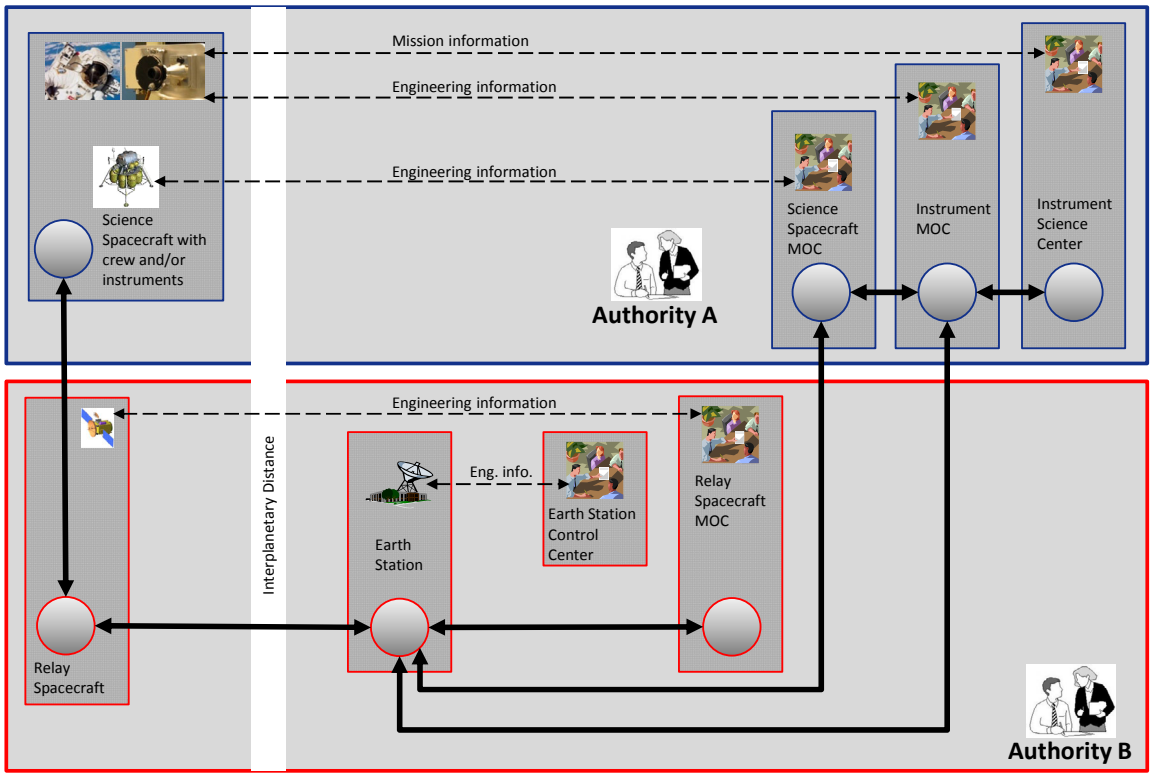


Figure 4-9: Mission Architecture for a Cross-Supported Relay Mission

4.1.4.2 Coordination of Mission Data Communications

The corresponding flow of coordination of mission data communications coordination for the example in figure 4-9 is shown in figure 4-10.

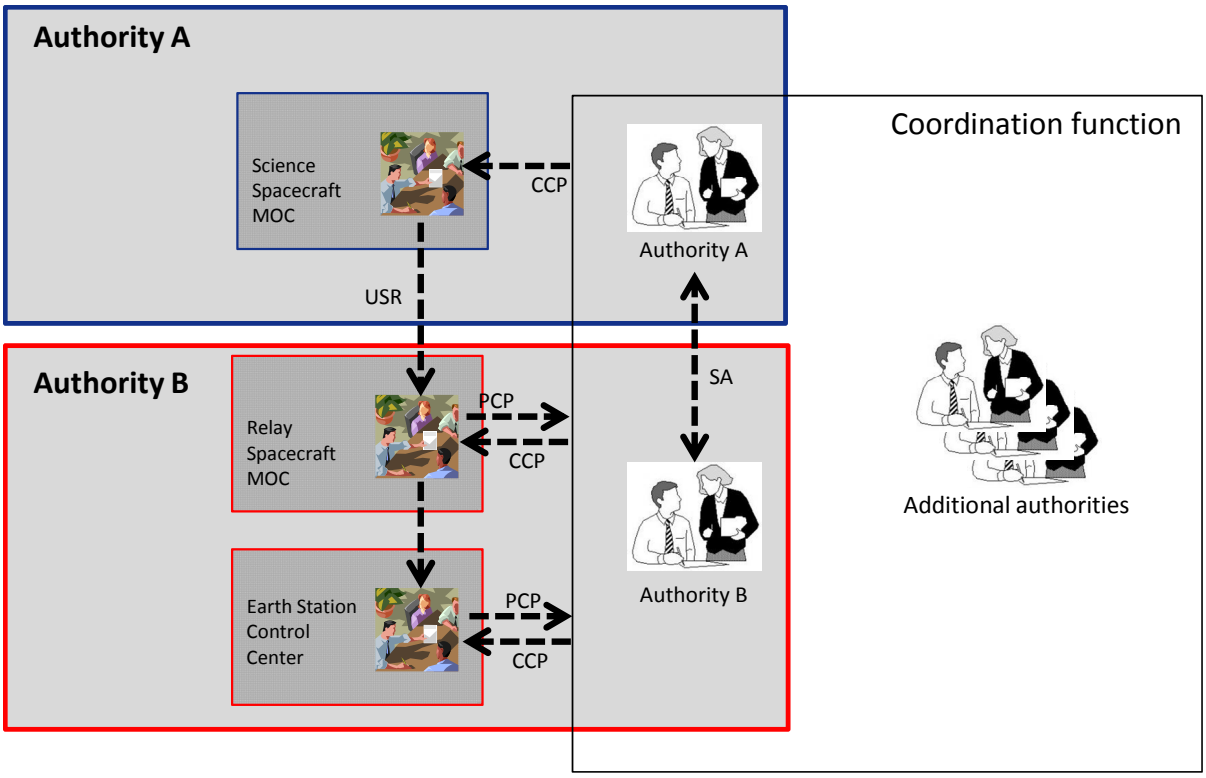


Figure 4-10: Coordination of Mission Data Communications in a Cross-Supported Relay Mission

This basic topology can be readily extended to include multiple Earth stations, multiple relay orbiters, and/or multiple science spacecraft.

4.1.5 INDIRECT CROSS SUPPORT

4.1.5.1 General

The SSI architecture also enables user nodes to obtain network service from provider nodes where no direct NSA has been negotiated between the user organization's and provider organization's authorities. The indirect cross support example shown in figure 4-11 is made possible by a PA between two provider organizations' authorities. The PA between Authority A and Authority B allows the Authority B Earth station to provide support when the Authority A Earth station is unavailable (gray arrows indicate the unavailable SSI communications path within Authority A). Such an agreement could similarly allow a relay spacecraft operated by Authority B to provide support when a relay spacecraft operated by Authority B is unavailable.

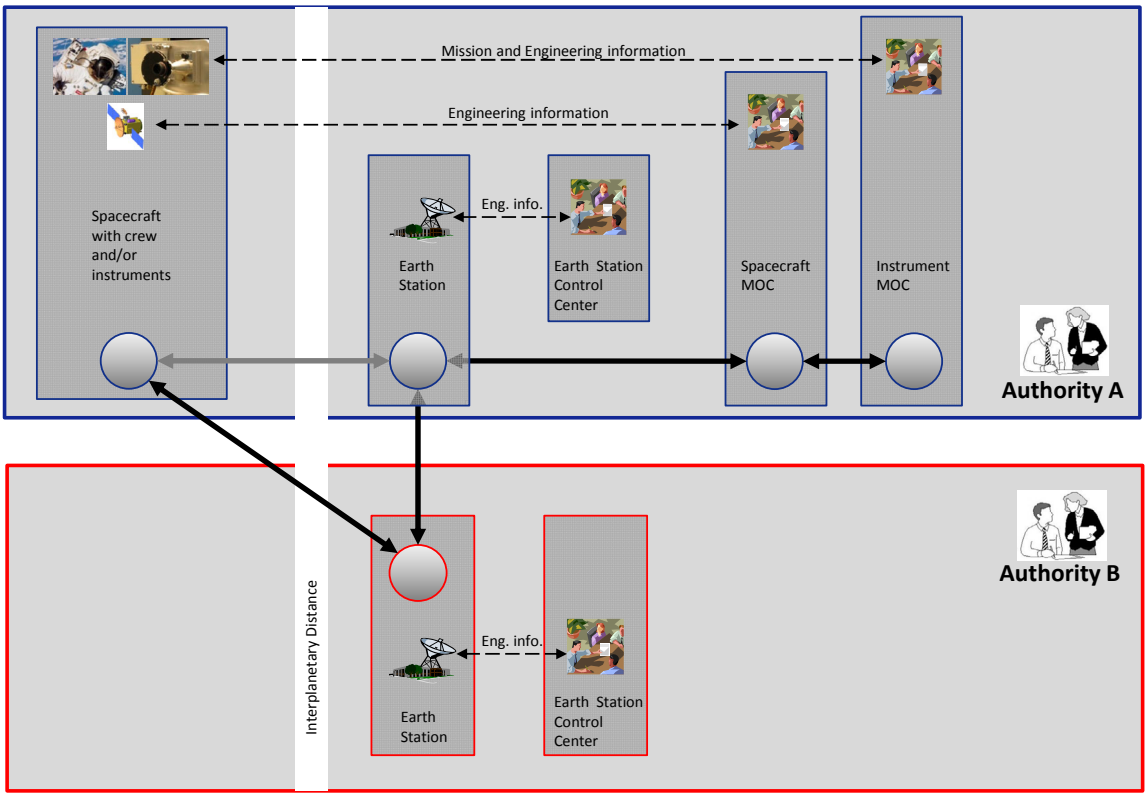


Figure 4-11: Indirect Cross Support for a Simple Mission

4.1.5.2 Coordination of Mission Data Communications

The flow of mission data communications coordination for the example shown in figure 4-11 includes additional elements, as shown in figure 4-12.

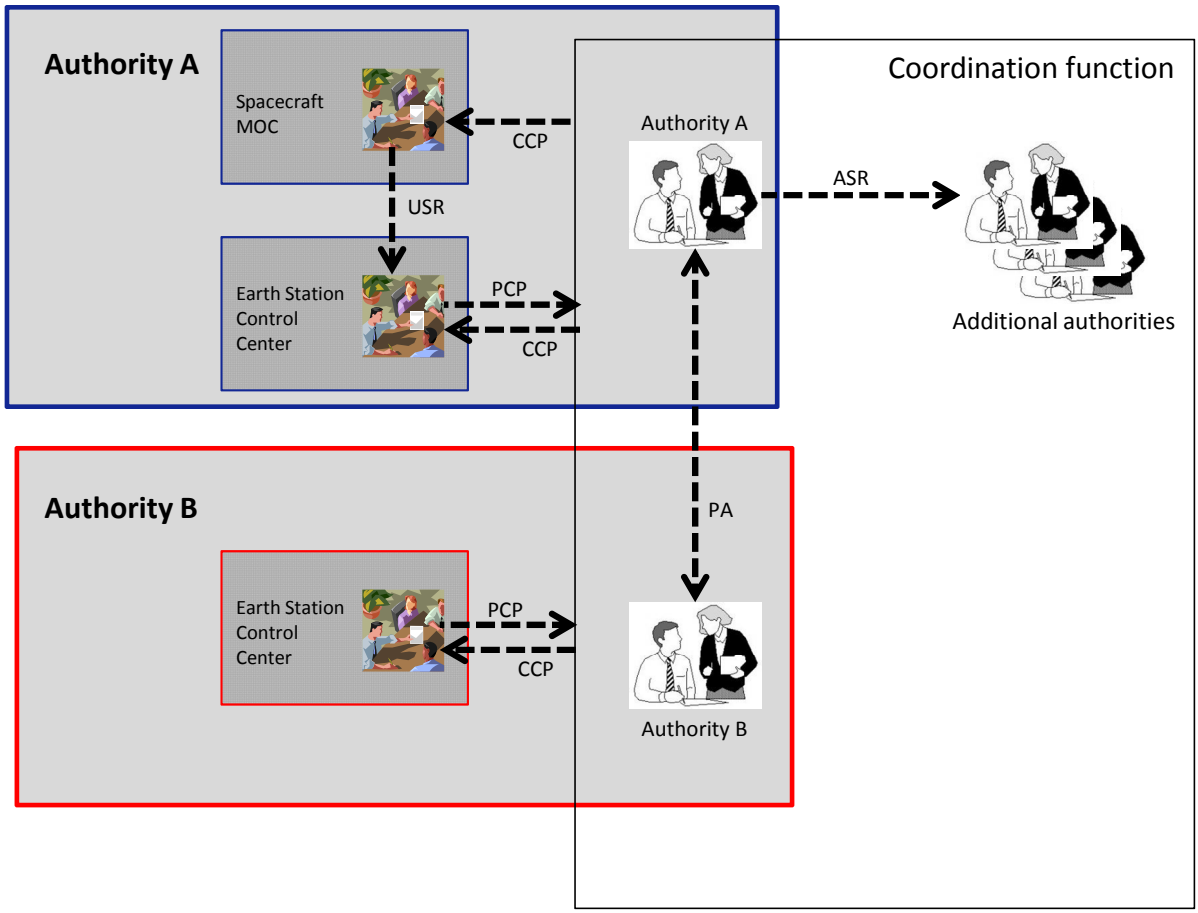


Figure 4-12: Coordination of Mission Data Communications for Indirect Cross Support for a Simple Mission

4.1.6 INDIRECT CROSS SUPPORT WITH MORE THAN ONE AUTHORITY

4.1.6.1 General

The simple indirect cross-supported mission topology shown above can also be extended to include more complex indirect cross-support scenarios, such as the example shown in figure 4-13, which involves an additional authority. In this scenario, Authority A has an NSA with Authority B, enabling the Authority B Earth station to provide service to the Authority A mission. Authority B has a PA with Authority C that allows the Authority C Earth station to provide support when the Authority B Earth station is unavailable (gray arrows indicate the unavailable SSI communications path).

