Operations Concept for a Solar System Internetwork

Charles D. Edwards, Jr.
Jet Propulsion Laboratory, California Institute of Technology
M/S 321-630, 4800 Oak Grove Dr
Pasadena, CA 91001, USA
chad.edwards@jpl.nasa.gov

Michel Denis
European Space Operations Centre
Darmstadt, GER

Lena Braatz
Booz Allen Hamilton
Annapolis Junction, MD, USA

Abstract—Space communications to date has been largely managed at the link layer, with simple point-to-point links between a spacecraft at Earth. However, future space exploration scenarios involve much richer communications scenarios, with complex network scenarios involving space assets communicating back to Earth via multiple intermediate relay service providers. To support these more complex network scenarios, the Space Internetworking Strategy Group has developed an operations concept for a Solar System Internetwork (SSI). The operations concept draws on the successes of the terrestrial Internet while addressing unique aspects of space communications. Key elements of the operations concept include a standardized network layer across the end-to-end SSI and the underlying processes for development of a contact plan that captures the link layer connectivity among SSI network nodes.

TABLE OF CONTENTS
1. INTRODUCTION ................................................. 1
2. GENERAL DESCRIPTION OF THE SSI .............. 2
3. KEY SSI PRINCIPLES ........................................ 3
4. NETWORK MANAGEMENT PROCESSES .......... 5
5. NETWORK OPERATION SCENARIOS ................. 7
6. CONCLUSIONS ................................................... 8
ACKNOWLEDGMENT ............................................. 8
REFERENCES ......................................................... 9
BIOGRAPHY .......................................................... 9

1. INTRODUCTION

The Interagency Operations Advisory Group (IOAG) has established a Space Internetworking Strategy Group (SISG), with participation by the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Deutsches Zentrum für Luft- und Raumfahrt (DLR), Centre National d'Etudes Spatiales (CNES), and Agenzia Spaziale Italiana (ASI), and with the charter to provide recommendations to the IOAG for a strategy to implement space internetworking. One element of this work involves the development and documentation of an operations concept for a solar system internetwork (SSI). This paper will summarize the SSI operations concept, as developed by the SISG.

To date, most space communication scenarios have involved simple point-to-point links between a single spacecraft in flight and its ground operations control center. However, future space exploration concepts are envisioned which would introduce more complex topologies involving multiple spacecraft, with data flowing over multiple hops and potentially via several different end-to-end paths. Already we see initial examples of such scenarios with the support of Mars landed spacecraft (e.g., the Spirit and Opportunity Rovers and the Phoenix Lander) by an ensemble of relay-equipped Mars orbiters (e.g., Odyssey, Mars Express, and the Mars Reconnaissance Orbiter). Future trends include ambitious Mars exploration plans leading towards the potential return of samples from the Martian surface, high-rate Earth remote sensing missions with multiple sensors potentially deployed across a multi-spacecraft constellation, and human exploration missions beyond Earth orbit.

These future mission scenarios call for the development of a functional network layer in the space communications protocol stack to provide for the reliable routing of data across more complex network scenarios. Like the terrestrial Internet, the SSI would provide users with a simple, standardized network interface. A pair of applications at two disjoint nodes on the SSI would be able to seamlessly exchange data, with the network layer handling the routing of those data across intermediate nodes. (In fact, this is a key discriminator between the envisioned SSI, with a standardized network layer operating at all the intermediate nodes, and today’s Mars relay scenarios, where each relay orbiter utilizes a set of ad hoc application-layer functions to implement its store-and-forward relay capability.) However, unlike the terrestrial Internet, which takes advantage of continuously-available network connections
and relatively short paths between nodes, the SSI would in many cases have to operate across networks with intermittent connectivity between nodes and with long propagation times across interplanetary links. In these cases, the standard Internet protocol suite (IP) cannot operate and instead the network layer would be based on the Disruption Tolerant Networking (DTN) Bundle Protocol (BP).

The paper will address in detail the key operational activities associated with SSI operations, including planning and dissemination of the contact plan defining the temporal connectivity among SSI nodes, peering agreements to facilitate interagency cross-support, network monitor and control functions, and last-hop services to support emergency telemetry and command and for support of legacy, non-DTN-enabled spacecraft.

2. General Description of the SSI

The fundamental objective of the SSI is to provide internetworked data communication services across the solar system. By establishing a standardized interface for network-layer functionality modeled on the network layer of the International Standards Organization (ISO)/Open Systems Interconnection (OSI) Reference Model, the SSI would enable cross-support among a confederation of space agencies.

