70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.
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IAC-19,B2,7,3,x53530

The Benefits of Delay/Disruption Tolerant Networking (DTN) for Future NASA Science Missions

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Abstract

The National Aeronautics and Space Administration (NASA) Science Mission Directorate (SMD) has undertaken a study to identify the benefits of a Delay/Disruption Tolerant Networking (DTN) communications architecture and recommend strategies to implement DTN for SMD missions. The development of the DTN protocol suite began in the early 2000s. The goal of DTN is to enable networked-based communications—analogous to those provided by the terrestrial Internet—in any mission scenario, including scenarios where the terrestrial Internet Protocol (IP) suite cannot be used.

In the Fall of 2018, SMD completed the first phase of its DTN study. The purpose of this initial study phase was to identify and verify the benefits SMD missions would realize by implementing DTN. To ensure identified benefits were valid, the study team worked closely with NASA representatives from a variety of mission types to understand and evaluate the effects of DTN implementation and operations.

To accomplish this task, the DTN study team conducted a series of meetings with mission representatives to:

- Review what DTN is and how it works
- Discuss how communications are currently accomplished for each mission, including operational constraints typically encountered and solutions to remediate such constraints
- Discuss how DTN implementation would affect the mission (or similar future missions) and identify expected benefits

This paper summarizes the results of this first study phase, including material gleaned from this phase that will inform the study's second phase, in which the team will determine strategy options for implementing a DTN architecture.

Keywords: NASA, Delay/Disruption Tolerant Networking, DTN, space communications, networking, spacecraft operations

Nomenclature

In this document, the following terms are used:

- The term "node" refers to an entity that is part of a data flow. Examples of nodes include instruments, onboard systems, and ground stations.
- The terms "source node" and "destination node" refer to the entities that originate and consume data, respectively.
- The term "network data unit" refers to a block of data including fields that allow network-layer protocol operations
- The term "bundle" refers to the network data unit of the DTN bundle protocol.
- The terms "bundle source node" and "bundle destination node" refer to the entities that originate and consume bundles, respectively.
- The term "intermediate node" refers to an entity that relays data and/or bundles between nodes.
- The term "link" refers to a connection between any two nodes.
- The term "path" refers to the end-to-end aggregation of all links between the source and destination nodes.
- The term "application" refers to software that performs a specific function.

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Acronyms/Abbreviations

AWS	Amazon Web Services
BP	Bundle Protocol
C&DH	Command and Data Handling
CCSDS	Consultative Committee for Space Data Systems
CFDP	CCSDS File Delivery Protocol
DARPA	Defense Advanced Research Projects Agency
DIXI	Deep Impact Extended Investigation
DSN	Deep Space Network
DTN	Delay/Disruption Tolerant Networking
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
EO-1	Earth Observing-1
EPOCh	Extrasolar Planet Observation and Characterization
EPOXI	A mission consisting of elements from the EPOCh and DIXI missions
FTE/WYE	Full-Time Equivalent/Work Year Equivalent
GDS	Ground Data System
HEOMD	Human Exploration and Operations Mission Directorate
ICSIS	International Communication System Interoperability Standards
IOAG	Interagency Operations Advisory Group
IP	Internet Protocol
ISRO	Indian Space Research Organisation
ISS	International Space Station
IXPE	Imaging X-ray Polarimetry Explorer
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEO	Low Earth Orbit
LLCD	Lunar Laser Communications Demonstration
LRO	Lunar Reconnaissance Orbiter
MAIA	Multi-Angle Imager for Aerosols
MOC	Mission Operations Center
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
NISAR	NASA-ISRO Synthetic Aperture Radar
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
RF	Radio Frequency
RSLV	Reusable Suborbital Launch Vehicle
SDS	Science Data System
SLE	Space Link Extension
SMD	Science Mission Directorate
TDRSS	Tracking and Data Relay Satellite System
TRL	Technology Readiness Level
WFIRST	Wide Field Infrared Survey Telescope
WS1	White Sands Ground Station

1. Introduction

With its beginnings in Defense Advanced Research Projects Agency (DARPA)-funded (and later NASA-funded) studies into an "Interplanetary Internet" architecture [1], DTN has been recognized as a viable and executable candidate for extending networking applications and Internet-like capabilities into environments where standard Internet protocols would be troublesome [2]. While the communications standards currently in use can allow missions to operate as if they have a direct link between spacecraft and the Mission Operations Center (MOC), the limitations of this approach manifest when there are data rate mismatches or disconnections or if intermediate nodes do not know a priori where to send the data. DTN enables the mission to operate as if there is a single link or point-to-point connection between the spacecraft and MOC in a standard, data-driven manner even for scenarios in which IP cannot operate.