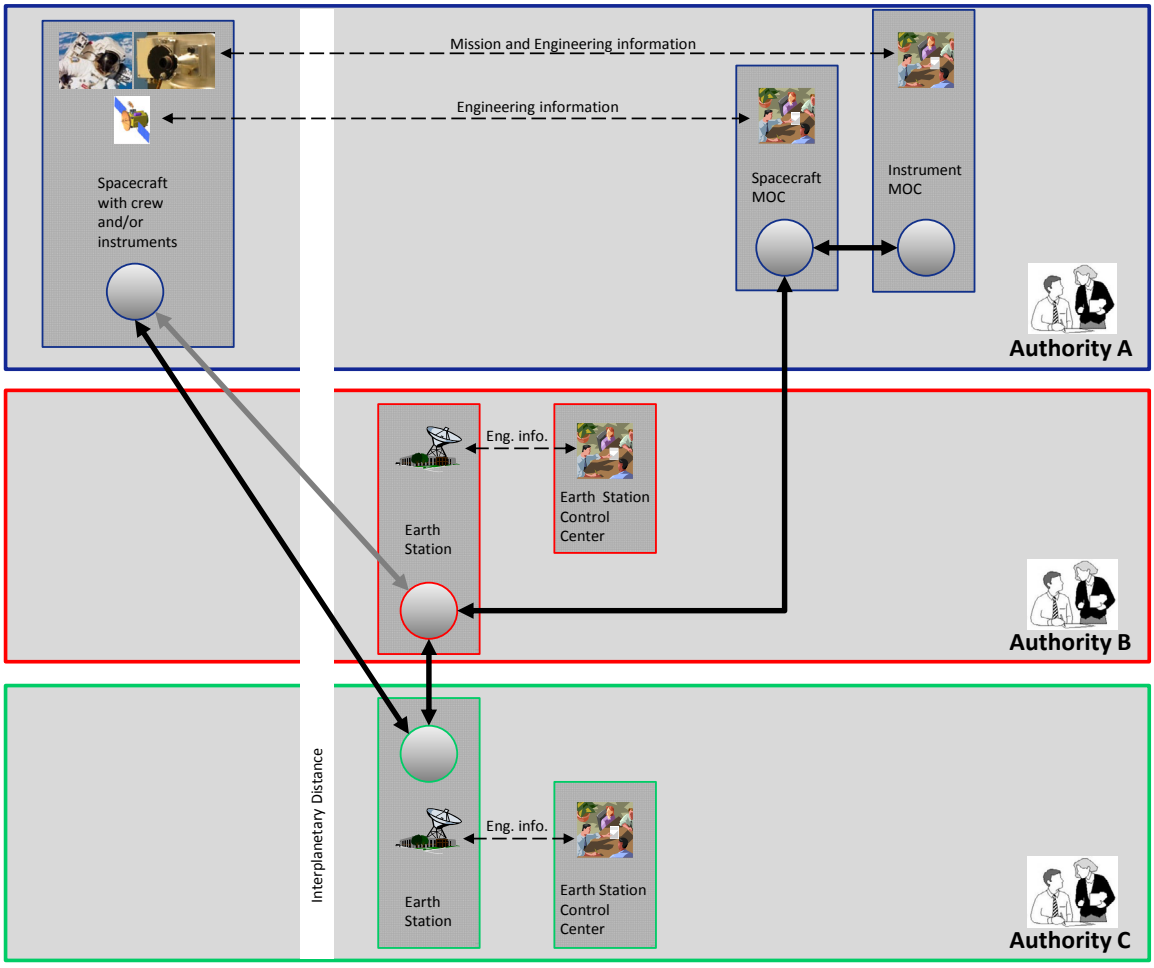


Figure 4-13: Indirect Cross Support Involving Multiple Authorities for a Simple Mission

4.1.6.2 Coordination of Mission Data Communications

The flow of mission data communications coordination for the example in figure 4-13 includes additional elements as shown in figure 4-14.

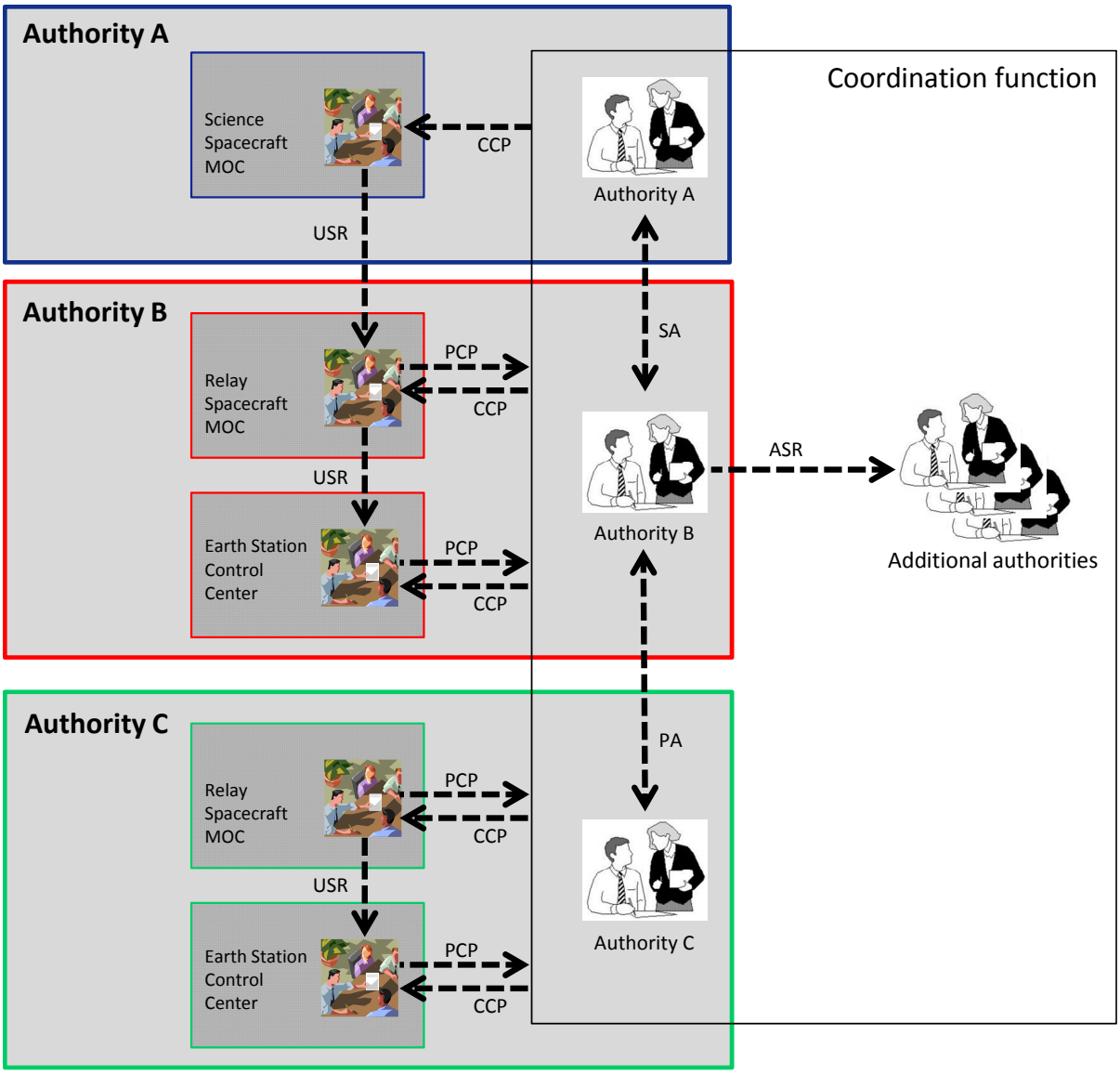


Figure 4-14: Coordination of Mission Data Communications for Indirect Cross Support Involving Multiple Authorities for a Simple Mission

4.1.7 INDIRECT CROSS SUPPORT FOR A RELAY SCENARIO

4.1.7.1 General

An analogous example of indirect cross support for a relay mission is shown in figure 4-15. In this scenario, Authority A has an NSA with Authority B, enabling the Authority B Earth station and relay spacecraft to provide service to the Authority A mission. Authority B has a PA with Authority C that allows the Authority C Earth station and relay spacecraft to provide support when the Authority B Earth station and relay spacecraft are unavailable (gray arrows indicate the unavailable SSI communications path).

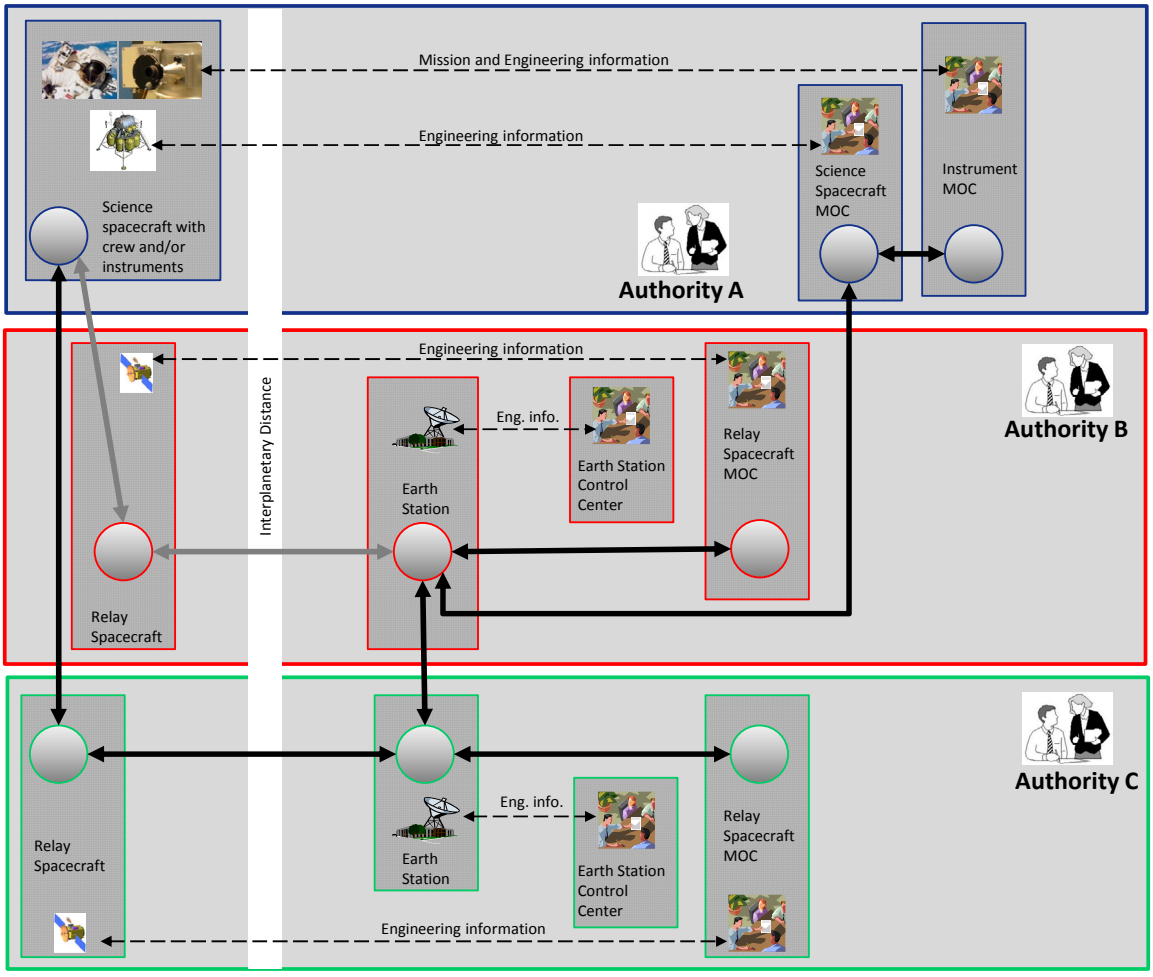


Figure 4-15: Indirect Cross Support for a Relay Mission

Alternatively, Authority C's Earth station could transmit to Authority B's orbiter, which then could forward the bundles to the science spacecraft as usual.

And again this configuration could be augmented to include multiple relay spacecraft and/or multiple Earth stations for Authority C. Moreover, Authority C might likewise be operating a science mission of its own.

