Report of the
Interagency Operations Advisory Group
Lunar Communications Architecture Working Group

Recommendations on the Selection of End-to-end Space Internetworking Protocol

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Space Internetworking Strategy Group - Membership

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1. Introduction

1.1 Purpose and Scope

The purpose of this document is to recommend where and when to use the Internet Protocol (IP) and the Bundle Protocol (BP) for communications. These recommendations complement the guidance provided by the Interagency Operations Advisory Group (IOAG) Lunar Communications Architecture Working Group [1], the IOAG Space Internetworking Strategy Group (SISG) [2], and the Consultative Committee for Space Data Systems (CCSDS) [3]. Though the example scenarios discussed in this document reference lunar and Mars missions, the recommendations herein are not limited to those scenarios.

1.2 Definition of Terms

In this document, the following terms are used.

Term	Definition
Application	Software that performs a specific function
Bop	The path between two adjacent bundle nodes
BP network	A communications network where the network layer is based on BP
Bundle	The network data unit of the Bundle Protocol
Bundle Hop Protocol(s)	Communications protocols that deliver bundles between two adjacent bundle nodes
Bundle node	A node in a BP network; bundle nodes are capable of receiving and transmitting bundles
Bundle Protocol (BP)	The primary communications protocol within the DTN Protocol Suite
Convergence Layer Adapter	The convergence layer adapter enables a bundle node to send and receive bundles using the services of some “native” link, network, or Internet protocol.
Destination node	An entity that consumes data
End-to-end path	The aggregation of all links between the source and destination nodes; a single operations scenario may include multiple end-to-end paths
Intermediate node	An entity that relays data between nodes
Internet Protocol (IP)	The primary communications protocol within the Internet Protocol Suite that provides Earth-based terrestrial communications
IP network	A communications network where the network layer is based on IP
IP node	A node in an IP network; IP nodes are capable of receiving and transmitting IP packets
Link	A direct connection between any two adjacent nodes
Network data unit	A block of data including fields that allow network-layer protocol operations
Node	An entity that is part of a data flow. Examples of nodes include instruments, onboard systems, and ground stations.
Operations scenario	Description of activities conducted to support mission objectives, including the actors involved and their locations, etc.
Path	The sequence of one or more links between two nodes
Source node	An entity that originates data

Transmission Control Protocol (TCP)	A communications protocol that is used with IP and ensures reliable transmission of packets (i.e., it performs error checking and retransmissions, as necessary)
User Datagram Protocol (UDP)	A communications protocol that works with IP and provides unreliable transmission of packets (i.e., it performs error checking but not retransmissions)

1.3 Reference Documents

[1] Interagency Operations Advisory Group Lunar Communications Architecture Working Group, *The Future Lunar Communications Architecture*, https://www.ioag.org/_layouts/15/WopiFrame.aspx?sourcedoc={97054575-1F69-4C0C-985C-65031A9F12C7}&file=Lunar%20communications%20architecture%20study%20report%20Final%20v1.2%202-1-2020.docx&action=default.

[2] Interagency Operations Advisory Group Space Internetworking Strategy Group, *Recommendations on a Strategy for Space Internetworking*, https://www.ioag.org/Public%20Documents/SISG%20Phase%20I%20report%20%E2%80%93%20final.pdf.

[3] Consultative Committee for Space Data Systems, *Rationale, Scenarios, and Requirements for DTN in Space*. Green Book. Issue 1. August 2010. https://public.ccsds.org/Pubs/734x0g1e1.pdf.

[4] Burleigh, Scott, et al. "Delay-tolerant networking: an approach to interplanetary internet." *IEEE Communications Magazine* 41.6 (2003): 128-136.