The Consultative Committee for Space Data Systems (CCSDS) recommends key DTN protocols for space internetworking services [3], and the International Communication System Interoperability Standards (ICSIS) [4] require the use of DTN for the command and telemetry links on NASA Cislunar Space Platforms.

A combination of the Extrasolar Planet Observation and Characterization (EPOCh) and Deep Impact Extended Investigation (DIXI), known as the EPOXI mission, successfully demonstrated the use of DTN in deep space [5], and the Earth Observing-1 (EO-1) mission demonstrated use of DTN in low Earth orbit, including recovery of real-time housekeeping telemetry that would have been lost due to a previous hardware failure [6]. In 2013, the Lunar Laser Communications Demonstration (LLCD) mission used DTN to transfer data using an optical link subjected to cloud and scheduled disruptions [7]. Additionally, several payloads aboard the International Space Station (ISS) currently use DTN to deliver data back to Earth [8]. The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission—scheduled for launch in 2022—will be the first NASA free-flyer science mission to employ DTN in day-to-day operations [9].

NASA's Science Mission Directorate (SMD) has commissioned a study to assess the feasibility and desirability of developing and implementing DTN technology for infusion into the ground and flight segments of SMD missions. The study team will leverage previous and ongoing DTN efforts within the Human Exploration and Operations Mission Directorate

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(HEOMD). It will also engage SMD personnel from existing and past missions to validate the study assumptions and recommendations. The study will be executed via three primary phases:

1. Evaluate proposed benefits of a DTN architecture with mission implementers and operators
2. Identify implementation strategy options
3. Produce final recommendations on technical implementation

This report summarizes the results from phase 1 of the study, in which the study team worked with mission implementers and operators to identify and evaluate potential benefits of DTN architecture implementation. The report also summarizes the issues and challenges associated with DTN implementation identified during this phase. Study team members will investigate these issues during the second and third phases of the study, as they identify implementation strategy options and develop final recommendations.

2. Study Phase 1 Activities

The study team engaged personnel from various NASA science missions representing a wide array of mission types and orbit regimes to validate the proposed benefits and determine the utility of DTN for future missions. To ensure a consistent understanding of DTN among study participants, the study team defined the terms "DTN" and "DTN architecture." During the discussions, the study team also sought to understand how current mission communications are conducted so that the impact of DTN implementation could be accurately assessed.

2.1 Defining DTN

DTN is a suite of *standard protocols* that use information within the data stream (headers attached to data units) to accomplish end-to-end data delivery through network nodes. The essential protocol that enables DTN is the Bundle Protocol (BP). The DTN bundle is the network data unit. DTN nodes can be capable of storing data, which is important if the link to the next node in the path is immediately unavailable. Therefore, DTN can operate in scenarios where a continuous, full-bandwidth, end-to-end path between source and destination nodes may not exist for the duration of a communication session. In addition, DTN can successfully operate in scenarios where timely and stable feedback from data destinations is not always available, since the acknowledgements and retransmissions for reliable data delivery are done on a link-by-link basis. Furthermore, DTN enables successful data delivery in situations where there are data rate mismatches—for example when a high data rate science downlink is delivered to a ground station with lower data rate capabilities. In addition, the data bundles that comprise a message from the source node may reach the destination node via different paths. This routing may result in bundles being delivered out of order. Certain DTN protocols can ensure the message is received automatically in its original order.

The DTN protocols provide transport and network layer functionality. That is, they provide the means for the delivery of data across multiple links. The data can be reliably or unreliably delivered, and users can select the reliable option to guarantee data completeness.

DTN is an emerging capability and there are many misperceptions regarding its implementation and potential impacts. Table 1 lists some common myths and counters them with facts that are supported by the information detailed in subsequent sections of this report.