4.1.7.2 Coordination Of Mission Data Communications

Figure 4-16 shows the corresponding flow of coordination for the example depicted in figure 4-15 (indirect cross support for a relay mission).

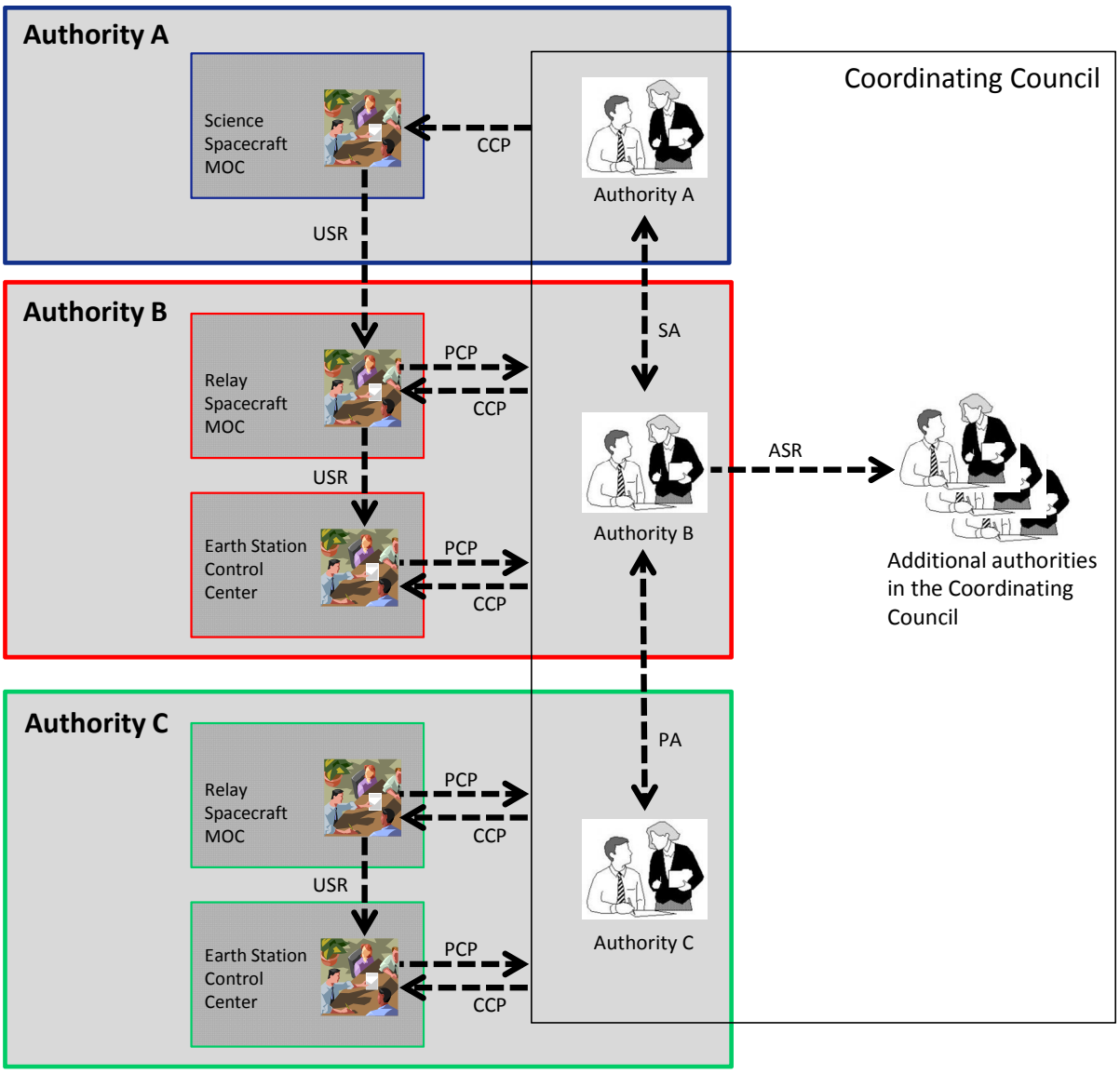


Figure 4-16: Coordination of Mission Data Communications for Indirect Cross Support for a Relay Mission

4.1.8 NETWORK COORDINATION ELEMENTS

4.1.8.1 Overview

In addition to the elements in Stage 1 of SSI deployment, Stage 2 will include the following elements (elements whose description significantly changed from the previous stage are also listed).

4.1.8.2 Provider Node

In Stage 2, provider nodes additionally reside in Earth stations and/or in Earth station control centers.

4.1.8.3 User Node

In Stage 2, user nodes additionally reside in Earth stations and/or in Earth station control centers.

4.1.8.4 User Schedule Request

In Stage 2, USRs are standardized.

4.1.8.5 Provider Contact Plan

In Stage 2, PCPs are standardized. Provider organizations must submit PCPs to the SSI coordination function to facilitate development of the CCP.

4.1.8.6 Authority

In Stage 2, because ground network service providers are among the SSI provider nodes, authorities may arrange for a provider organization under one authority to provide network cross support to a user organization under another authority via NSAs. A user organization's authority establishes an NSA with the authority responsible for the provider organization(s) that will supply communications services to the user organization. Authorities may also negotiate PAs to coordinate indirect cross support between provider organizations under separate authorities. Authorities will develop an ASR to request SSI provider support from another authority.

4.1.8.7 Network Service Agreement

An NSA is a written agreement between a user organization's authority and the authority responsible for the provider organization(s) that will supply the needed communications services. The NSA documents the SSI services that the provider organization(s) will provide to the user organization. NSAs will take into account the resource constraints of the provider organization(s) and the aggregate anticipated needs of its users.

4.1.8.8 Peering Agreement

PAs are negotiated between authorities to enable SSI provider support across authority boundaries. PAs typically include definitions of interfaces between provider organizations in the different authorities.

It should be noted that, while an NSA is an agreement between a user organization's authority and a provider organization's authority, a PA is an agreement between the authorities of two provider organizations.

4.1.8.9 Authority Schedule Request

An ASR is an authority's request for SSI provider support from the provider organizations of some other authority.

4.1.8.10 SSI Coordination Function

The scheduling offices of authorities participating in the SSI cooperatively perform SSI network planning and management functions that require coordination across multiple authorities, reconciling ASRs with PCPs. The staff of these cooperating scheduling offices are responsible for developing the CCP and distributing it to SSI provider organizations and user organizations. It should be noted that such scheduling offices are already in operation as of the time of publication of this Informational Report, e.g., the ESA scheduling office, the NASA Network Integration Management Office (NIMO), and the flight control teams of various relay-capable spacecraft missions.

4.1.8.11 Composite Contact Plan

The CCP (known as the 'network contact plan' in the SSI Operations Concept, reference [1]) establishes the temporal windows and communications capabilities (e.g., bandwidth) of all individual node-to-node links in the SSI.

4.2 PRINCIPLES

The following principles pertain to Stage 2:

a) A provider node may support a mission that is under a different authority (i.e., interagency cross support is supported).

b) Provider nodes in the SSInet that are supporting a given mission may be under multiple authorities (i.e., interagency indirect cross support is supported).

c) At this stage of SSI implementation, the coordination of mission data communications is still not an automated process.

d) A coordinating function is responsible for ensuring successful negotiations among member authorities.

4.3 PROCEDURES

4.3.1 REQUESTING SSI SERVICE

At Stage 2 of SSI deployment, requesting SSI services is a formally defined, but still manual administrative procedure.

4.3.2 PUBLISHING SSI PROVIDER CONTACT PLANS

At Stage 2 of SSI deployment, publication of the contact plan is a formally defined, but still manual administrative procedure.

4.3.3 REQUESTING CROSS SUPPORT

In Stage 2, two types of agreements may be negotiated between authorities to accomplish mission objectives: NSAs and PAs. If a user organization requires support from a provider organization in a different authority, this support may be negotiated in an NSA. If the provider organizations under an authority cannot support the communication needs of a user organization, the authority may arrange for another authority to provide support to that user organization according to a previously established PA. If it is necessary to arrange for user support with one or more other authorities, the authority will develop an ASR based upon the aggregate needs of the user organizations for which it has established NSAs. The authority will submit its ASR to the SSI coordination function to request the required SSI services. At Stage 2 of SSI deployment, this is a manual administrative procedure.

4.3.4 PUBLISHING THE COMPOSITE CONTACT PLAN

Given a set of ASRs submitted by authorities and the PCPs submitted by individual provider organizations, the SSI coordination function generates the CCP, bearing in mind the PAs in effect among authorities. Subsets of the CCP are then distributed to provider and user organizations. At Stage 2 of SSI deployment, this is a manual administrative procedure.

The amount of information conveyed to each node is scalable; it could be limited to nearest-neighbor contact information or could entail full end-to-end network information. The more information a given node has, the better it can make routing decisions in terms of end-to-end service latency.

4.3.5 ESTIMATING THE TIME A BUNDLE WILL BE DELIVERED

User organization personnel may use the BDTE capability, in conjunction with the CCP and the aggregated network processing statistics issued via NMP, to obtain an estimate of the time at which a bundle of given size, transmitted from a given node at a given time, will arrive at its destination endpoint.

5 STAGE 3—ADVANCED FUNCTIONALITY

5.1 NETWORK OPERATIONS

5.1.1 OVERVIEW

To utilize advanced SSI functionality, a flight mission deploys the automated network management capabilities provided by the DTN NMP and KDP and adopts operational procedures that utilize these protocols. Operations flows remain unchanged from Stage 2.

5.1.2 AUTOMATED NETWORK OPERATIONS

5.1.2.1 General

All of the network topologies supported in Stage 2 continue to be supported in Stage 3.

5.1.2.2 Coordination of Mission Data Communications

In Stage 3, the coordination of network communication operations changes as automation is introduced. Figures 5-1 through figure 5-5 depict the mission data communications coordination flows for the examples shown in figures 4-7, 4-9, 4-11, 4-13, and figure 4-15, respectively.

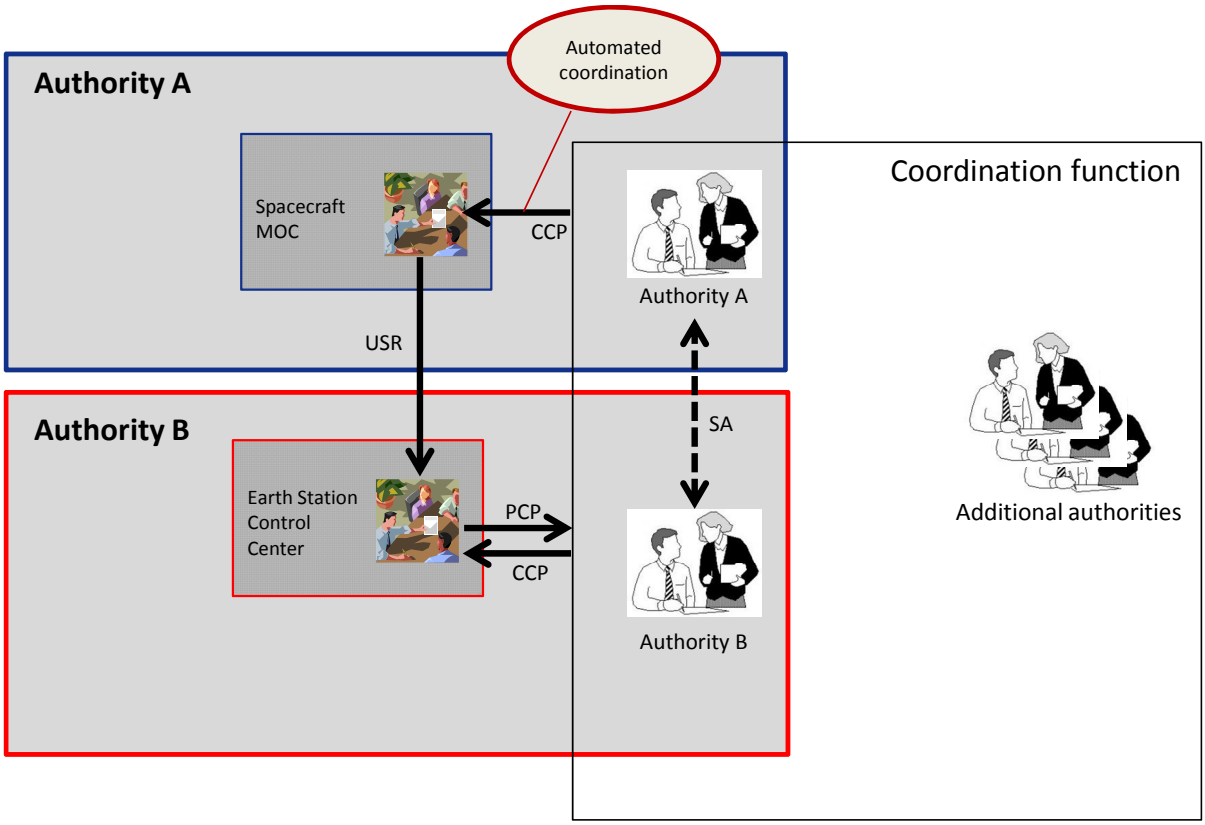


Figure 5-1: Automated Coordination of Mission Data Communications in a Simple Cross-Support Mission (Corresponds to Figure 4-7 Example)