2. Descriptions of the Internet Protocol and DTN Protocol Suites

2.1 Internet Protocol Suite

The Internet Protocol Suite is a set of communications protocols developed to provide networked end-to-end communications between a software application at the source node and a software application at the destination node. The Internet Protocol (IP) is the primary communications protocol within the Internet Protocol Suite that provides terrestrial networked communications. An IP network typically uses Transmission Control Protocol (TCP) (connection-oriented with acknowledgments and re-transmission of lost packets) or User Datagram Protocol (UDP) (connectionless, no re-transmissions or acknowledgments) for end-to-end data delivery. The underlying Internet Protocol is used to deliver the data from a source to a destination host via intermediate hops and the IP packet serves as the network data unit. IP packets are generated at the source node and can be multiplexed and de-multiplexed together at various points along the communication path, allowing for maximum utilization of the path. At intermediate nodes along the path, individual packets may be automatically forwarded to different nodes, based on information within the IP packet header, the node configurations, protocols in use, and network policies. However, if an intermediate IP node cannot forward the packet (e.g., the next node in the path is unavailable) the node will discard the data. Nodes and network access points using the standard interfaces and protocols can be easily added to the network. Once a new node is connected, data can be exchanged by routing to and from the new node address. In an IP network, any acknowledgements and retransmissions to ensure reliable data delivery are accomplished across the full end-to-end path (i.e., between source and destination nodes).

The Internet Protocol Suite is well suited to operations in environments where the following conditions are assured:

- Low latency (i.e., no long delays that would hamper use of "chatty" protocols)
- Continuous end-to-end connectivity (no disruptions beyond momentary dropouts)
- Sufficient bandwidth along the end-to-end path (no data rate mismatches at intermediate nodes)

2.2 DTN Protocol Suite

Like the Internet Protocol Suite, the DTN Protocol Suite is a set of communications protocols developed to provide networked end-to-end communications between a software application at the source node and a software application at the destination node. The DTN Protocol Suite also uses information within the data stream (headers attached to data units) to accomplish end-to-end data delivery through network nodes. The Bundle Protocol (BP) is the network-layer communications protocol within the DTN Protocol Suite (note there are additional protocols that can be used in a BP network to ensure reliability and security). A BP network (a.k.a. a DTN network) uses BP for end-to-end data delivery and the bundle serves as the network data unit. Like the nodes in an IP network, intermediate nodes along a BP network path may automatically forward individual network data units to different nodes based on information within the header, the node configurations, protocols in use, and network policies. If the link to the next node is available, an intermediate node in a BP network forwards the data without interruption just as an intermediate node in an IP network would.

In contrast to IP network nodes, however, BP network nodes (a.k.a. bundle nodes) can store data if the link to the next node in the path is not immediately available. In addition, any acknowledgements and retransmissions to ensure reliable data delivery can be accomplished for each link in a BP network (i.e., between adjacent bundle nodes). This store-and-forward approach enables networking to operate in scenarios where a continuous, full-bandwidth, end-to-end path between source and destination nodes is not consistently available. The store-and-forward approach also enables automated data buffering, which allows the network to provide successful data delivery in situations where there are data rate mismatches, such as when a high-data-rate science downlink is delivered to a ground station with lower data-rate capabilities. BP, therefore, can offer networked communications in situations where IP cannot—for example, in scenarios involving long delays, disruptions, data rate mismatches, etc.

3. Selection of an End-to-End Networking Protocol

The decision to use the IP Protocol Suite in an IP network or the DTN Protocol Suite in a BP network for end-to-end networking should be based on the characteristics of the operations scenario and the end-to-end paths it entails, not the physical location of the nodes.

Consider the operations scenario depicted in Figure 1. Astronauts in a Human Landing System (the Lander) on the surface of the Moon or Mars employ a control console to teleoperate a rover using video and other data from the rover to facilitate navigation and control. The rover collects science data using an onboard instrument and these data are sent to a science operations center on Earth. There are two end-to-end communications paths in this scenario: (1) the path between the rover and the lander (shown in red in Figure 1), and (2) the path between the rover and the science operations center on Earth (depicted in black in Figure 1).

