

The NASA Space Communications Data Networking Architecture

David J. Israel¹
NASA/Goddard Space Flight Center

Adrian J. Hooke.²
NASA/Jet Propulsion Laboratory, California Institute of Technology

Kenneth Freeman³
NASA/Ames Research Center

John J. Rush⁴
NASA Headquarters

The NASA Space Communications Architecture Working Group (SCAWG) has recently been developing an integrated agency-wide space communications architecture in order to provide the necessary communication and navigation capabilities to support NASA's new Exploration and Science Programs. A critical element of the space communications architecture is the end-to-end Data Networking Architecture, which must provide a wide range of services required for missions ranging from planetary rovers to human spaceflight, and from sub-orbital space to deep space. Requirements for a higher degree of user autonomy and interoperability between a variety of elements must be accommodated within an architecture that necessarily features minimum operational complexity. The architecture must also be scalable and evolvable to meet mission needs for the next 25 years. This paper will describe the recommended NASA Data Networking Architecture, present some of the rationale for the recommendations, and will illustrate an application of the architecture to example NASA missions.

I. Introduction

THE National Aeronautics and Space Administration (NASA) has been developing a space communication and navigation architecture to support NASA Science and Exploration missions through the 2030 time frame. This work has been performed by the Space Communication Architecture Working Group (SCAWG), which is led by NASA Headquarters and includes members from across all of NASA. The initial SCAWG architecture was completed and approved by NASA in May 2006. This paper will focus on its Networking Architecture component.

As illustrated in Figure 1, the Networking Architecture is one of four crosscutting architectures that overlay four physical elements of the overall architecture. The Networking Architecture is required to support all NASA missions in all locations and operational scenarios and so the SCAWG Networking Architecture Team (NAT) had open representation from all NASA centers that have a stake in networking operations for previous, existing and future missions. The experience base of the participants therefore spanned everything from sub-orbital to deep space and robotic to human spaceflight missions.

¹ SCAWG Networking Architecture Team Lead, NASA/Goddard Space Flight Center, Communication and Microwave Systems Branch, Code 567.3, Greenbelt, MD 20771, USA.

² Manager, NASA Space Data Standards Program. Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, m/s 303-402, Pasadena, CA 91109-8099, USA. AIAA Member.

³ Manager, NASA Research and Engineering Network, NASA/Ames Research Center

⁴ Insert Job Title, Department Name, NASA Headquarters, etc. and AIAA Member Grade for fourth author (etc).