The constituents of the SSI are a set of spatially distributed nodes, where each node can act as a source or destination of network layer data transfer. There are two types of SSI nodes:

- **User nodes** reside at the periphery of the SSI and have the ability to access SSI services, but do not have the capability to provide network-layer forwarding functionality (i.e., store-and-forward capability, potential support for multiple simultaneous links, etc.). User nodes can use SSI services, but cannot provide SSI services for other nodes. A terrestrial Internet analogy for an SSI user node is the computer belonging to an individual Internet user, who is accessing services offered by a local Internet Service Provider.

- **Provider nodes** have the ability to offer network-layer routing and forwarding capabilities. Such nodes can perform routing over one or more links, have store-and-forward capability, and may support multiple simultaneous links to enable simultaneous support to multiple user nodes and/or real-time forwarding functionality. These nodes act as intermediate relay nodes for end-to-end network services. When it is acting as the terminus

![Diagram of SSI configuration](image)

**Figure 2.1:** Example SSI configuration, illustrating various types of nodes.
Figure 2.1 illustrates various types of SSI nodes, briefly defined here:

- **Earth Station (e.g., Earth-space link terminals or ground stations)**: Provides network-layer connectivity between a terrestrial Wide Area Network (WAN) and space SSI nodes.

- **Relay Spacecraft**: Capable of forwarding and routing network data units over multiple space links.

- **Planetary Station (e.g., Planet-Space Link Terminal)**: The planetary analog of an Earth Station, such as a lunar communication terminal on the surface of the moon at a future human outpost. (The term “planet” is generalized here to include any non-terrestrial body.)

- **Terrestrial Wide Area Networks**: An extension of today’s WANs, providing network-layer connectivity among terrestrial SSI nodes.

- **Planetary Wide Area Networks**: The planetary analog of terrestrial WANs.

- **Spacecraft**: Includes vehicles in space, landers and rovers on the surface of another planet, and airborne vehicles in the atmosphere of another planet.

- **Spacecraft Mission Operations Center**: Responsible for operating one or more spacecraft missions.

- **Earth Station Control Center**: Responsible for preparing, controlling, and monitoring one or more Earth Stations.

- **Planetary Station Control Center**: Analogous to an Earth Station Control Center, responsible for preparing, controlling, and monitoring one or more Planetary Stations.

- **Science Operations Center**: Responsible for controlling and monitoring individual science instruments and receiving science data.

The SSI supports intercommunications between applications residing on SSI nodes. Examples of SSI user applications include:

- File transfer services
- Messaging services
- Voice/video streaming services
- Timing services
- Navigation services

These applications will employ the underlying layered SSI protocol stack, including the SSI network, link, and physical layers to implement the required data exchange.

The network layer is responsible for the routing and forwarding of data across the network. For SSI scenarios involving continuous, low-delay connectivity between network nodes, the existing Internet Protocol (IP) network layer that supports terrestrial links can be used. More generally, however, the SSI must also be capable of supporting network scenarios in which links between nodes may be only intermittently available and/or may involve long light-time delays. For example, Earth Stations may only provide periodic communication sessions with a given spacecraft, outer planet missions may involve one-way light times of hours, a planetary orbiter may experience occultations of its link to Earth when the spacecraft orbits behind the planet, or a Mars lander may only obtain a few short relay communications opportunities each sol during the overflight of a low-altitude orbiter. For such scenarios, the existing Internet Protocol (IP) network layer supporting terrestrial links is not applicable; instead, such SSI scenarios would utilize Delay-Tolerant Networking (DTN, sometimes also referred to as Disruption-Tolerant Networking) protocols, including the Bundle Protocol (BP) network layer specification [1, 2].

Successful operation of the SSI is reliant on various elements of network management. A key construct is the notion of a “contact plan”, describing the (potentially time-varying) link connectivity among all of the SSI network nodes, including the bandwidth capabilities of each link connection. Knowledge of this contact plan is essential in order to enable individual SSI nodes to decide how to route and forward network traffic to its ultimate destination.

Individual SSI nodes would provide quantitative accounting metrics to support overall SSI network management. In the event of anomalous network performance, more detailed diagnostic information would be examined to support fault identification and recovery.

### 3. Key SSI Principles

The SISG has established a number of principles guiding the management, planning, and execution of the SSI. In many cases these principles have heritage to successful practices and lessons-learned from the terrestrial internet; at the same time, they also reflect years of experience with many of the unique challenges of space communications. We highlight a number of these principles here.
3.1 Management Principles

- **Asset Responsibility**: Each agency is responsible for the planning, control, and operations of its own assets, including payload configuration (e.g., for cross support).