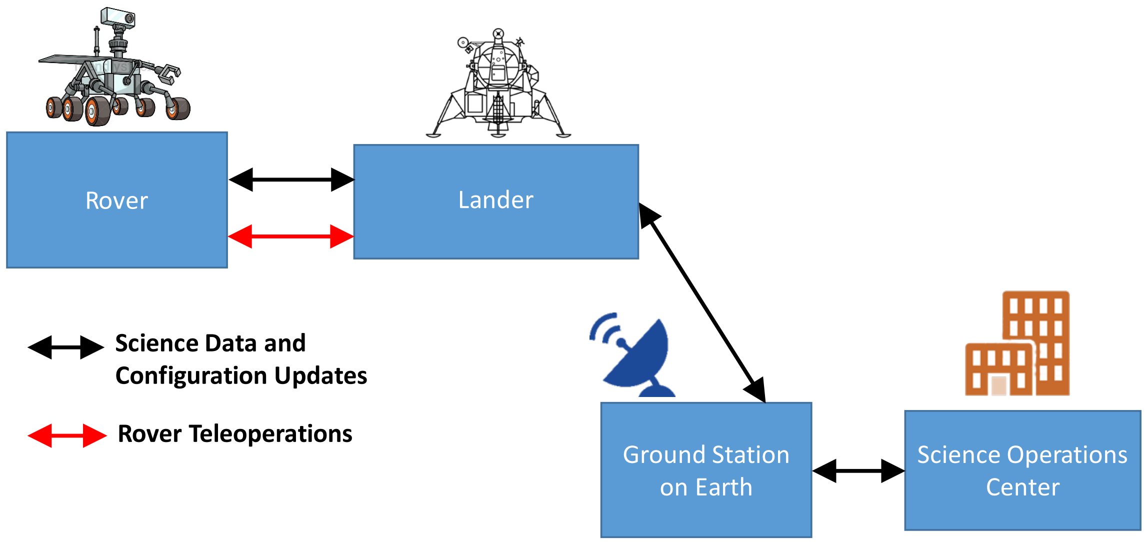

Figure 1. Astronauts in a Human Landing System (the Lander) on the surface of the Moon or Mars employ a control console to teleoperate a rover using video and other data from the rover to facilitate navigation and control.

If a low-latency path with continuous end-to-end connectivity is assured, then an IP network can be employed to provide communications. In Figure 1, the end-to-end path between the rover and the lander requires low latency and end-to-end connectivity to enable successful teleoperations; therefore, either an IP or a BP network could be used successfully to support communications on this end-to-end path. As an example, the protocol configuration using an IP network on this end-to-end path is shown on the left in Figure 2. Connections requiring reliable transfer (control and science data) may make use of TCP, while real time data connections (video) may make use of UDP to ensure timeliness. Alternatively, the protocol configuration using a BP network on this end-to-end path is shown on the right in Figure 2. Note that a TCP/IP-based application is used in the IP network depicted in Figure 2 on the left, while a BP-based application is used in the BP network depicted on the right.