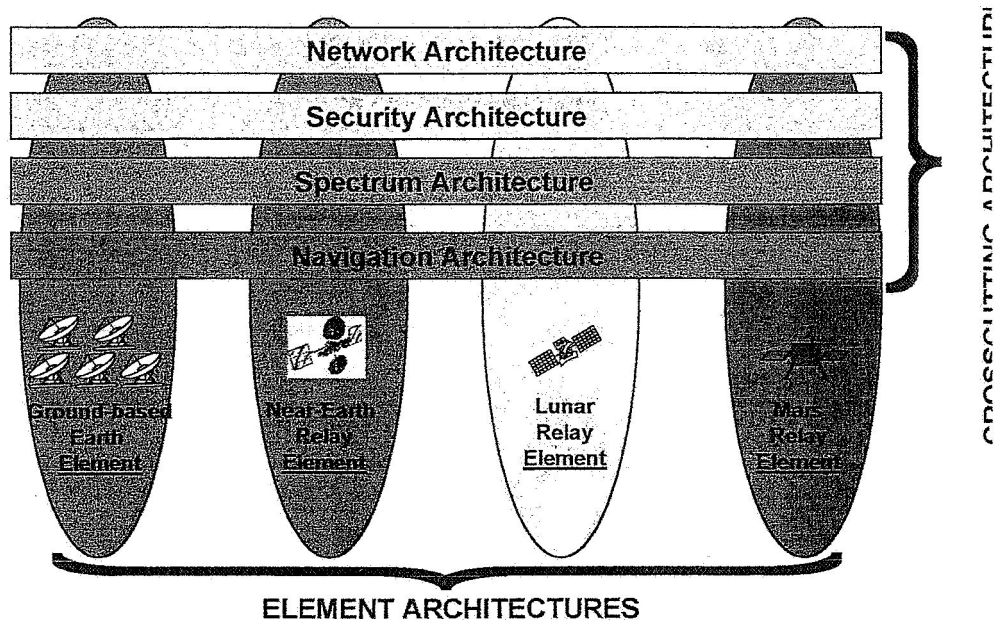


Figure 1. Communications and Navigation Architectural Components

II. The Recommended Networking Architecture

The Networking Architecture is built upon a *Security Architecture* and a *Spectrum Architecture*. The Spectrum Architecture establishes the spectrum bands that will be used when implementing individual point to point data communication “hops” between space systems. Such hops are components of the end to end space data communications network – spanning both Earth and space assets – that interconnects space mission user applications. The Networking Architecture defines how the overall network containing those hops is structured in the context of the Security Architecture, which establishes how the information transiting that network is to be protected. Security services can be implemented at multiple points in the Networking Architecture. A *Navigation Architecture* defines how the various network elements are utilized in order to control the flight path of the space vehicle. The Security, Spectrum and Navigation components of the overall architecture are not further discussed here.

A. Overview of the Networking Architecture

In common with the terrestrial Internet, the underpinning of the Networking Architecture is a set of standard, low cost, layered data communications services that support end-to-end user applications. “On-ramps” are defined in the layered structure such that legacy systems, new services or diverse service providers can be easily integrated into the network. The Networking Architecture provides an open, flexible, and evolvable networked data communications services across all elements. This architecture enables mission selectable end-to-end communication options in accordance with established and evolving network policies that also govern the set of communication standards in use at any given time.

The Networking Architecture presents a long term (25-40 year) vision and strategy for the evolution of NASA’s space communications systems, conceptually towards eventual provision of ubiquitous end-to-end user connectivity across the entire solar system. To accomplish this, the Network Architecture absorbs evolving terrestrial Internet technologies within its ground segment and extends them into and across space. The progressive and evolutionary build-up of standard infrastructure is a fundamental architectural tenet: it assumes that NASA will progressively invest in ground and flight data handling system designs that are engineered to be re-usable and that, over time, accrete into an “Interplanetary Internet” which spans the solar system in support of our missions of Science and Exploration.

The Networking Architecture supports the full lifecycle of a space mission. It benefits mission planning by stimulating opportunities for interoperability with different organizations and by being easily scalable (up and down) to meet variable mission loading. It benefits the development, test and launch phases by reducing costs via re-use of common hardware and software infrastructure. It benefits the mission operations phase by enabling increased automation and security, by fostering the use of standard commercial products, and by reducing the need for unnecessary redundancy and labor-intensive planning. It benefits its operational users by providing access to familiar network-based applications using robust and reliable communications services (even when intermediate nodes are not available).

B. Driving Requirements on the Networking Architecture

The Networking Architecture is driven by a set of top-level requirements either taken from existing requirements documents or derived from analysis of NASA's integrated mission set. The key driving requirements are:

- Provide multi-mission data communication services for:
 - Legacy missions
 - New Science missions
 - New Exploration missions
- Support internetworked space and ground elements
- Provide data communication service "on-ramps" for future government and, potentially, commercial service providers
- Accommodate both scheduled and unscheduled communications
- Accommodate both continuous and intermittent connectivity
- Provide service over space data links characterized by:
 - Both large and small signal propagation latencies
 - Both uni-directionality and bi-directionality
 - Both low and high bit error rates
- Support data flows that:
 - Originate at arbitrary user locations on Earth and in space
 - Terminate at arbitrary user locations or sets of user locations (i.e., multi-point delivery) on Earth and in space
 - Traverse N-hop transmission paths where $N > 1$
- Support transmission of the following types of data:
 - Command
 - Telemetry
 - Files (including web pages)
 - Messages (e.g., electronic mail)
 - Voice
 - Video
 - Range safety
- Provide the following qualities of data communication service (not necessarily in all combinations):
 - Isochrony
 - Reliability
 - Transmission order preservation
 - Timeliness
 - Priority
- Provide data communication performance metrics and accountability

C. Scope of the Space Communications Network

NASA's Space Communications Network logically interconnects end users via a series of physical layer "hops" or transmissions, as shown in Figure 2.