Table 1. Common DTN Myths vs Facts

DTN Myth	DTN Fact
DTN increases the speed of data delivery on an individual link	***DTN may reduce end-to-end latency by allowing more efficient use of available links***
DTN requires additional link hardware because all missions will be required to be relay nodes	***DTN does not require all missions to be relay nodes***
DTN changes how radio frequency (RF) links are scheduled	***Links still need to be pre-established***
DTN is only of value for Deep Space missions	***Many mission types benefit from reuse, standardization, and networking provided by DTN***
DTN requires the addition of intermediate nodes to a mission's data delivery architecture	***DTN does not mandate the use of intermediate nodes***
All missions have the same data delivery requirements	***Mission science is not always severely impacted by loss of data*** ***Onboard storage is becoming less of a cost driver***

2.2 Defining a DTN Architecture

A communications architecture consists of multiple nodes. During a data exchange, one node serves as the source node that generates data and another serves as a destination node that consumes the data. In a "point-to-point" scenario, the source node communicates directly with the destination node over a single link or "hop." In

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a "multi-hop" scenario, one or more additional nodes serve as intermediate nodes that forward the data between the source and destination nodes.

Figure 1 depicts an example communication architecture that could be used to support an instrument onboard a spacecraft. In the data exchange depicted, the onboard instrument is the source node, the onboard system (e.g., the command and data handling [C&DH] subsystem) and ground station are intermediate nodes, and the MOC and the Science Data System (SDS) are the destination nodes. Onboard storage or storage at the ground station could also be intermediate nodes along the path. Note that even though there is only a single space link, the scenario is a multi-hop scenario.

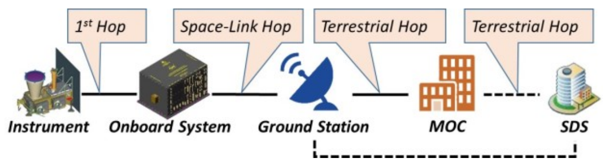

Fig. 1. *Example communication architecture for a spacecraft with an onboard instrument.* Dashed lines indicate that the ground station may send data directly to the SDS or the data could be sent to the SDS via the MOC.

A DTN architecture is a store-and-forward communications architecture in which source nodes send DTN bundles through a network to destination nodes. In a DTN architecture, nodes use BP to deliver data across multiple links to the destination nodes. Architecture implementation trades include the determination of which nodes are the source and destinations of the DTN bundles, which intermediate nodes have the ability to store and forward bundles, and even which data within a mission's data is sent using BP. For example, an instrument can be the source node for the data and a later node, such as an onboard flight computer or C&DH subsystem, may put this data into a DTN bundle and be the bundle source node that originates the bundles for transmission of science data to the MOC. In this case, the ground station serves as an intermediate node and runs BP to route the data to the MOC, which serves as the bundle destination node.

When using BP, it is not necessary to ensure all links on a path are available prior to data transmission. If a link along the path becomes unavailable, a node employing BP can be capable of storing the data until the next link in the path is re-established. For example, if the ground station in Figure 1 was unavailable to receive data during a communications exchange, due to a communications link outage or the pass had not yet begun, etc., the onboard C&DH subsystem would automatically store the data and forward it once the ground station became available. The ground station could also store the data for future transmission if required—for example, if there was an outage between the ground station and the terrestrial link to the MOC or if there was a data rate mismatch requiring the ground station to buffer the data before transmission to the MOC (e.g., if the transmission rate of the space link to the ground station exceeded the rate of the link between the ground station and the MOC).

If reliable data delivery is desired, then at each node in the DTN architecture BP automatically assesses whether the data transfer from the previous node was successful. If data transfer was successful, custody of the data is released from the previous node and assumed by the current node. If data transfer from the previous node was not successful, BP automatically ensures the previous node retains custody of the data for retransfer.

DTN architectures provide a network-layer-based data delivery capability that enables data delivery across multiple links using bundles. When an IP-based network is available, DTN can take advantage of existing IP infrastructure by using BP as a store-and-forward overlay. In such a case, BP provides the functionality to deliver data end-to-end reliably even if disruptions, disconnections, or data rate mismatches occur within the IP network.

To provide initial context for the discussion of benefits, Section 2.3 details the typical communications scenarios currently employed by most SMD missions. Section 2.4 describes how a communication scenario employing DTN functions. Sections 3.1 through 3.3 detail the benefits—as verified by mission representatives—that missions can realize if they employ DTN. Section 3.4 discusses the ways in which DTN can impact and enable science.

2.3 Typical Communications Scenarios Currently Employed

Figure 2 illustrates a typical current SMD mission scenario.