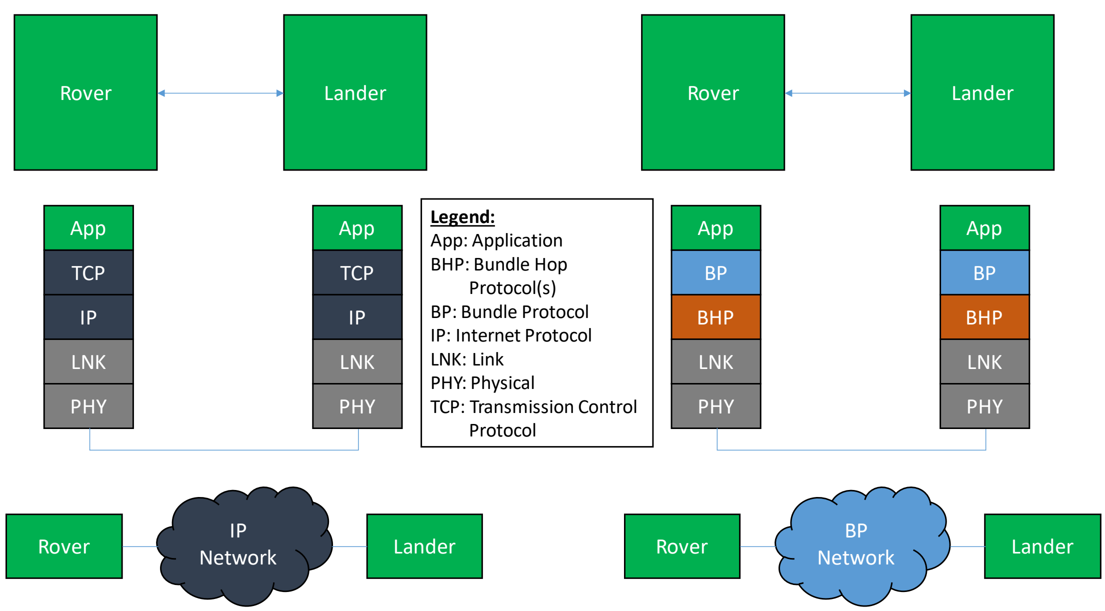

Figure 2. The protocol configuration for the end-to-end path between the rover and the lander using an IP network (left) and a BP network (right).

In contrast, the transfer of science data and configuration updates between a rover on the surface of the Moon or Mars back to a science operations center on Earth as shown in Figure 1 may not need to be accomplished in real time. Communications between Mars and Earth will experience disruptions due to the lack of an available end-to-end path and will involve delays due to the long time it takes signals to travel between Mars and Earth. Because of the disruptions and delays involved, a BP network is required to support a reliable end-to-end path between Mars and Earth. For communications between the Moon and Earth, the distance between the two bodies will introduce some delay; in addition, maintaining end-to-end connectivity may not always be possible (e.g., due to lack of available bandwidth, assets that are on the far side of the Moon, etc.), and significant disruption could result. Although a customized IP-based solution could be made to enable use of an IP network to support an end-to-end path between the Moon and Earth, BP was designed to work in this type of situation and could be employed without modification. Furthermore, NASA's current lunar efforts are intended to support future Agency efforts to explore Mars. Instead of creating customized IP network solutions to support these types of end-to-end paths in lunar operations scenarios, it would be more efficient to develop solutions for the Moon that can also be employed for Mars exploration. Therefore, a BP network should also be used to support this type of end-to-end path between Earth and the Moon.

Note, however, that it is possible to employ IP in certain sections of a BP network. If IP is available to support communications on the path between two bundle nodes in a BP network, IP can be used to transport the bundles between those nodes. For example, Figure 3 depicts a possible implementation of the scenario shown in Figure 1. The path between two adjacent bundle nodes is called a "bop." In this specific scenario, there are three bops along the end-to-end path of the BP network. On the bops where IP is functional, IP is used to transport the data bundles.