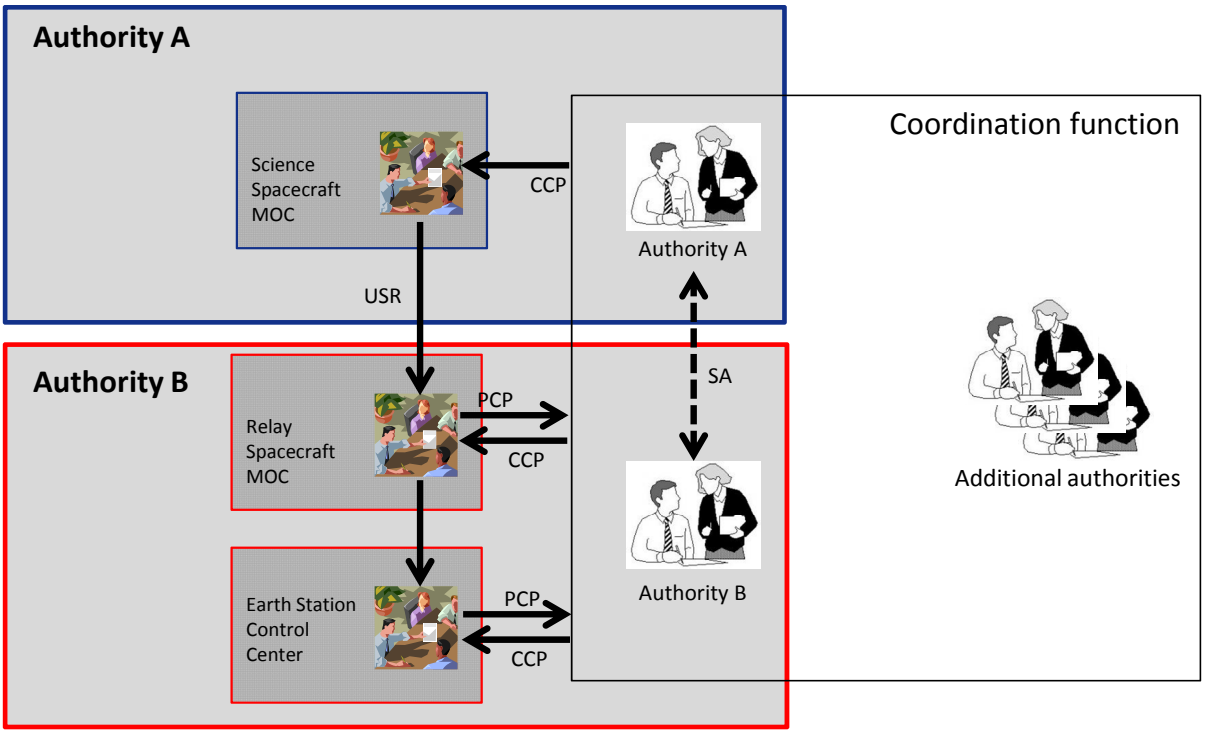


Figure 5-2: Automated Coordination of Mission Data Communications in a Cross-Supported Relay Mission (Corresponds to Figure 4-9 Example)

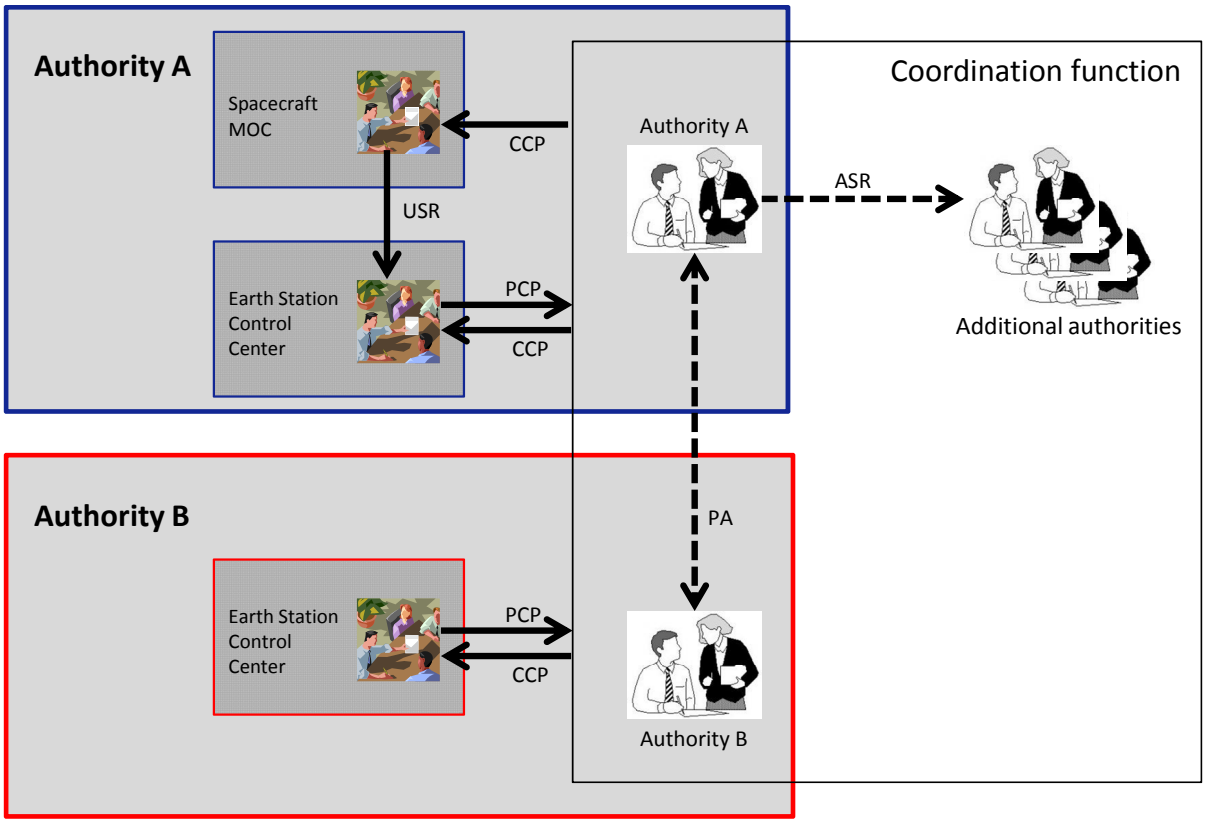


Figure 5-3: Automated Coordination of Mission Data Communications for Indirect Cross Support for a Simple Mission (Corresponds to Figure 4-11 Example)

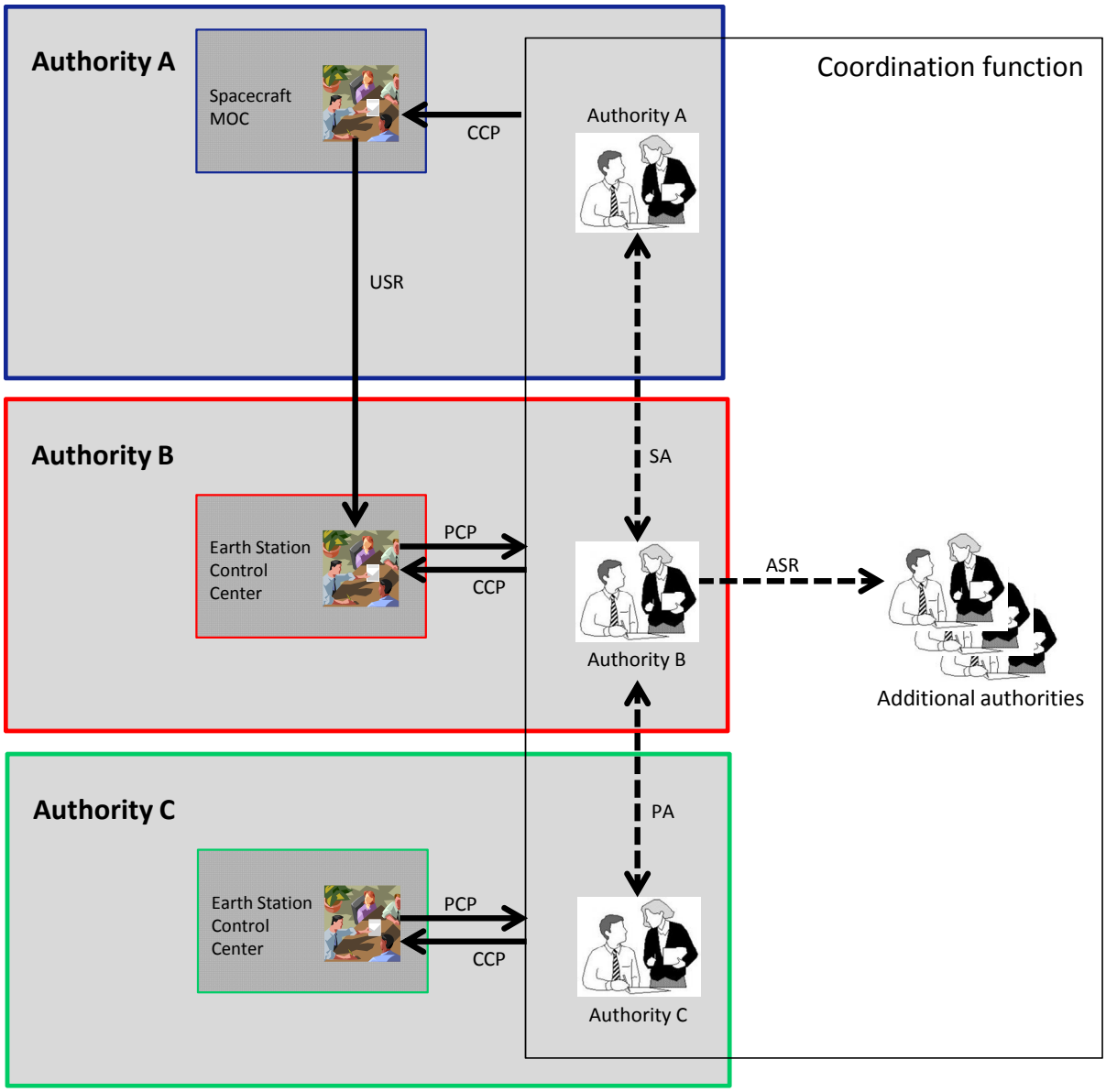


Figure 5-4: Automated Coordination of Mission Data Communications for Indirect Cross Support Involving Multiple Authorities for a Simple Mission (Corresponds to Figure 4-13 Example)

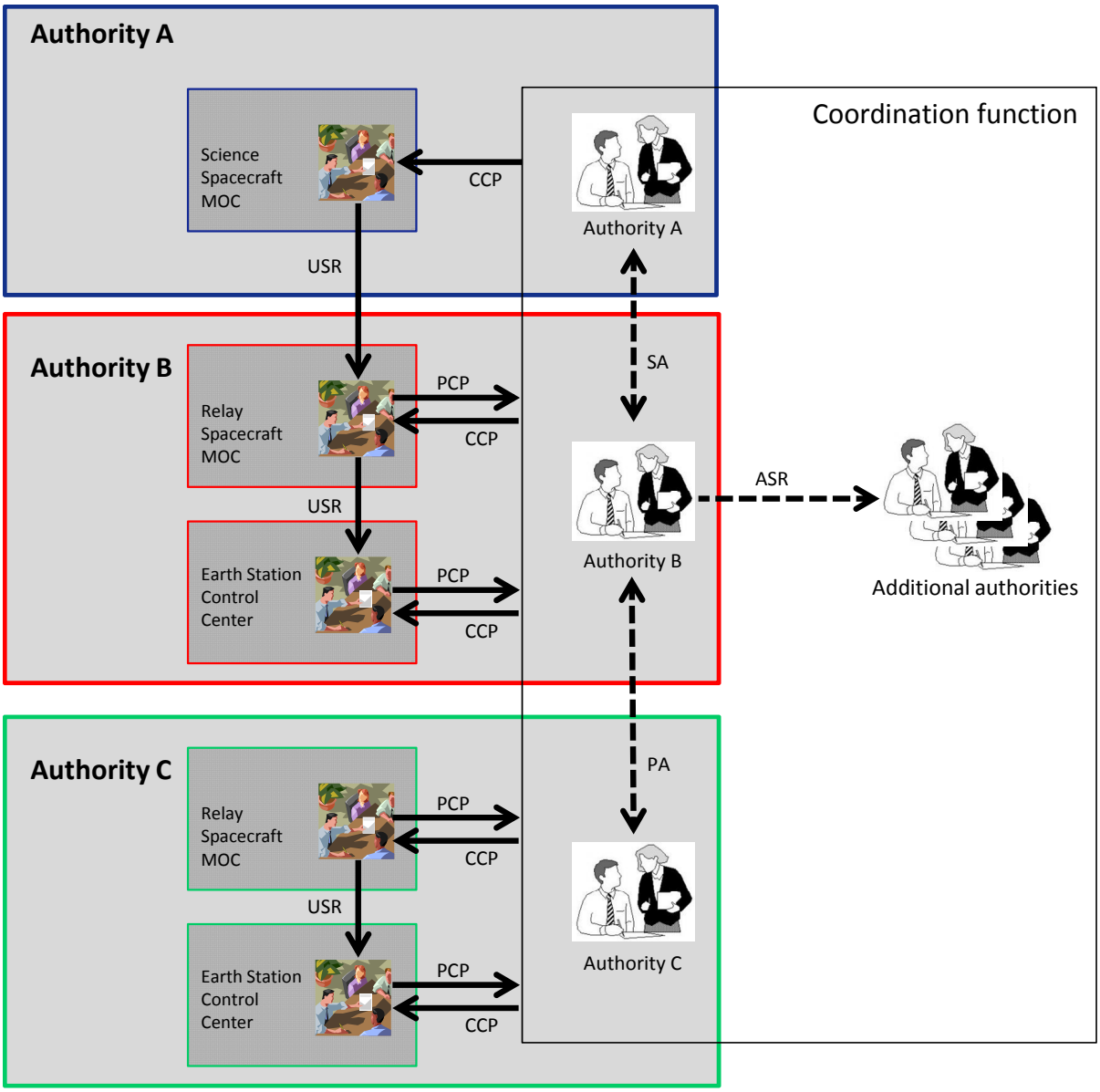


Figure 5-5: Automated Coordination of Mission Data Communications for Indirect Cross Support for a Relay Mission (Corresponds to Figure 4-15 Example)

5.1.3 NETWORK COORDINATION ELEMENTS

No additional elements of network coordination are introduced at Stage 3.