- **Communications Protocols**: The operations concept shall, as far as possible, be independent of the communications protocols below the network layer to offer stable guidelines robust to the risks inherent to space missions (financial, delays, technical difficulties) and to ensure it is not bound to the specific implementations of such protocols.

- **Addressing**: Asset addressing must be constructed and managed at the network level using network-layer identifiers (IP address, DTN node name). The SSI will require an entity to manage and maintain a repository of addresses.

- **Network Services**: The defining characteristic of the SSI end state operations concept is the presence of a functional network layer in the protocol stack. Application layer functionality is only present at the endpoints of an end-to-end service (e.g., CCSDS File Delivery Protocol [CFDP], Asynchronous Message Services [AMS]); all processing at intermediate nodes is performed at the network layer.

- **Interoperability**: To provide a functional network layer in the protocol stack, all nodes that agree to provide SSI services will offer an agreed set of interoperable IP and/or DTN protocol services.

3.2 Planning Principles

- **Network Planning and Management**: In addition to standardized SSI network protocols, the SSI requires network planning and management functions to develop the network contact plan and execute network services.

- **Overall Planning**: The planning entities of the provider and user agencies must coordinate at long-term (typically geometry or flight dynamics), medium-term (typically resources or mission planning), and short-term (typically service request and delivery) levels.

- **Network Planning**: Network planning shall compile the routing possibilities and the loading level of affiliated provider assets. It shall answer user planning requests over the agreed time periods, and in case of conflict, propose feasible alternatives. It shall ensure that the finalized routing options are published to the users and providers for implementation.

- **User Planning**: User planning shall produce and manage consolidated user requests in a manner globally compliant with the known capabilities of the network, as defined by the high-level agreements and applicable policies. Depending on the network planning feedback, user planning shall refine these requests with its end users at all envisaged planning cycles.

- **Re-Planning**: The SSI shall allow re-planning or cancellation of a network service request prior to completion of the service or in event of an anomaly.

- **Contact Plan**: Network planning and execution in the SSI end state hinge on a network contact plan, which establishes the temporal windows and communications capabilities (e.g., bandwidth) of individual node-to-node network links. A key element of SSI end state operations is the dissemination of all (or a relevant subset) of the network contact plan to each individual network node.

- **Peering Agreements**: Peering agreements will be used to implement interagency interfaces within the SSI. When planning mission communications, an individual user will arrange for service with its agency-level provider, who will, in turn, employ peering agreements to arrange end-to-end data flows that use different agencies’ provider nodes.

3.3 Execution Principles

- **User Control**: The user MOC is responsible for the overall decision on when/whether to use the SSI network and what to do in case of a problem. The user MOC authorizes the sending of the forward products that shall transit via the SSI to the target asset and receives reporting accordingly.

- **Provider Node Control**: The MOC of the provider node is responsible for the management and scheduling of that SSI node, and determines what to do in case of a problem.

- **Verification**: The SSI communications architecture and protocols shall allow the user MOC to verify proper execution of the data delivery operations, taking into account the delays resulting from physical constraints and operational latencies.

- **Monitoring/Reporting**: The SSI providers shall provide the user MOC with feedback on the progress and success of the intermediate steps in the relaying process.

- **Traceability**: It shall always be possible for the provider agency to accomplish the following for its
own nodes: 1) successfully trace the items which have transited on a given node on Earth or in space in a certain period of time, 2) to report on delivery success or failure, and 3) to support redelivery of requested data for a certain (limited) time after the nominal transit date.

- Robustness: Each node agreeing to participate as a service provider node in the network shall be robust to nominal operating variations, provided that the data stream respects the protocols in place, the data dimensions (volumes, transfer rates, transfer frequency), the service agreement, and the technical specification of the network and the node.

- Transparency: Each node agreeing to participate in the network shall be indifferent and transparent to any contents of the transferred data units, provided that the data stream respects the protocols and the technical specification of the network.

- Integrity: The SSI shall be capable of delivering complete, gap-free data products between any two nodes.

- User Emergency: The SSI shall allow for defining and using, under pre-agreed conditions, a path from the user MOC to the user node that is completely deterministic in geometry and timing (e.g., to recover from anomalies in the network and/or the user node).

- Routing Functions: The SSI end state operations concept supports data flow over multiple possible network data paths. Forwarding of information is based on static or dynamic routing tables in the network-layer protocol with forwarding decisions based on information in the network-layer Protocol Data Units (as opposed to being driven by metadata or manually sequenced operations).