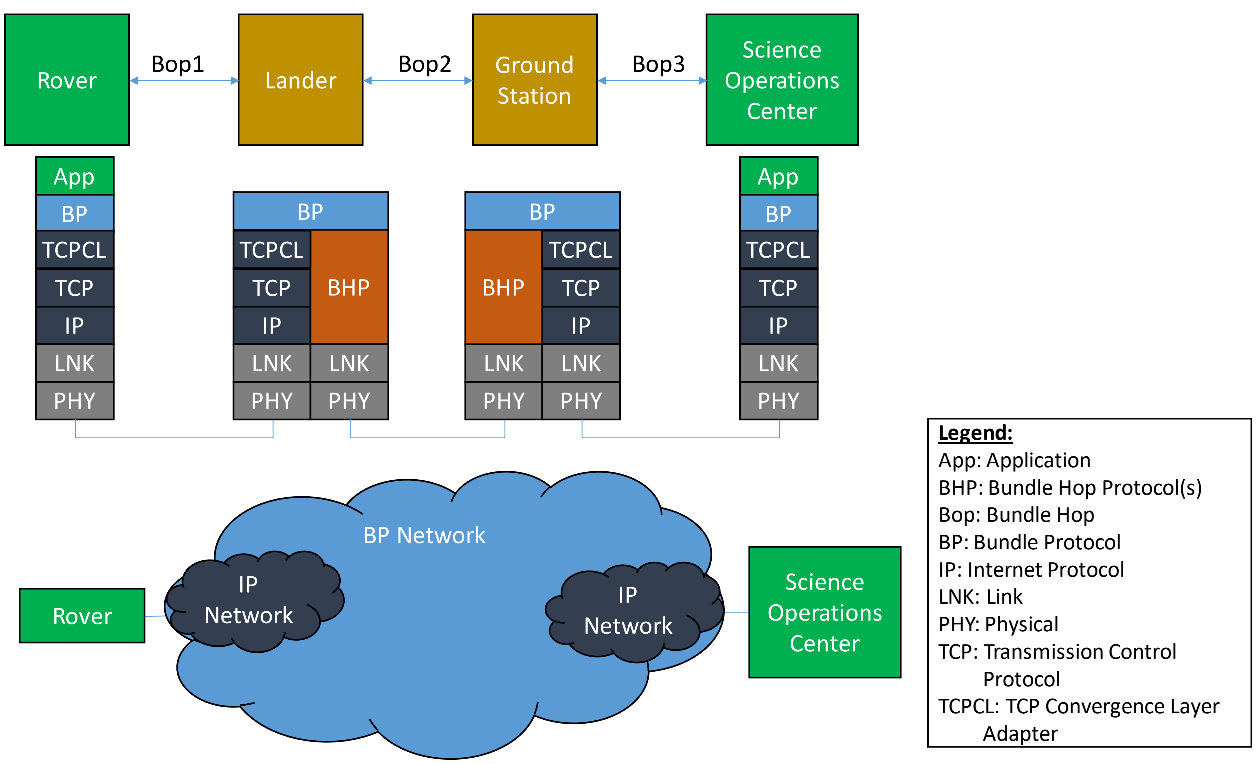

Figure 3. A potential protocol configuration for the end-to-end path between the Rover and Science Operations Center. Note that IP can be employed to transport bundles on bops where IP is functional.

In the scenario depicted in Figure 3, the BP network transporting science data from the rover to the science operations center would operate as follows. Since an IP network is available to support communications between the rover and the lander, IP is also available on Bop1 to transport the bundles containing the science data between the rover and the lander. Onboard the lander, the bundles are received via the TCP Convergence Layer Adapter and forwarded via the appropriate Bundle Hop Protocol(s) to the next bundle node—the ground station. At the ground station, the bundles are extracted from the space link and then forwarded to the next bundle node—the science operations center. Since an IP network is available to support communications on the path between the ground station and science operations center, a new IP connection could be used to transport the bundles on Bop3.

As shown in Figure 3, nodes can be in both an IP network and a BP network. For example, in the operations scenario depicted in Figure 3, the rover, the lander, the ground station, and the science operations center reside in both an IP network and a BP network. The BP network, however, is the only network that includes all the nodes in the scenario.

4. Recommendations

When determining whether to use the IP Protocol Suite in an IP network or the DTN Protocol Suite in a BP network for end-to-end networking, mission implementers should consider the characteristics of the operations scenario and the end-to-end paths it entails, not the physical location of the network nodes. On end-to-end paths where low latency and continuous end-to-end connectivity are assured and sufficient bandwidth is always available along the end-to-end path (there are no data rate mismatches at intermediate nodes), an IP network can be employed. A BP network can support communications over any end-to-end path, including those that involve delays, disruptions, or data rate mismatches. Use of a BP network to provide end-to-end networking does not preclude use of IP in certain segments of the end-to-end path; if IP is functional on a bop in a BP network, IP can be used to transport the bundles on that bop.

Mission implementers and software developers should take the above considerations into account when developing new software applications. IP-based applications can be used to support data transfer activities that involve end-to-end paths that will never incur delays, disruptions, or data rate mismatches, regardless of the physical location of the assets involved. If, however, an application is to support current or future data transfer activities that will involve an end-to-end path that could potentially incur delays, disruptions, or data rate mismatches, missions should develop and use a BP-based application.