Since there may be coexisting SSI participants in different stages of SSI implementation, the deployment of automated network management capabilities does not necessarily imply that the roles of the coordination elements introduced in earlier stages are diminished. The automated functions must be capable of interacting with SSI participants whose interfaces are not automated.

5.2 PRINCIPLES

The following principles pertain to Stage 3:

– The coordination of mission data communications is an automated process.

5.3 PROCEDURES

5.3.1 DISTRIBUTING SECURITY KEYS

Distribution of security keys is initiated via KDP by the user or provider organization that is responsible for the nodes receiving the new keys. Bundles containing new keys are themselves encrypted in keys that are private to those organizations, so that they may be securely forwarded by nodes operated by other organizations.

5.3.2 REVOKING A SECURITY KEY

Revocation of a security key is initiated via KDP by the user or provider organization that is responsible for the node to which the key revocation is directed. Bundles containing key revocation are accompanied by integrity hash codes computed in keys that are private to the revoking organizations, so that their integrity can be verified at the receiving nodes.

5.3.3 DETECTING A PROBLEM IN THE NETWORK

Network processing statistics and diagnostic messages are automatically conveyed via NMP to the user and provider organizations that are responsible for the nodes issuing that information. User and provider organizations are responsible for monitoring this information, detecting anomalies, and analyzing those anomalies, using NMP to obtain additional diagnostic information as applicable.

5.3.4 REMEDYING A NETWORK PROBLEM

On determination of a problem requiring reconfiguration of a node, the user or provider organization responsible for that node uses NMP to convey reconfiguration commands to the node and/or distribution of revisions to the CCP. The results of this management activity will appear in the network processing statistics and diagnostic messages subsequently issued by the reconfigured node.

ANNEX A

DEFINITION OF TERMS

TERM	DEFINITION
administratively heterogeneous	If nodes are configured, managed, and operated by more than one authority, the nodes are said to be administratively heterogeneous.
administratively homogeneous	If all nodes in a single subnet are configured, managed, and operated by a common authority, the subnet is said to be administratively homogeneous.
advanced functionality	The automation of internetwork functionality by the deployment of automated network management capabilities, as provided by the DTN NMP and KDP, and the adoption of operational procedures that utilize these protocols, as described in section 5.
application	A cybernetic artifact (typically comprising multiple constituent cybernetic artifacts distributed among multiple computing devices) that includes at least one sender and at least one receiver of application data units.
application data units	The user data units encapsulated in the PDUs of an application protocol.
application protocol	The protocol at the highest layer in a stack.
application protocol data plane	A data plane at the Application Layer in a protocol stack (also known as an Application-Layer data plane),
Application-Layer data plane	A data plane at the Application Layer in a protocol stack (also known as an application protocol data plane).
authority	A single functionally autonomous organization (such as a space agency or commercial space flight operator) that configures, manages, and operates one or more SSI nodes.
bits	Binary digits.
block	Bundles aggregated by LTP for transmission.
bundle	The PDUs employed by BP.
communicating entities	Data senders and receivers.
communication protocol	A set of rules for accomplishing data communication, to which both the sender and receiver of data units must adhere.

TERM	DEFINITION
convergence-layer adapter	A cybernetic artifact that presents BP bundles to a specific convergence-layer protocol for transmission and extracts BP bundles from convergence-layer PDUs.
Convergence-layer protocol	A protocol underlying BP that enables virtual transmission from one BP node to another.
data communication	The automatic copying of data units from some location in the memory of some computing device to some other location in the memory of some (often distant) computing device.
data plane	A set of entities assembled to enable data communication conforming to some single protocol among an arbitrary population of computing devices.
data unit	A bounded sequence of octets.
DTN applications	Applications designed for use over the DTN network infrastructure; they are implemented to utilize CFDP and other DTN Application-Layer services (optionally) over a BP network.
dtnet	A set of SSI nodes among all of which the exchange of DTN bundles is possible.
encapsulation	Transmittal of some number of octets of protocol-specified header data before transmittal of some sequence of octets of user data (possibly followed by transmittal of some number of octets of protocol-specified trailer data after transmittal of those user data octets).
endpoint	The source or destination of a bundle; endpoints are abstract locations in the network topology, identified by strings called ‘endpoint IDs’.
entities	Data senders and receivers.
exchange	The transmittal and receipt of PDUs among devices.
forwarding	The sending of PDUs received by an intermediate receiver; forwarding is governed by network protocol on the corresponding data plane.
Header	Some number of octets of protocol-specified data that are transmitted before some sequence of octets of encapsulated user data.
internet	A set of SSI nodes among all of which the exchange of IP datagrams is possible.
Internet applications	Applications designed for use in the Internet and implemented to utilize protocols from the Internet ‘protocol suite’.

TERM	DEFINITION
internetwork functionality	The extension of communication process automation to ground network service providers, enabling expanded coordination of missions, as described in section 4.
layer	The level of a protocol involved in a virtual transmission; layers in a stack are ordered according to the order of transmission, with the first sender considered to be at the highest layer of the stack and the protocol of the subsequent underlying senders at corresponding lower layers.
link service adapter	A cybernetic artifact that presents LTP segments to a specific link service protocol for transmission and extracts LTP segments from link service PDUs.
link service protocol	A protocol underlying LTP that enables virtual transmission from one LTP engine to another.
mission functionality	The automation of the basic communication processes that might be performed for the MOC(s) and vehicle(s) of a single space flight mission, as described in section 3 above.
network	Data plane whose protocol is a network protocol.
network automaton	A collection of senders and receivers (entities) at all layers of some protocol stack that includes at least one network protocol.
network infrastructure	The stacked underlying network(s) and other data planes that make communication within the application protocol data plane(s) possible.
network protocol	A protocol that includes rules for forwarding.
network system	One or more application protocol data planes and the supporting network infrastructure common to those application protocol data planes.
node number	A positive, non-zero integer that is assigned to an SSI node by its authority for the purpose of uniquely identifying that SSI node.
octet	A sequence of eight binary digits (bits) of data.
payload	A bundle’s encapsulated user data unit.
physical transmission	Transmission of a PDU by a sending entity by modulation of a signal in some electromagnetic or acoustic medium.
protocol	A set of rules for accomplishing data communication, to which both the sender and receiver of data units must adhere.
protocol data units	Data units whose structure and semantics are prescribed by a protocol, and which encapsulate user data units.

TERM	DEFINITION
provider node	An SSI node that acts as an intermediate relay node for end-to-end network services.
receiver	A cybernetic artifact operating on a device to which a data unit is copied.
reception	The data communication actions of the receiver.
segment	A portion of an LTP block that is small enough to fit in Link-Layer transmission frame.
sender	A cybernetic artifact operating on a device where some data unit to be transmitted originally resides.
service number	The identifying number of a recognized application function; service numbers are reserved for specified applications by registration with SANA.
SSI node	A physical element, equipped with a computing device, that is the locus of operation of a network automaton and may therefore be regarded as an active participant in network communications.
SSInet	One of the networks, built on either Internet or DTN architecture, that are interconnected to form the Solar System Internet; an SSInet may be either an internet or a dtnet.
stack	The ordered set of protocols involved in a virtual transmission, with the first sender considered to be at the highest layer of the stack and the protocol of the subsequent underlying senders at corresponding lower layers.
subdtnet	An administratively homogeneous subset of a larger dtnet that is administratively heterogeneous.
subnet	An administratively homogeneous subset of a larger internet that is administratively heterogeneous.
subSSInet	An administratively homogeneous subset of a larger SSInet that is administratively heterogeneous; a subSSInet may be either a subnet or a subdtnet.
trailer	Some number of octets of protocol-specified data that are transmitted after some sequence of octets of encapsulated user data.
transmission	The data communication actions of the sender.
user	A human who directly or indirectly, through some cybernetic artifact, motivates the copying of a data unit from one memory location to another by the SSI,

TERM	DEFINITION
user data units	A bounded sequence of octets that can be encapsulated according to a protocol, and whose structure and semantics may vary but are in any case irrelevant to the communicating entities.
user node	An SSI node whose network protocol entities are not configured to forward network PDUs received from other entities, but whose application protocol entities routinely send and receive data via the SSI.
virtual transmission	Transmission of a PDU by a sender for some other protocol; i.e., the PDU produced by one sender is presented to the second sender as a user data unit, and the second sender encapsulates that user data unit in the PDU(s) of its own protocol for transmission.

ANNEX B

ABBREVIATIONS

TERM	DEFINITION
AMS	Asynchronous Message Service
AOS	Advanced Orbiting Systems
ASR	Authority Schedule Request
BDTE	Bundle Delivery Time Estimation
BP	Bundle Protocol
BPA	Bundle Protocol Agent
BSP	Bundle Security Protocol
BSS	Bundle Streaming Service
CCP	Composite Contact Plan
CFDP	CCSDS File Delivery Protocol
CLA	Convergence-Layer Adapter
CSSE	Cross Support Service Element
CSTS	Cross Support Transfer Service
DTN	Delay-Tolerant Networking
DTPC	Delay-Tolerant Payload Conditioning
EP	Encapsulation Packet
ESLT	Earth-Space Link Terminal
FTP	File Transfer Protocol
HTTP	Hypertext Transfer Protocol
IETF	Internet Engineering Task Force
I/F	Interface
IOAG	Interagency Operations Advisory Group
IOP	Interoperability Plenary
IP	Internet Protocol
IPSec	Internet Protocol Security

TERM	DEFINITION
KDP	Key Distribution Protocol
LAN	Local Area Network
LSA	Link Service Adapters
LTP	Licklider Transmission Protocol
MOC	Mission Operations Center
NIMO	Network Integration Management Office
NMP	Network Management Protocol
NSA	Network Service Agreement
PA	Peering Agreement
PCP	Provider Contact Plan
PDU	Protocol Data Unit
RAMS	Remote Asynchronous Message Service
RF	Radio Frequency
RFC	Request for Comments
SANA	Space Assigned Number Authority
SCCS-ADD	Space Communications Cross Support-Architecture Description Document
SD	Service Delivery
SIS-DTN	Space Internetworking Services-Delay-Tolerant Networking
SISG	Space Internetworking Strategy Group
SLE	Space Link Extension
SM	Service Management
SOC	Science Operations Center
SSI	Solar System Internetwork
SIS-DTN	Space Internetworking Services-Delay-Tolerant Networking
SSI-ISP	Solar System Internetwork-Internet Service Provider
TCP	Transmission Control Protocol
TM/TC	Telemetry/Telecommand

TERM	DEFINITION
TT&C	Telemetry, Tracking, and Command
TTL	Time To Live
UDP	User Datagram Protocol
UE	User Element
URI	Uniform Record Identifier
USR	User Schedule Request
UT	Unitdata Transfer
UTC	Coordinated Universal Time
VPN	Virtual Private Network
WAN	Wide Area Network

ANNEX C

OPERATIONS CONCEPT

C1 OVERVIEW

As noted in the Foreword, this Informational Report further defines elements and services that were identified in the SSI Operations Concept (reference [1]). While the SSI Operations Concept as a whole will not be reiterated in this Report, several points that further define SSI Operations Concept formulations are presented here.

C2 TERMINOLOGY

C2.1 PROTOCOLS AND APPLICATIONS

An *octet* is a sequence of eight binary digits (*bits*) of data.

A *data unit* is a bounded sequence of octets.

Data communication is the automatic copying of data units from some location in the memory of some computing device to some other location in the memory of some (often distant) computing device. Data communication is effected by the actions of two cybernetic artifacts (software, hardware, or firmware): one, termed the *sender*, operating on the device where some data unit originally resides; and another, termed the *receiver*, operating on the device to which that data unit is copied. The data communication actions of the sender are termed *transmission*; the data communication actions of the receiver are termed *reception*. Data senders and receivers are collectively termed *communicating entities*, or simply *entities*.

A *communication protocol* (or, for the purposes of this Report, simply *protocol*) is a set of rules for accomplishing data communication, to which both the sender and receiver of data units must adhere. Typically these rules entail the *encapsulation* of one or more *user data units* (data units whose structure and semantics may vary but are in any case irrelevant to the communicating entities) in one or more PDUs whose structure and semantics are prescribed by the protocol.