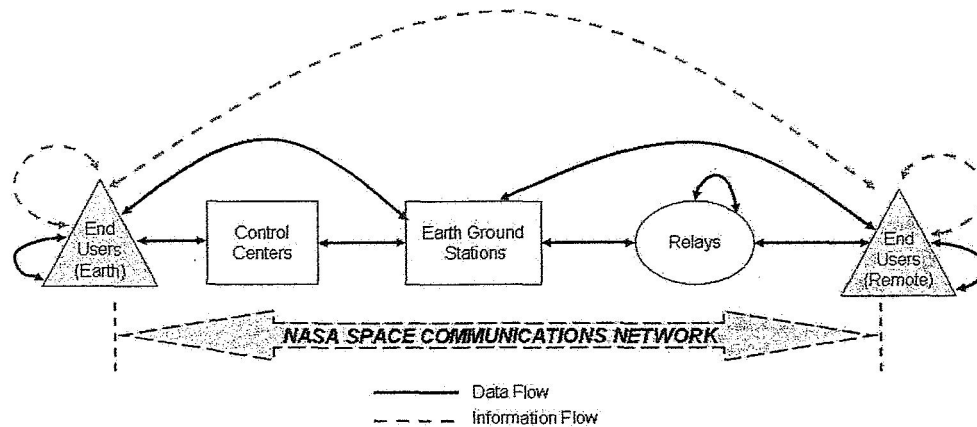


Figure 2: Network Connects End Users via Physical Layer "Hops"

The individual hops connect adjacent elements of the architecture and feature:

- Terrestrial links connecting users to control centers, users to ground stations, or control centers to ground stations.
- In-space links connecting ground stations to remote user vehicles, ground stations to relays, relays to relays, relays to remote user vehicles, remote vehicles to remote vehicles, or interconnecting end systems within remote vehicles.

Information exchange between users flows logically (dashed lines) from source to destination independent of the underlying network structure. This flow is either wholly on Earth, between Earth and space, or wholly in-space. Although most transfers are between a single source and a single destination, the architecture supports point-to-multipoint (single source, multiple destinations) delivery where required.

D. Layered Service Architecture

In accordance with modern practices, user information exchange within the Networking Architecture is achieved by drawing upon a stack of "layered" services (Figure 3). Within a layered architecture, peer functions that exchange information across a data communications path are organized so that they provide a standard service to the layer above and draw upon standard service(s) from the layer below. As long as the service interfaces are preserved, an individual layer can be easily replaced as technology and mission requirements evolve.

Peer functions at the sending and receiving ends of a layer exchange information across the network using a standardized dialog known as a data communications protocol. The protocol is represented by the "bits on the wire" and it is the standardized mechanism by which senders and receivers in different organizations achieve interoperability. Interoperability is defined in *The IEEE Standard Computer Dictionary*⁵ as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged."

Note that some of the service layers may reside in the user end systems and some may reside in the supporting mission-independent communications systems. The Networking Architecture encompasses all layers independent of the implementing organization.

⁵ Institute of Electrical and Electronics Engineers. *IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*. New York, NY: 1990.