- Delay-Aware And Delay-Unaware Operations: The SSI end state will allow support for both delay-unaware operations (where short delay [<2 sec], continuous, end-to-end data paths are available) using the IP protocol suite, and delay-aware operations (where long transmission delays and multiple, temporally disjoint, piecewise network hops may be required to support end-to-end data flow) using the DTN protocol suite.

- Reporting: Individual network nodes will report status information in standardized formats to support network management and anomaly resolution.

4. Network Management Processes

The SSI would represent a confederation of network elements from multiple international space agencies. There is no plan for a central management authority for the SSI; rather, current practices for documenting interagency cross support agreements would be extended to address SSI planning and operations. Nonetheless, streamlined processes and increased levels of automation would be

![Figure 4.1: An overview of SSI coordination](image-url)
required to ensure efficient SSI operations.

Figure 4.1 illustrates SSI coordination at a high level. In analogy to the role of an Internet Service Provider (ISP) for the terrestrial Internet, each agency serves as an SSI Service Provider for its user nodes, establishing service agreements to meet each user’s communication requirements across its mission lifecycle in accordance with the agency’s provider node capabilities. When augmented services are required, a user’s agency would also negotiate cross-support agreements with other agencies to access services from that other agency’s provider nodes. This process of inter-agency SSI Service Provider cross-support is referred to as “peering,” to reflect the similar process used by terrestrial ISPs to route data between their respective networks.

As noted above, a key element of SSI operations involves the development and distribution of a contact plan. This contact plan, describing the temporal connectivity and bandwidth capabilities of the network, is essential to enable routing and forwarding decisions by individual SSI nodes in support of end-to-end network data delivery. The depth of information in the contact plan can be tailored to individual mission scenarios. At a minimum, individual nodes need to know full information about their contact plans with SSI neighboring network nodes. To the extent that an individual node has more complete information about the full network contact plan, it can make more informed routing decisions among multiple potential paths to minimize end-to-end data latency. For example, consider the case of a planetary lander with two relay orbiters providing intermittent relay contact opportunities. With full contact plan information, the lander could choose to relay data to the second relay orbiter passing overhead if it knew that that second orbiter had an earlier scheduled opportunity to forward that data to an Earth Station, thereby completing the end-to-end data transfer in a shorter time.

Development and dissemination of the contact plan is a cyclical process, as illustrated in Figure 4.2, and involves the following four elements:

- **Mutual Contact Determination**: This first phase identifies potential contact opportunities based on geometric trajectory information as well as known spacecraft constraints.
- **Contact Plan Generation**: The second phase involves negotiations to establish actual link layer service commitments between SSI nodes, typically for only a subset of all the potential contact opportunities. This phase established the actual time windows during which data can flow between any pair of nodes. Peering agreements would be invoked where necessary to obtain interagency cross-support services.

![Figure 4.2: Overview of the SSI Contact Planning Process](image)

- Space link performance extraction
- Network data volume and latency calculations, reports
- Trajectory predictions
- Communications geometry
- Spacecraft constraints

Network Utilization, Monitoring, Reporting

Contact Plan Release + Verification (of Release)

Contact Plan Generation

Mutual Contact Determination
- Contact Plan Release and Verification: The negotiated contact plan is distributed to each of the agency-level SSI Service Providers, who then take the necessary steps to plan for the execution of the committed link services per the contact plan.

- Network Utilization, Monitoring, and Reporting: Each node will take the necessary steps to establish the negotiated link-layer and physical-layer connectivity in accordance with the negotiated contact plan. At that point, actual network operations are highly automated, with the SSI network layer handling the forwarding and routing of protocol data units from their source application at a user node to their ultimate destination node. Individual nodes would monitor and report key performance metrics to verify nominal operation or to identify and trace any network anomaly.

5. Network Operation Scenarios

SSI network operations would involve multiple participants, potentially from multiple international space agencies, interacting on a variety of time scales to implement SSI network services. Figure 5.1 provides another view of the confederated contact planning process, from the perspective of the various SSI participants.

A user spacecraft MOC would provide inputs to the contact planning process for both the user spacecraft itself and for the user spacecraft MOC. Based on the user spacecraft mission plan, science planning objectives trajectory data, and flight system constraints, the user MOC would submit requested contact periods while providing relevant spacecraft constraints.