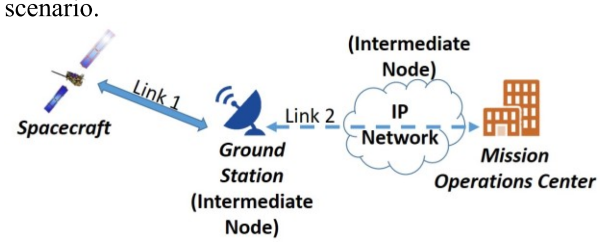

Fig. 2. *Typical End-to-End Scenario: Spacecraft and MOC exchanging data through Ground Station and IP Network intermediate nodes.* IP-based applications at the ground station and MOC allow the multiple links through the IP network to function as a single link, reducing the complete end-to-end path to the functional equivalent of a two-hop path.

To simplify this discussion, the systems onboard the spacecraft (e.g., the instrument, C&DH subsystem, etc.) are depicted as single node, even though a spacecraft is

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likely to contain several nodes. For the delivery of science data, the spacecraft is the source node, the MOC is the destination node, and the ground station and IP Network are intermediate nodes. (Note that a terrestrial entity other than a MOC could serve as a data source/destination; a MOC is used in this example since it is common to many mission scenarios.) The spacecraft communicates over a radio frequency (RF) link to/from the ground station. The characteristics of the RF link (e.g., the distance and data rates) vary greatly, but functionally, this general scenario applies to the vast majority of SMD missions, with the exception of missions employing assets on the surface of Mars that communicate via Mars orbiter. (Since the Tracking and Data Relay Satellite System [TDRSS] relays do not demodulate or modulate data, even TDRSS users' RF links are terminated at a ground station.) The ground station exchanges data with a MOC or other terrestrial destination over an IP network.

To ensure successful data delivery, contact times are established in advance to ensure all links on the path are available prior to initiation of data exchange and/or other operational procedures and systems are employed to successfully transfer data. During the mission design phase, trade studies are conducted to determine how data will be assessed to determine whether retransmission is required due to corruption or incompleteness (assessment may occur at the MOC or at an intermediate node), and when and where to forward the data. Though current missions may use common methods and approaches that build upon those used to support previous missions, there are no network-layer standards in use at each node along the path to facilitate the full end-to-end delivery.

Nearly all NASA missions use IP for the terrestrial portions of the data path only (e.g., the links between the ground station and MOC). IP-based applications are implemented at the ground station and at the MOC to allow the multiple intermediate nodes (IP routers) to all appear as a single connection, as seen in Figure 2. Note that this configuration allows the path to operate as a two-hop path from spacecraft to MOC.

In cases where the data rates between the spacecraft and ground station are less than or equal to those of terrestrial data lines between the ground station and MOC, CCSDS Space Link Extension (SLE) and other similar protocols can allow the data to be "tunneled" through the ground station in real time (no buffering is required). This process allows the mission to operate as if there is a single link or point-to-point connection between the spacecraft and MOC, as seen in Figure 3. When the path operates as a virtual single link under these circumstances, the transfer of data can be completely accomplished between applications onboard the spacecraft and within the MOC. This scenario allows the MOC to have immediate knowledge of which data has been successfully transferred and, if necessary and desired, request re-transmission of any missing data.

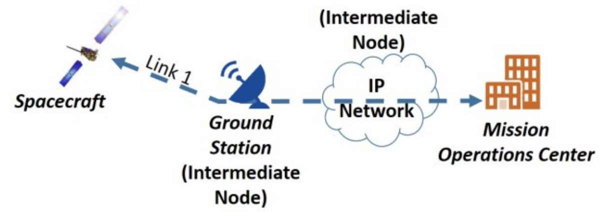

Fig. 3 *Virtual single link for missions where there are no data rate mismatches*. These types of missions use Space Link Extension (SLE) or equivalent link-layer "tunneling" to allow the end-to-end communications path to be a virtual single direct link between spacecraft and MOC.

For the missions and mission data streams that can transmit their data in real time through the ground station, the data is transferred directly as streams of frames or packets or with a point-to-point file transfer. The CCSDS File Delivery Protocol (CFDP) [10] is the international standard for file transfer between source and destination over a single link. There are two classes of CFDP in use – *Class 1 Unreliable Transfer* and *Class 2 Reliable Transfer*. Both have been proven operationally and are employed on missions throughout the solar system.