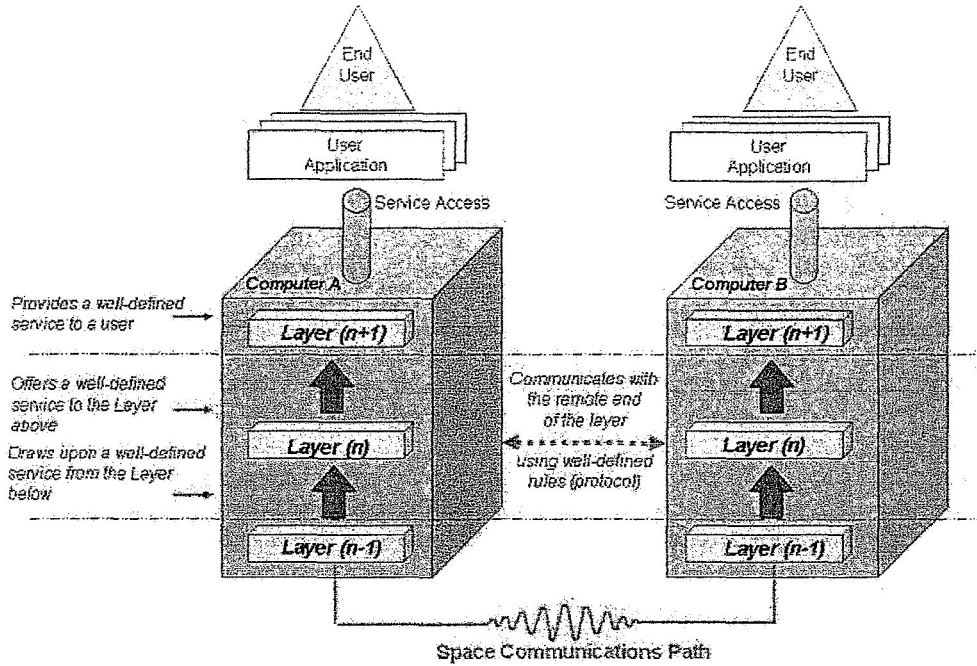


Figure 3. Network Architecture: A Stack of Layered Services

E. Exposed Services

The service layers within the Networking Architecture are constructed as a staircase (Figure 4), with multiple service access points (“on-ramps”) provided so that users can reach-down as needed to access the services of lower layers if they don’t need the service of a higher layer.

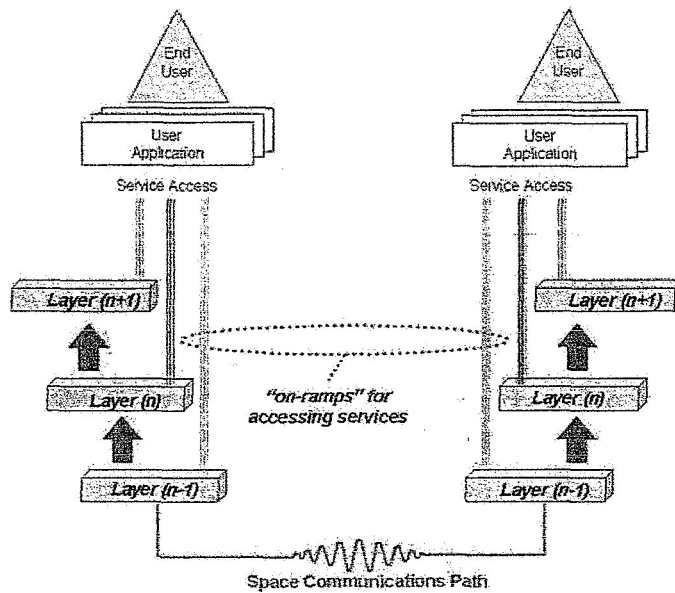


Figure 4. Service Access Points in the Network

The “on-ramps” enable several key capabilities:

- Basic emergency commanding can be done by bypassing all but the most rudimentary communications services;
- Legacy systems, which do not necessarily conform to all the standard service layers, may be accommodated; and,
- Different organizations (e.g., future commercial providers) may “drop in” their services as a confederated contribution to the overall end-to-end network.

F. Definition of Networking Layers

The Networking Architecture follows international standard service layering conventions as embodied in the well-known Open Systems Interconnection (OSI) model, including its terrestrial Internet derivative which reduces the OSI model to five layers:

- Application Services reside in the Application layer and provide common utilities in support of familiar user applications (File Transfer, Messaging, Web browsing, audio and video formatting, etc.). The Application Services (which are part of the Networking Architecture) sit directly below the user applications (which are not).
- Transport layer services support user-selectable levels of end-to-end data transfer reliability.
- Network layer services automatically route data between user applications.
- Link layer services support structured data transfer through a single point-to-point hop.
- Physical layer services support unstructured symbol transfer through a single point-to-point hop.