To encapsulate user data in a PDU is to transmit some number of octets of protocol-specified *header* data before transmitting some sequence of octets of user data (and, in addition, possibly to transmit some number of octets of protocol-specified *trailer* data after transmitting those user data octets) (see figure C-1). The effect of encapsulation is to ensure that the receiver of a PDU will receive the header data before receiving any user data, giving the receiver information it needs to receive the user data (and possibly trailer) in conformance with the protocol.

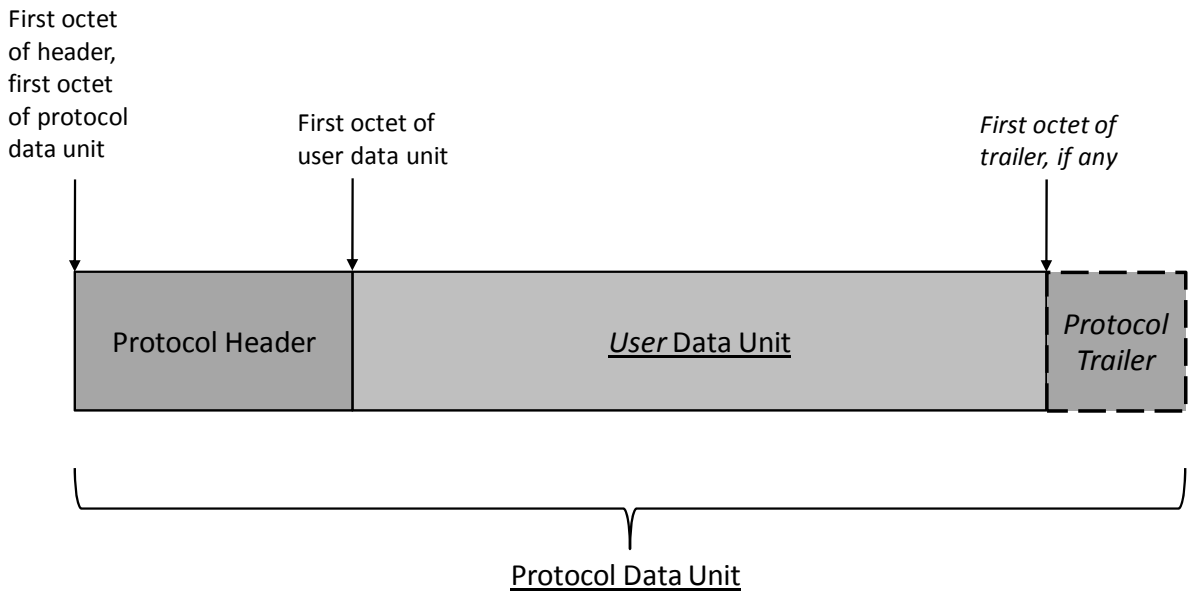


Figure C-1: A Protocol Data Unit

The transmission of a PDU by a sending entity may entail the modulation of a signal in some electromagnetic or acoustic medium. This is here termed *physical transmission*.

Alternatively, though, a sender may accomplish transmission of a PDU by instead requesting that a sender for some other protocol transmit it: the PDU produced by one sender is presented to the second sender as, in effect, a user data unit; the second sender encapsulates that user data unit in the PDU(s) of its own protocol for transmission. For the purposes of this report, this is termed *virtual transmission*.

The two protocols involved in a virtual transmission are said to form a *stack*, with the protocol of the first sender considered to be at the higher *layer* of the stack, and the protocol of the second sender—the 'underlying' sender—considered to be at the lower layer of the stack. The protocol at the higher layer of the stack is said to be running 'over' the lower-layer protocol.

For example, the stack diagram in figure C-2 indicates that the PDUs of protocol '3A' are encapsulated in the PDUs of protocol '2A', which in turn are physically transmitted using modulation mechanism '1A'.

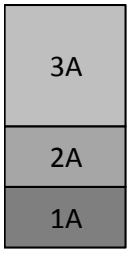


Figure C-2: A Simple Protocol Stack

Figure C-2 implies that the PDUs physically transmitted by a sender for protocol 2A will have the structure shown in figure C-3 (assuming neither 2A nor 3A require the transmission of trailers).

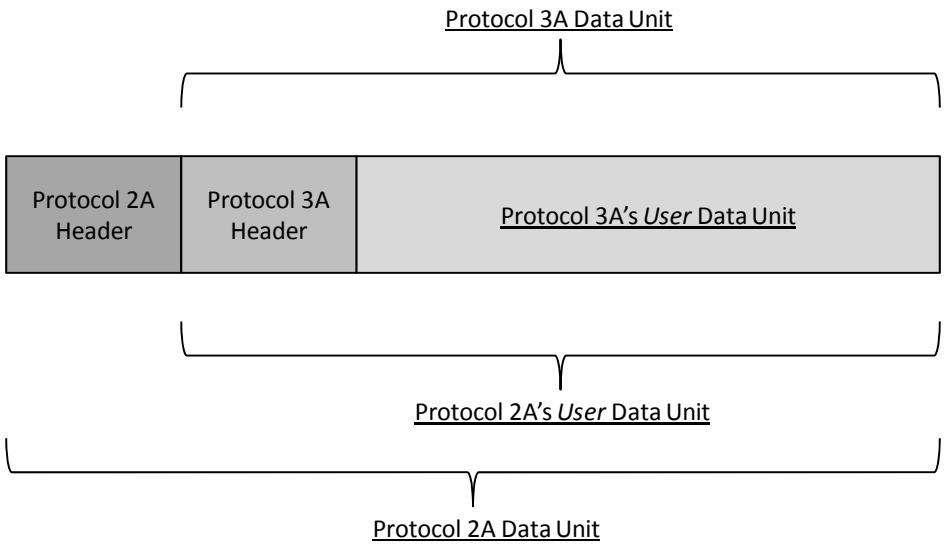


Figure C-3: A Protocol Data Unit Transmitted by This Stack

(It should be noted that the protocol stack from which a PDU was transmitted can generally be inferred from the structure of the PDU itself, simply by rotating a representation of the PDU 90 degrees counter-clockwise.)

A protocol stack may have any number of layers. The protocol at the highest of those layers is termed the stack's *application protocol*. The user data units encapsulated in the PDUs of an application protocol are termed *application data units*. A cybernetic artifact (typically comprising multiple constituent cybernetic artifacts distributed among multiple computing devices) that includes at least one sender and at least one receiver of application data units is here termed an *application*.

C2.2 DATA PLANES

For the purposes of this Report, a set of entities assembled to enable data communication conforming to some single protocol among an arbitrary population of computing devices is termed a *data plane*. Typically at least one sender and at least one receiver will be operating on each computing device served by a given data plane, enabling PDUs to be *exchanged* (both transmitted and received) among the devices.

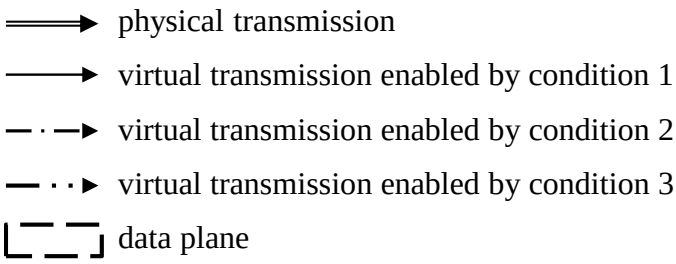
Communication between some pair of entities in a data plane is possible whenever one of the following three conditions is met:

a) PDU transmission between the two entities is physical, and the receiver is physically able to detect the signals modulated by the sender.

b) PDU transmission between the two entities is virtual, and communication is possible between the underlying sender and underlying receiver.

c) PDU transmission between the two entities is virtual, communication between the sender and an intermediate receiver on some computing device is possible, communication between an intermediate sender on that same computing device and the (final) receiver is possible, and the data plane's protocol includes rules for ***forwarding***, i.e., causing the intermediate sender to send the PDUs received by the intermediate receiver. (The underlying protocol used to send the forwarded PDUs may be different from the one used to receive those PDUs.) A protocol that include such rules is here termed a ***network protocol***, and a data plane whose protocol is a network protocol is termed a ***network***.

The transmission diagrams in this document use the following notation:



The label in each block indicates the layer of the protocol or modulation mechanism (1, 2, 3, etc.) and the specific protocol or modulation mechanism in use at that layer between the two devices (A, B, C, etc.).

Figure C-4 indicates that communication is possible between the sender for protocol 2A on device W and the receiver on device X because condition 1 is met: modulation mechanism 1A is used for physical transmission of the PDUs.

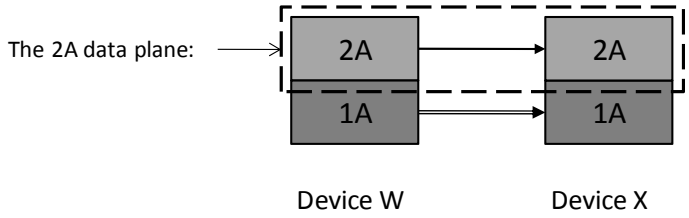


Figure C-4: Physical Transmission between Two 2A Entities

Figure C-5 indicates that communication is possible between the sender for protocol 3A on device W and the receiver on device X because condition 2 is met: communication is possible between the underlying sender and receiver (because condition 1 is met for those entities as in the case described above).

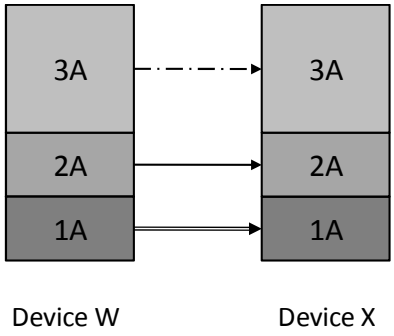


Figure C-5: Virtual Transmission between Two 'Neighboring' 3A Entities

Figure C-6 indicates that communication is possible between the sender for protocol 3A on device W and the receiver on device Y because condition 3 is met: communication is possible between the sender on device W and an intermediate receiver on device X (because condition 2 is met), and communication is possible between an intermediate sender on device X and the receiver on device Y (because condition 2 is met).

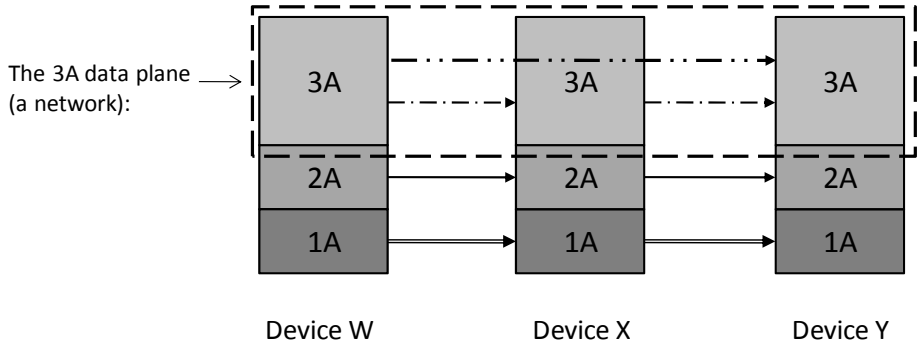


Figure C-6: Virtual Transmission between Two 3A Entities via Forwarding Entities

Figure C-7 indicates that communication is possible between the sender for protocol 5A on device W and the receiver on device Z because condition 2 is met: communication is possible between the underlying sender on device W and the underlying receiver on device Z, because condition 3 is met for those entities (both the 4A sender on W and the 4A receiver on Z can communicate with intermediate entities on device Y).

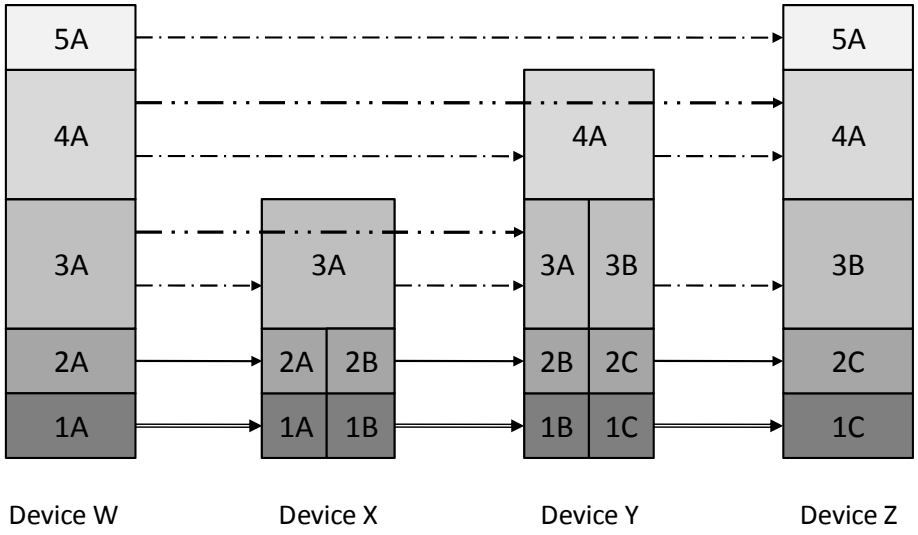


Figure C-7: Virtual Transmission between Two 'Neighboring' 5A Entities

C2.3 NETWORK SYSTEMS

The purpose of data communication is the operation of applications, i.e., the exchange of PDUs in *application protocol data planes*.