In a similar manner, each provider spacecraft and corresponding provider spacecraft MOC would supply contact planning inputs, identifying contact opportunities, requests, and constraints. Note that for hybrid science/telecom orbiters, similar to today’s Mars relay assets, these inputs and constraints must also reflect orbiter science plans.

Finally, Earth station control centers from each participating agency must also engage in this confederated contact planning process, reflecting the negotiated tracking schedule for space-to-Earth links.

All of these inputs feed into an iterative planning process that yields a committed contact plan that is distributed to all parties for execution. Typically each agency would seek to meet the needs of its own users based on its own provider assets, invoking interagency cross-support as needed, via peering agreements, to meet user requirements.

With the contact plan established, SSI network operations proceed with a high level of automation. Figure 5.2 illustrates the run-time operations concept for an SSI network service request for data transfer between a user MOD and user spacecraft, via one or more intermediate provider nodes. The fundamental service request is for data transfer between a pair of application-layer entities, one in the user MOC and one on the user spacecraft. (Examples include delivery of a command file from the user MOC to the user spacecraft, or delivery of science and engineering telemetry files from the user spacecraft to the user MOC.)

![Confederated Contact Planning Process](image)

**Figure 5.1: SSI Contact Planning Process**
The applications at the source and destination end-points for the network service (in this case the user MOC and user spacecraft) would then engage SSI network-layer services to oversee the end-to-end transfer of data across the network. Link layer services would be invoked across each hop of the end-to-end network path, based on the negotiated contact plan. Individual hops may use different link-layer protocols. For instance, a user MOC might utilize CCSDS Space Link Extension (SLE) services, while a deep space link might employ CCSDS TM/TC link layer protocols or AOS protocols, and a planetary relay link might utilize the CCSDS Proximity-1 Space Link Protocol.

6. CONCLUSIONS
The SISG, under the auspices of the IOAG, has established an operations concept for a solar system internetwork that would provide robust and efficient end-to-end data services spanning terrestrial and space links on up to interplanetary distance scales. Unlike current planetary relay scenarios that use mission-unique application-layer functionality to provide store-and-forward services, the SSI would utilize standardized network layer protocols to establish interoperable end-to-end network services between SSI nodes.

The SSI operations concept incorporates many aspects of the terrestrial Internet, while reflecting the unique challenges of space communications. DTN protocols would support network layer functionality for scenarios involving networks with disrupted or long-delay links, while standard IP protocols could be used for network scenarios that only involve low-latency, continuously-available links.

A key aspect of the SSI operations concept involves the development and dissemination of the contact plan describing the temporal connectivity of SSI nodes and the bandwidth characteristics of individual links. Once this contact plan has been established, network communication can proceed in a highly automated fashion, with intermediate notes using knowledge of the contact plan to drive forwarding and routing decisions.

Ultimately, the SSI has the potential to revolutionize communications across the solar system in the same way as the terrestrial Internet has revolutionized terrestrial communications.

ACKNOWLEDGMENT
Part of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors thank all the members of the Space Internetworking Strategy Group for their many valuable inputs in reviewing and refining this SSI operations concept.

Figure 5.2: SSI Run-time operations
REFERENCES


BIOGRAPHY

Charles (Chad) Edwards, Jr. is the manager of the Mars Network Project Office within the Interplanetary Network Directorate at the Jet Propulsion Laboratory and Chief Telecommunications Engineer for NASA’s Mars Exploration Program. Prior to this current assignment he managed the research and development program of NASA’s Deep Space Network. He received an A.B. in Physics from Princeton University and a Ph. D. in Physics from the California Institute of Technology.

Michel Denis is the Spacecraft Operations Manager for Mars Express and has covered all phases of this ESA science mission from preparation through routine operation in orbit, including relay support to the NASA landers on Mars. He joined the European Space Agency as a flight control team engineer for Meteosat, and then worked on Cluster, Huygens and XMM-Newton. Before joining ESA he was employed in the aerospace industry in France, where he developed embedded software systems. He graduated as an engineer in the Ecole Centrale de Paris, and later obtained a master's degree in Space Engineering.

Lena Braatz is a consultant with Booz Allen Hamilton supporting the Space Communications and Navigation (SCaN) Program at NASA Headquarters. Her previous clients include project, division, and directorate offices at NASA’s Goddard Space Flight Center (GSFC), including the Space Network, Near Earth Network, Rapid Spacecraft Development Office, and Global Precipitation Measurement mission. Before joining Booz Allen, she contributed to gravity modeling and orbit determination efforts at GSFC. She received a B.A. in Earth and Planetary Science from the Johns Hopkins University.