The relationship between these layers when two end systems are separated by a single space link hop is shown in Figure 5.

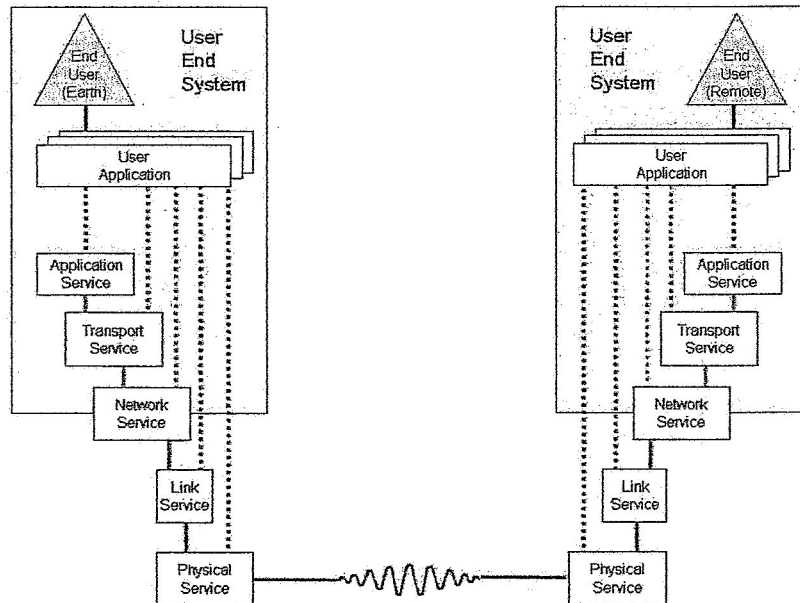


Figure 5. Definition of Networking Services

The network comprises all of the devices that may participate in the transmission of data between two users of NASA's end-to-end data communications infrastructure. The Application service and Transport service are hosted within the user end systems, yet they are still part of the end-to-end Networking Architecture. These are network utilities that are provided to users. The Networking Architecture therefore embraces the spacecraft and the

supporting ground networks, including control centers. The Network, Link and Physical services are implemented as part of an underlying "core" of multi-mission service infrastructure.

How these abstract networking services are allocated to physical mission elements varies. One example is shown in Figure 6.