The exchange of PDUs in an application protocol data plane (or *Application-Layer data plane*) can usually only 'scale up' to support pervasive data communication among a large number of geographically separated computing devices if condition 3 is met, either by the application protocol itself or by at least one of the protocols somewhere below it in the stack. (In the absence of a network protocol, every device must be able to accomplish physical transmission directly to every other device—a scenario typically not possible for large numbers of geographically separated devices.) Moreover, since forwarding rules are often complex, it is usually more cost-effective for multiple application protocols to rely on the operation of a common underlying network protocol than to perform PDU forwarding themselves.

So large-scale data communications can in practice only be conducted among computing devices served by a complete *network system* comprising not only one or more application protocol data planes but also the supporting *network infrastructure* common to those application protocol data planes. That infrastructure consists of the stacked underlying network(s) and other data planes that make communication within the application protocol data plane(s) possible (see the example in figure C-8).

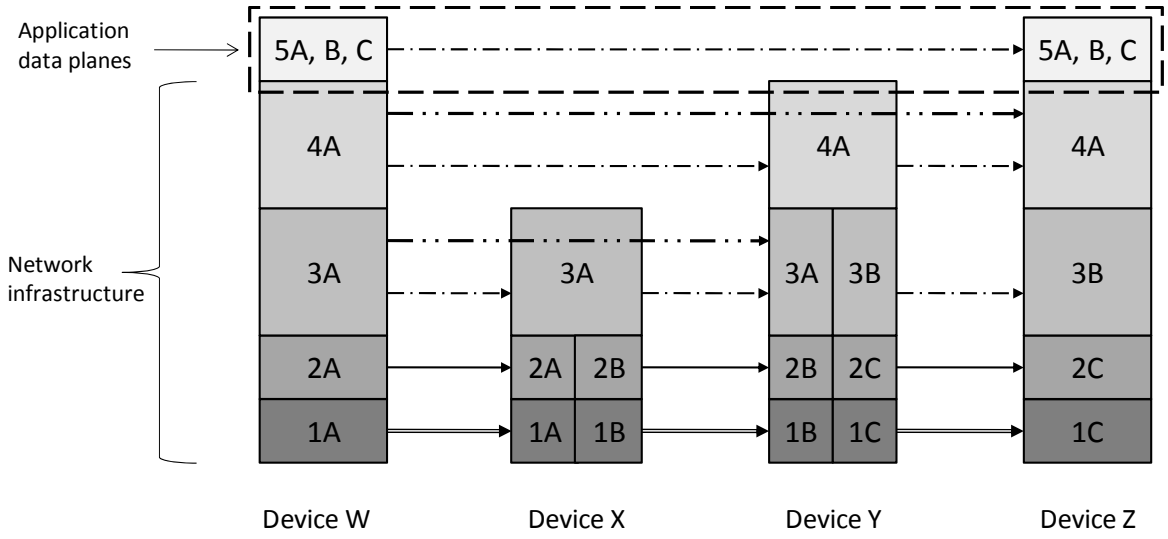


Figure C-8: A Network System with Two Network Protocols, 3A and 4A

C3 SSI CONCEPTS

C3.1 IP AND DTN IN THE SSI

The SSI is a single network system designed to enable communication in the exploration of space.

As section 2.2 of the SSI Operations Concept (reference [1]) makes clear, two different network protocols may be utilized in the operations of the SSI, i.e., in the engineering of the SSI's network infrastructure: the IP of the Internet, and the BP of DTN.

Figure C-9 depicts an abstract composite of the SSI network system elements, reflecting this dictum and identifying the protocols that can therefore be used to compose any single stack for virtual transmission of application data units via the SSI. The structure of the stack diagram indicates which protocols are able to run over which others, implicitly constraining the protocol stack options supported by the SSI architecture.

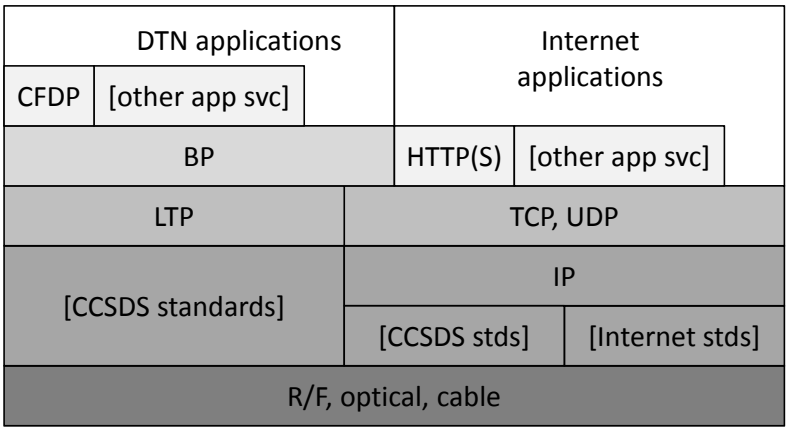


Figure C-9: SSI Composite Protocol Stack

Some observations on this diagram:

– 'DTN applications' are applications designed from the outset for use over DTN network infrastructure. Unlike most Internet applications, they are engineered for successful operation even when transmission is characterized by very high and/or variable latency due to large signal propagation delays, lengthy outages in physical transmission capability, or both. They are implemented to utilize CFDP and other DTN Application-Layer services (optionally) over a BP network.

– *'Internet applications'* are applications that were designed for use in the Internet and implemented to utilize protocols from the Internet 'protocol suite': Hypertext Transfer Protocol (HTTP) and other Internet Application-Layer services (optionally), over TCP and UDP, over one or more IP networks whose underlying data planes conform to Internet standards published by the Internet Engineering Task Force.

– The BP network runs over LTP (over CCSDS standard Link-Layer protocols) in space, but it may also run over Internet network infrastructure (e.g., TCP/IP). **The reverse is not true:** in the SSI, Internet network infrastructure cannot run over the BP network, because the BP network may span environments in which the preconditions for successful Internet protocol operation (continuous connectivity and relatively low delay, as noted in the SSI Operations Concept, reference [1], section 2.2) do not hold. Consequently, a BP network can operate in any scenario in the SSI, but use of protocols from the Internet 'protocol suite' is restricted to scenarios in which the communicating entities are well connected (i.e., the network path between them is continuously connected and relatively low-delay).

The SSI stack diagram shown in figure C-9 can therefore be thought of as having two distinct facets, an Internet facet (figure C-10) and a DTN facet (figure C-11).

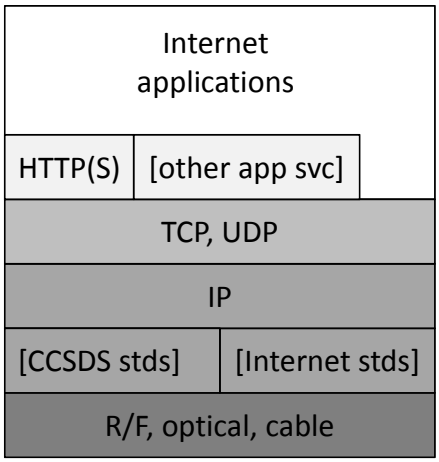


Figure C-10: Protocols of the Internet Facet of the SSI Architecture

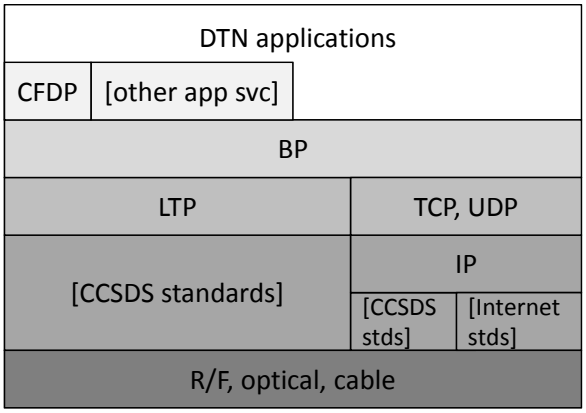


Figure C-11: Protocols in the DTN Facet of the SSI Architecture

C3.2 NODES

The term *network automaton* is used to denote a collection of senders and receivers (entities) at all layers of some protocol stack that includes at least one network protocol; because senders and receivers are cybernetic artifacts, a network automaton is a composite cybernetic artifact.

The SSI Operations Concept (reference [1]) defines 'SSI node' as 'any network entity that can serve as a source or destination of information at the Network Layer,' which would make an 'SSI node' one component of a network automaton.

However, the SSI Operations Concept (reference [1]) often implicitly extends the notion of a 'node' to include not only the computing device on which this cybernetic artifact is executed, but also the physical site at which that device resides. Although in theory a single physical site of functionality in the SSI could host multiple individually addressable network automata that execute on one or more computing devices, in practice this configuration is rare. The

distinction between a network automaton and the physical element at which it operates—which is what is most often meant when the term ‘node’ is used in space networking—is generally of only academic interest. Accordingly, in this document the term ‘node’ is freely used to denote a physical element that, because it is the locus of operation of a network automaton, may be regarded as being itself an active participant in network communications.

The SSI Operations Concept (reference [1]) uses the term *user nodes* to refer to SSI nodes that ‘do not have the capability to provide Network-Layer forwarding functionality’ (section 2.2). By the definition above, every node necessarily has the ‘capability’ to forward network PDUs, because it includes one or more network protocol entities. So here a ‘user node’ is more narrowly defined as a node whose network protocol entities are not currently configured to forward network PDUs received from other entities, but whose application protocol entities routinely send and receive data via the SSI. It should be noted that this leaves open the possibility of converting a user node to a ‘provider node’ (discussed below) simply by reconfiguring its network protocol entities.

The SSI Operations Concept (reference [1]) uses the term *provider nodes* to refer to SSI nodes that ‘act as intermediate relay nodes for end-to-end network services’ (section 2.2). That is, they are nodes whose network protocol entities are configured to forward network PDUs received from other entities. Such nodes act as user nodes when their application (e.g., network management) protocol entities send and receive data, but it is expected that most of the activity of a provider node will be network PDU forwarding rather than application data unit transmission and reception.

A number of types of sites or devices on Earth, on a planet, or in space may be SSI nodes:

- Earth stations (or Earth-Space Link Terminals, ESLTs);
- Earth station control centers (components of ESLTs);
- terrestrial (or Earth) WAN routing nodes;
- planetary stations (or Planet-Space Link Terminals, PSLTs);
- planetary station control centers (components of PSLTs);
- planetary (or planet) WAN routing nodes;
- spacecraft (or Space User Nodes, space relay nodes, hybrid science/relay nodes, Planet Relay Nodes);
- spacecraft MOCs (or Earth User Nodes, Earth relay nodes);
- SOCs (a class of Earth User Nodes).

These types of nodes are referenced throughout this document and are described further in section 2.3 of the IOAG SSI Operations Concept (reference [1]). The alternate names given here (in parentheses) are those used in the SCCS-ADD (reference [9]); they are provided to offer an easy mapping into the CCSDS terminology defined in that document.

C3.3 ADMINISTRATION

For the purposes of this Report the following terms are defined:

- An *internet* is a set of SSI nodes among all of which the exchange of IP datagrams is possible.
- A *subnet* is an *administratively homogeneous* (i.e., all nodes are configured, managed, and operated by a common authority) subset of a larger internet that is *administratively heterogeneous* (i.e., nodes are configured, managed, and operated by more than one authority).
- A *dtnet* is a set of SSI nodes among all of which the exchange of DTN bundles is possible.
- A *subdtnet* is an administratively homogeneous subset of a larger dtnet that is administratively heterogeneous.

The DTN facet of the SSI is a single administratively heterogeneous dtnet. It comprises one or more subdtnets administered by national space agencies, space flight centers, commercial spacecraft operators, and/or other functionally autonomous organizations.

In order for the DTN protocols to operate correctly, each node must be uniquely identified. In the SSI, node identifiers are positive, non-zero integers termed *node numbers*. Each node is assigned a unique node number by its authority. The node numbers assigned to an authority's nodes are taken from one or more ranges of consecutive node numbers assigned to that authority. Node number ranges are assigned to authorities by the SANA of CCSDS.

C4 TECHNOLOGY

C4.1 INTERNET PROTOCOLS

The core Internet protocols include:

- TCP, which ensures reliable end-to-end data transmission and prevents data traffic congestion in the Internet;
- IP, which forwards IP data units (called datagrams) from source nodes to destination nodes via routes through forwarding nodes, under the control of routing protocols that detect and report on changes in network topology;
- IP Security (IPSec), which ensures the confidentiality and integrity of Internet communications;
- File Transfer Protocol (FTP), which conveys files among Internet nodes;
- HTTP, which retrieves information from the World Wide Web for presentation in applications called 'browsers'.

The Internet protocols are highly successful in deployment environments characterized by continuous, pervasive end-to-end connectivity and extremely brief signal propagation delay, such as the local area networks (LANs) of research centers and, indeed, the public Internet. Although they are unsuitable for use where these conditions are absent, including communications over frequently disrupted radio links or over distances much in excess of a light second, they are ideal for communications within continuously connected planetary networks such as those supporting Earth station operations. In addition, as noted earlier, the DTN protocols can easily be run over IP infrastructure, enabling easy integration of IP-based and DTN-based networking.