The difficulties arise when real-time tunneling through a ground station is not possible and establishing a virtual single link is not possible. For example, a spacecraft may be trying to send a file to the MOC, but the data rate from space to the ground station is higher than the rate transmitted by the ground station to the MOC, or a MOC may be trying to send a file to a spacecraft and the uplink from the ground station to the spacecraft is at a lower data rate than the terrestrial data connection. Such situations are equivalent to the two-hop scenario introduced above. The CCSDS originally defined two classes of CFDP for these scenarios – *Class 3 Unreliable Transfer Via One Or More Waypoints In Series* and *Class 4 Reliable Transfer Via One Or More Waypoints In Series* – though neither have ever been fully implemented or used operationally. Instead, missions implement various solutions to accomplish data transfers, as explained below.

Missions that cannot tunnel data and that transfer files have developed and implemented a variety of augmentations of CFDP Class 1 or Class 2. These augmentations are typically a combination of operational procedures, constraints, and additional software within the MOC and ground station systems. For example, Lunar Reconnaissance Orbiter (LRO) uses CFDP Class 2 to transfer science files to its White Sands Ground Station (WS1) but employs a non-standard implementation to pass information to the

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MOC to allow it to manage retransmissions and data accounting. The PACE mission plans to follow the same basic approach but needs additional modifications to allow file delivery to multiple ground stations (LRO only uses a single ground station).

Missions that cannot tunnel data through the ground station and choose not to use files also develop unique solutions to achieve the two-hop scenario. For example, the NASA-Indian Space Research Organisation (ISRO) Synthetic Aperture Radar (NISAR) mission will be supported by a system at each ground station that will capture streams of data into files, buffer it, and forward the data to the Amazon Web Services (AWS) Cloud. The mission will then publish the information to the Science Data System (SDS), which is co-located in the AWS Cloud for processing. NISAR further simplified its design and operations by not requiring retransmissions of any lost data.

In summary, current missions use a variety of different—and sometimes unique—approaches to achieve end-to-end data delivery.

2.4 DTN Communication Scenario

Because it employs the store-and-forward approach and provides the capability for hop-by-hop reliable delivery, DTN allows spacecraft to communicate via a virtual single link to the MOC, even when data rate mismatches or disruptions exist and tunneling through the ground station is not possible (see Figure 4). Though there is no real-time end-to-end connectivity between the spacecraft and MOC, the use of a network layer provided by BP allows the "direct" connection between applications at the source and destination. The augmentations of CFDP for the multi-hop scenario are no longer necessary. However, if a mission desires, CFDP can still be used as the application to send a file from the spacecraft to the MOC if DTN protocols are used to provide the reliable multi-hop delivery service.

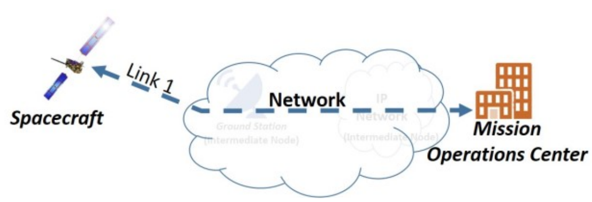

Fig. 4 *Virtual Single Link accomplished through use of networking.* Using DTN, a mission can exchange application data "directly" between applications at the MOC and spacecraft even with data rate mismatches and disconnections.

3. Identified Mission Benefits

The DTN study team consulted with SMD management to determine the mission types to analyze for DTN Study phase 1. Table 2 lists the mission types analyzed and the specific mission teams the study team worked with to identify and confirm DTN benefits.

Table 2. Mission Scenarios Analyzed and Missions Consulted for DTN Study Phase 1

Mission Types	Missions Consulted
Low Earth Orbit (LEO)	• Imaging X-ray Polarimetry Explorer (IXPE) • NASA-ISRO Synthetic Aperture Radar (NISAR) • Plankton, Aerosol, Cloud, ocean Ecosystem (PACE)
Planetary Relay and Deep Space	• Kepler/K2 • Mars Missions • Parker Solar Probe
Instrument-only	• ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) • Multi-Angle Imager for Aerosols (MAIA)
Cislunar	• Lunar Reconnaissance Orbiter (LRO)
Sun-Earth Lagrange (L1 and L2)	• Wide Field Infrared Survey Telescope (WFIRST)
Suborbital (e.g., balloons and airplanes)	• NASA Balloon Program
Other	• Explorers Program

When identifying DTN benefits, the study team focused on concepts that would provide improvements when compared to communications methods in use today. After analyzing data gathered from consultations with the missions, the study team categorized DTN benefits into three types: benefits from standardization, benefits from networked communications, and benefits from the use of the DTN store-and-forward communications approach, specifically.