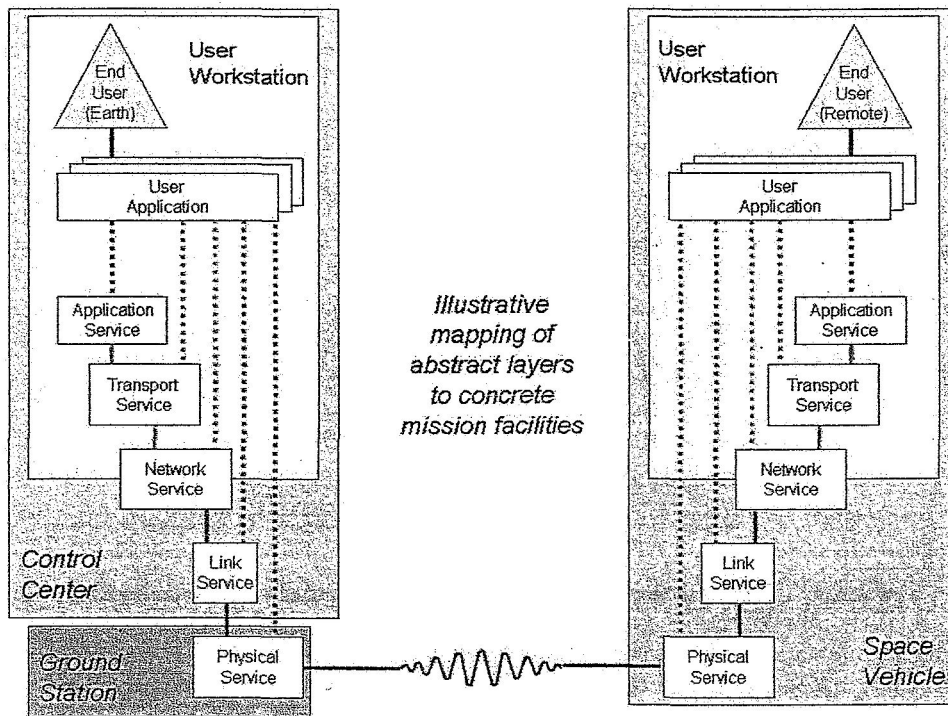


Figure 6. Example of Networking Services Allocated to Physical Elements

In some current and many future mission configurations, end-to-end data transfer may involve multiple hops, with core services embedded within in-space relays. Figure 7 shows how layered services may be configured in a simple two-hop intermediate space relay data flow.

The Physical and Link services can only be provided across a single hop. If it is desired to bridge either of them across the inbound and outbound sides of a relay so that they tunnel transparently through the relay, then a relay application must be provided for this purpose. This application may operate either in real-time or in a store-and-forward mode. Unless all inbound and outbound links are engineered to be homogeneous, this relay application may be complex.

The Network service, by its layering, is inherently independent of the underlying heterogeneous Link and Physical layers. It is relatively easy to standardize and as such it may be readily located at key hops in the end-to-end path, such as in-space relays.

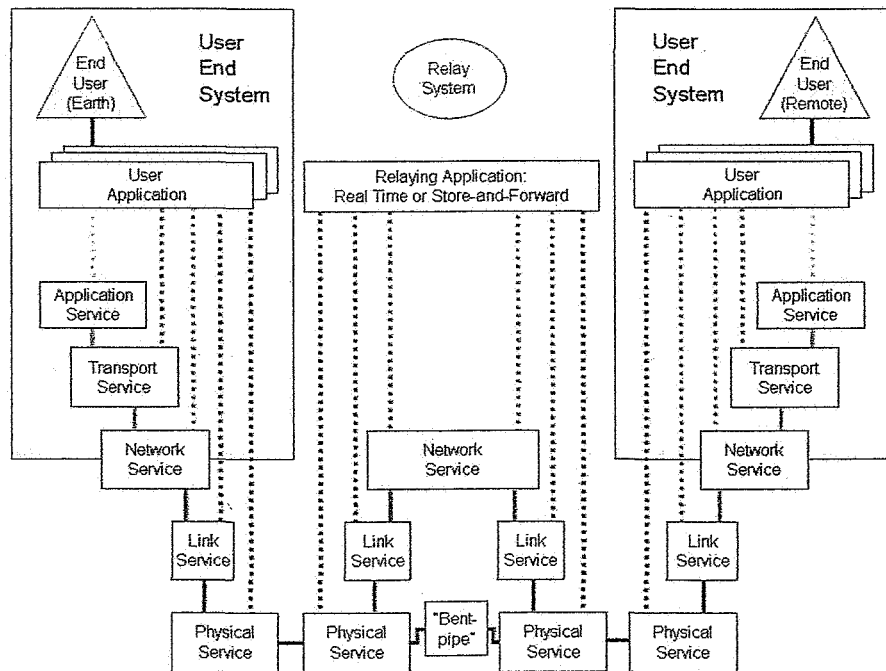


Figure 7. Layered Services in a Two-Hop Intermediate Space Relay Data Flow

In such a relay architecture, data protection via “bulk encryption” of the channel is usually only feasible if the in-space relay simply transponds (via a “bent-pipe”) the physical symbol stream in real time between its input and output sides. Such a scheme is currently implemented by legacy systems such as Space Shuttle and the ISS, which use the TDRSS in pure bent-pipe mode. To implement a Link or Network relay using such a data protection scheme, the Physical layer encryption(s) must be locally terminated. The Security Architecture allows bulk encryption of the channel for future systems, however, this is operationally complex.