The architectural elements, principles, and procedures of the Internet are abundantly documented and have been very widely implemented over the past 50 years. Internet applications are in routine daily use around the world, and the elements of Internet network infrastructure that may be utilized in the SSI have in many cases already been fully and successfully deployed by the national space agencies, complying with network design rules and principles that vary significantly among agencies.

For these reasons, including in this Informational Report a detailed description of the Internet facet of the SSI network system is unnecessary and indeed infeasible.

It should be noted that this **in no way** precludes the use of Internet applications in the SSI. Stacks such as those shown in figures C-12 through C-16 can be entirely valid in SSI operations. However, guidance in deploying, operating, and utilizing them is not provided by this Report.

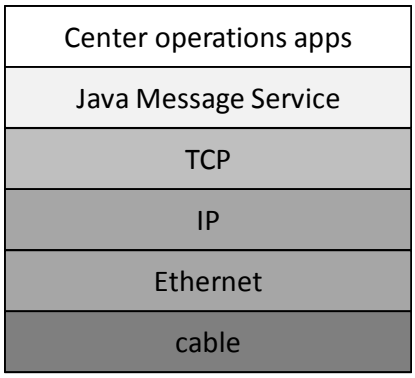


Figure C-12: Earth Station Control Center

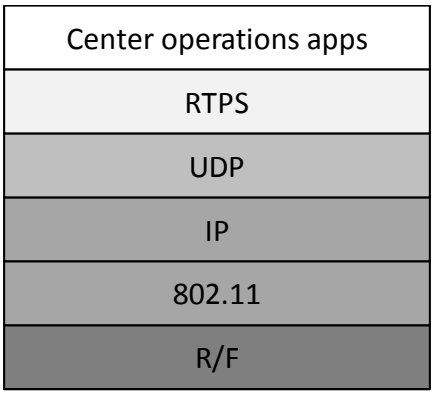


Figure C-13: Planetary Station Control Center

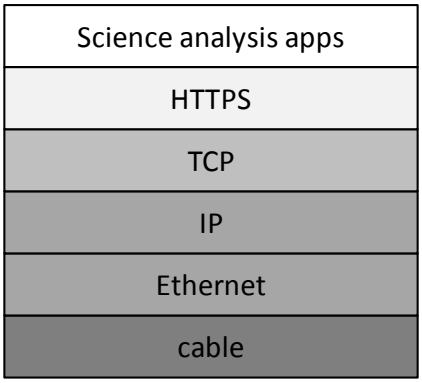


Figure C-14: Science Operations Center

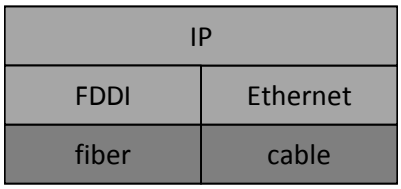


Figure C-15: Terrestrial Wide-Area Network Router

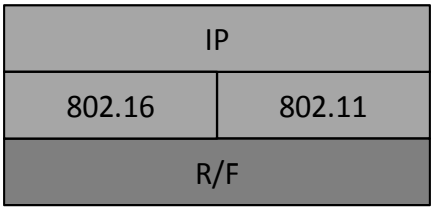


Figure C-16: Planetary Wide-Area Network Router

C4.2 DELAY-TOLERANT NETWORKING PROTOCOLS

C4.2.1 Bundle Protocol

BP is the network protocol for the DTN facet of the SSI architecture. It is defined in Internet RFC 5050 (reference [5]) and in a corresponding CCSDS forthcoming Recommended Standard (reference [10]). BP is similar in concept to IP (the network protocol for the Internet facet of the SSI architecture) in many ways, but it is quite different in operation:

– The BP PDUs are termed *bundles* and may be larger than IP datagrams.

– Outbound bundles for which no forward route is currently available are not immediately discarded, but may be retained in long-term storage pending availability of a route.

– Each bundle is automatically purged from the network on expiration of its stated lifetime if it has not yet been delivered to its final destination.

– The source and destination of a bundle are not the network addresses of computers, but rather the names of *endpoints*. Endpoints are abstract locations in network topology, identified by strings called ‘endpoint IDs’. The actual location of a bundle’s destination endpoint may not be known until late on the bundle’s end-to-end path.

C4.2.2 Bundle Protocol Agent Administration

The operational status of a BP entity (in BP terminology, a Bundle Protocol Agent [BPA]) typically will need to be continuously monitored, and the configuration of any given BP entity may need to be revised from time to time. BPA administration may be accomplished in ad-hoc fashion using private node administration tools, or in standard fashion using the DTN NMP.

C4.2.3 Time to Live Expiration

BP automatically releases the long-term storage resources occupied by an in-transit bundle when either of two conditions is met:

a) The bundle is delivered to its final destination.

b) The bundle’s Time To Live (TTL) expires.

The time at which a bundle’s TTL expires is the sum of (a) the time at which the bundle was created, and (b) the bundle lifetime specified by the user at the moment the bundle was created. In order for nodes throughout the network to compute bundles’ TTL expiration times correctly, the clocks of all nodes in the network must be synchronized to within a few seconds of correct Coordinated Universal Time (UTC). The clocks of SSI nodes on the surface of Earth can usually be synchronized by the Internet’s Network Time Protocol. The clocks of SSI nodes in space are typically synchronized by means of UTC offset values provided in the course of BPA administration.

C4.2.4 Convergence Layer

BP itself has no physical transmission or reception function, relying instead on virtual transmission via one or more underlying protocols which, in the context of BP, are termed *convergence-layer protocols*. Since all such protocols are pre-existing and may be used for transmission of the data units of protocols other than BP, deployment of a BP entity always additionally entails the deployment of one or more CLAs, cybernetic artifacts that present bundles to specific convergence-layer protocols for transmission and extract bundles from convergence-layer PDUs.

C4.2.5 Contact Plan

BP route computation at each node of the SSI is performed with reference to an asserted schedule of planned opportunities for data transmission and reception between pairs of neighboring nodes (that is, nodes between which communication on the BP data plane is possible because condition 2, described in C2.2 above, is satisfied). This schedule is termed a *contact plan*.

Contact plans list both the anticipated contacts between pairs of nodes and also the changes in the range (expressed as one-way light time) between pairs of nodes. Each contact in a contact plan states:

a) the identities of the sending node and the receiving node.

NOTE – A contact between a given sender and a given receiver does not imply a corresponding concurrent contact in which these roles are reversed. That is, 'simplex' and otherwise asymmetric communication opportunities can be readily represented in a contact plan; a bidirectional communication opportunity is expressed as a pair of contacts, one in each direction;

b) the UTC time at which the sending node can begin transmission;

c) the UTC time at which the sending mode must cease transmission;

d) the rate (in bytes per second) at which the sending node is authorized to transmit.

Contact plans are used:

– to compute plausible routes between source and destination nodes, so that appropriate convergence-layer transmission can be scheduled;

– to limit transmission and reception rates, thereby preventing long-term storage resource depletion at the nodes;

– to anticipate errors in transmission scheduling that could cause long-term storage resource depletion;

– in some cases, to compute retransmission timeout intervals;

– in some cases, to initiate and terminate data transmission and reception at the convergence layer.

The distribution of contact plans to SSI nodes is accomplished in the course of BPA administration.

C4.2.6 Endpoint IDs

In the SSI, endpoint ID strings take the form of Uniform Record Identifiers (URIs) conforming to the 'ipn' URI syntax. Each such string has the form **ipn**:***node_number.service_number***, where *node_number* is the identifying number of a node (as described in C3.3 above) and *service_number* is the identifying number of a recognized application function. Service numbers are reserved for specified applications by registration with SANA. Any number of BP endpoints may be resident on any single SSI node, with bundles being sent from and received at all of them. This 'multiplexing' of BP PDU exchange enables any number of applications to utilize the SSI DTN network infrastructure concurrently.

C4.3 BUNDLE SECURITY PROTOCOL

C4.3.1 General

BSP (Internet RFC 6257, reference [11]) defines several optional extensions to BP that improve its security in operational use:

– Bundle authentication blocks enable a node to detect and reject received bundles that were not sent by trusted nodes.

– Payload integrity blocks enable the destination of a bundle to detect any modification of the bundle's *payload* (i.e., its encapsulated user data unit) following issuance of the bundle by its source node.

– Payload confidentiality blocks enable encryption of a bundle's payload, ensuring that the bundle's user data unit is exposed only to the authentic destination node of the bundle.

C4.3.2 Keys

Every BSP extension operates by computing a hash or an encrypted value as a function of a key value. The distribution of BSP key values to SSI nodes may be accomplished in ad-hoc fashion using private node administration tools or in standard fashion using the DTN KDP.

C4.4 LICKLIDER TRANSMISSION PROTOCOL

C4.4.1 General

LTP (Internet RFC 5326, reference [6] and the corresponding forthcoming CCSDS Recommended Standard, reference [12]) is a delay-tolerant mechanism for improving the reliability of bundle transmission between two SSI nodes that are 'neighbors' in the dtnet.

LTP improves BP transmission reliability and efficiency by:

- aggregating bundles, presented by the sending node's BP entity, into large *blocks* for transmission;
- fragmenting LTP blocks into *segments* that are small enough to fit into Link-Layer transmission frames;
- presenting LTP segments as user data units for transmission by underlying protocols (such as the CCSDS Telemetry/Telecommand [TM/TC], Proximity-1, or Advanced Orbiting Systems [AOS] Link-Layer protocols);
- reassembling received LTP segments into blocks, extracting the aggregated bundles from the received blocks, and delivering the bundles to the receiving node's BP entity;
- detecting missing or corrupt segments and automatically requesting retransmission of those segments, ensuring eventual successful reassembly of the transmitted blocks.

C4.4.2 LTP Engine Administration

The operational status of an LTP entity (in LTP terminology, an LTP 'engine') typically will need to be continuously monitored, and the configuration of any given LTP entity may need to be revised from time to time. LTP engine administration may be accomplished in ad-hoc fashion using private node administration tools or in standard fashion using the DTN NMP.

C4.4.3 Link Service Layer

LTP itself, like BP, has no physical transmission or reception function, relying instead on virtual transmission via one or more underlying protocols which, in the context of LTP, are termed *link service protocols*. Since all such protocols are pre-existing and may be used for transmission of the data units of protocols other than LTP, deployment of an LTP entity always additionally entails the deployment of one or more *LSAs*, cybernetic artifacts that present LTP segments to specific link service protocols for transmission and extract LTP segments from link service PDUs.

C4.5 NETWORK MANAGEMENT PROTOCOL

At the time of release of this Report, the DTN NMP was not yet defined. In concept, NMP will:

- report periodically on aggregate bundle origination, forwarding, and delivery activity at network nodes;
- report on resource management issues at network nodes;
- convey reconfiguration directives to network nodes, to augment the network or to address network performance and resource management anomalies;
- convey contact plans to network nodes.

C4.6 KEY DISTRIBUTION PROTOCOL

At the time of release of this Report, the DTN KDP was not yet defined. In concept, KDP will:

- convey new encryption and hashing keys to network nodes, noting the times at which these keys will initially become effective and, eventually, expire;
- revoke previously distributed encryption and hashing keys, to defend against security breaches due to compromised keys.

C4.7 APPLICATION SERVICE PROTOCOLS

C4.7.1 Overview

The following protocols operate over BP to perform specific, standardized tasks on behalf of user applications in the SSI.

C4.7.2 Delay-Tolerant Payload Conditioning

The Delay-Tolerant Payload Conditioning (DTPC) protocol provides end-to-end services similar to those provided by TCP in the Internet:

- in-order delivery of user data units;
- suppression of duplicate user data units;
- end-to-end acknowledgment of received user data units;
- timeout-initiated retransmission of user data units;
- aggregation of multiple small user data units into larger application data units for presentation to BP, to increase mean bundle size and reduce net BP header overhead;

– elision of redundant user data units in an aggregated application data unit, to improve bandwidth utilization.

Select combinations of these services are made available to applications that utilize DTPC rather than presenting their user data units directly to BP for transmission.

At the time of release of this Report, the DTPC protocol definition was not yet standardized.

C4.7.3 Bundle Streaming Service

Bundle Streaming Service (BSS) is a profile for enabling efficient 'real-time' streaming of synchronous data (e.g., audio and video) over a dtnet.

At the time of release of this Report, the BSS configuration profile was not yet standardized. It may include definition of an additional protocol, but that protocol likewise was not yet standardized at the time of release of this Report.

C4.7.4 CCSDS Asynchronous Message Service

The CCSDS AMS (reference [8]) comprises three protocols that, together, enable efficient, reliable, delay-tolerant, multi-point transmission of relatively brief (up to 64 KB) messages over a dtnet.

C4.7.5 CCSDS File Delivery Protocol

The CFDP (reference [7]) enables delay-tolerant transmission of files over a dtnet. (Only the Class-1 unacknowledged procedures of CFDP are exercised.)

ANNEX D

BIBLIOGRAPHY

[D1] *Rationale, Scenarios, and Requirements for DTN in Space*. Issue 1. Report Concerning Space Data System Standards (Green Book), CCSDS 734.0-G-1. Washington, D.C.: CCSDS, August 2010.