III. Standardization Trade-Offs

The Networking Architecture traded-off five different options for where best to standardize the service infrastructure. The options considered were:

- At the Physical Layer (Bit/Symbol stream services only).
- Up to the Link Layer, with access to a standard Physical layer.
- Up to the Network Layer, with access to standard Link and Physical layers.
- Up to the Transport Layer, with access to standard Network, Link and Physical layers.
- Up to the Application Layer, with access to standard Transport, Network, Link and Physical layers.

Figures of Merit (FOMs) were used to evaluate the options in order to support the recommendation. The FOMS used in NASA-wide trade-offs were as follows:

- **Operational Efficiency:** The proportion of mission operations activity that must be performed by humans over the entire mission lifecycle, regardless of location.
- **Robustness:** A compound FOM consisting of: (a) The ease with which additional elements can be added to a mission or mission set (scalability); (b) the ease with which new operational capabilities can be introduced into mission operations systems (evolvability); (c) the ease with which data paths through the network can be changed in response to changing mission requirements (adaptability); (d) the proportion of the operational time in which the network operates without error (reliability); (e) the ease with which errors can be remedied (maintainability); and (f) the proportion of wall clock time in which the network operates (availability).

- **Infrastructure Capability:** (Communication Infrastructure Development and Maintenance Efficiency): The ease with which mission functionality is developed and maintained over the entire mission lifecycle, at vehicle end user terminals (spacecraft, aircraft, etc.); at ground stations and relay points; and Earth end user terminals (control centers, science centers, test facilities).
- **Ease of Transition:** The ease with which the option can be implemented within NASA, including the acquisition of new equipment, development of new technology, and training of mission operators.
- **Interoperability:** The ease with which users are able to complete all negotiations required to achieve successful and secure communication of mission information among both NASA and non-NASA assets and facilities.
- **Resource Utilization:** Total value of user data delivered, given fixed resources. These resources include link utilization, available memory, available power, visibility windows, and launch mass.

The Operational Efficiency and Infrastructure Capability FOMs were scored based entirely on requirements. Half of the Robustness FOM factors were scored based on requirements. The Ease of Transition, Interoperability, and Resource Utilization plus half of the Robustness FOM factors were scored based on team consensus. The conclusions of the tradeoff scoring were as follows:

- Standardization should reach at least to the Network layer, although the benefits of standardization continue to increase above this layer. The Network layer is the “thin waist” of interoperability. There are multiple choices for heterogeneity in the Transport and Application layers above it; multiple choices for heterogeneity in the Link and Physical layers below it; but a minimum requirement for interoperability is that these choices must converge in a homogenous Network layer.
- In order to support Network layer standardization, standardization of the underlying Physical and Link layers is required when different organizations act as the termini for the individual data links in the end-to-end path.

Detailed protocol selection tradeoffs were not performed by this study. The choice for a Network layer standard is assumed to be the Internet Protocol, IP. However, since the complete IP suite cannot be sustained across the entire Networking Architecture (which includes disconnected, highly asymmetric or long delay space communications), an enhanced version of Network service – such as Disruption Tolerant Networking (DTN)⁶ – should be developed to accommodate environments where the performance of the IP suite is inadequate.

IV. Conclusion

Following the acceptance of the initial recommendation for a Networking Architecture based on standardized, layered communications services, the NASA Space Communications Architecture Working Group has begun the next required phase in the development of the Networking Architecture. Standard protocols will be selected as options for each communications layer. The options will be accompanied with guidance for mission designers to assist in the selection based on the individual mission needs. This first set of standard protocol options will become the core of the NASA communications architecture and will continue to evolve as new protocols and new requirements evolve.

Acknowledgments

The authors would like to thank the many participants of the NASA Space Communications Architecture Working Group Networking Architecture Team.

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.

⁶ V. Cerf et. al., "Delay Tolerant Network Architecture", [draft-irtf-dtnrg-arch-05.txt](#), September 2006, Delay Tolerant Networking Research Group, Internet Research Task Force.