These benefits and their associated potential positive outcomes are described in the subsections below. The discussion includes information and examples gathered from the various SMD mission representatives who verified the potential benefits and positive outcomes that would affect a similar mission in the future if DTN were implemented.

3.1 DTN Drives Standardization

NASA utilizes numerous software, hardware, and operations implementations to meet communications requirements of the various missions within a mission type (e.g., LEO, Planetary Relay, etc.). There are no

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standards used to execute many common mission communications functions. The use of DTN drives standardization. The two main benefits that arise from standardization are reuse and interoperability.

3.1.1 Reuse

Benefit Description: *Proven DTN hardware, software, and operations procedures can be used by all mission types, reducing or eliminating the frequent implementation of different methods to achieve common mission communications functions.*

A standard provides savings because the resources individual missions spend to solve identical problems will be reduced or eliminated. In study team discussions with mission representatives, nearly every project team acknowledged that there was some effort expended to meet the mission's end-to-end data delivery requirements. In many cases, the effort included adding something new or altering systems used on a previous mission to meet the new mission's needs. These new non-standard implementations require missions to execute the following activities:

- Trade studies to determine the best method for meeting requirements
- Development of new interfaces between flight segment, ground station, MOCs, and SDSs, including accompanying documentation
- Development of new implementation and operations procedures
- Identification of additional risks and implementation of risk mitigation plans
- Additional integration and testing

While the expenses required to accomplish such activities are not a large portion of a mission's overall costs (the aggregate effort is approximately equal to one full-time position per year), these resources could be used for other purposes.

In an analogous situation, use of IP standards for terrestrial communications has resulted in tremendous collective cost savings. Almost all terrestrial data exchanges are accomplished using IP and existing computer hardware and communications networks that support IP communications. This standardization allows developers to spend their resources, time, and creative energy on applications instead of developing communications methods. Similarly, consistent implementation of the DTN protocol suite across SMD missions could lead to its widespread adoption as the "go to" solution for reliable communications, freeing up additional resources for other purposes.

3.1.2 Interoperability

Benefit Description: DTN provides a standard network layer interface, allowing data to be communicated among different systems employing it, including systems belonging to NASA, other government and international agencies, and industry.

Typically, the non-standard approach to accomplish end-to-end data delivery leads to specific and sometimes unique implementations and interfaces. Not only do these augmentations need to be implemented in all of the mission flight and/or ground systems, they also must be implemented in any ground stations the mission may use. The cost for such implementations may fall under the network provider's budget, but the augmentations may not significantly increase communications opportunities for other missions.

For example, in the case of LRO, implementing CFDP the same way in the Deep Space Network (DSN) stations as it is implemented in the WS1 ground station would allow LRO to use both networks, and enable more opportunities for LRO science data delivery. Since this implementation is non-standard, however, incorporating it in DSN stations would not necessarily provide the additional DSN communications opportunities for other missions, even if they use CFDP.

The interoperability resulting from the use of standards allows multiple missions to be supported by multiple stations and providers.

The primary purpose of CCSDS standards is to enable missions to receive communications services from more providers, including providers from other space agencies. The Interagency Operations Advisory Group (IOAG), the international organization established to address "issues related to interagency interoperability and other space communications matters," recommends that DTN be used for multi-hop data delivery. Since CCSDS standards to address multi-hop communications are not yet deployed, international missions also experience potential interoperability issues. For example, the Imaging X-ray Polarimetry Explorer (IXPE) mission will receive data through the Italian Space Agency's Malindi station and NASA's Near Earth Network (NEN). While it is a mission goal to use the same interface to Malindi and the NEN, it is not a given, since an enabling standard, such as DTN, is not employed by both providers. Interoperability between the NEN and the Malindi station would allow IXPE to use a consistent interface.

In the case of planetary and lunar relay scenarios, interoperability is of even greater value, since altering a relay spacecraft is not as easy as adding something new to a ground station. The success of the Mars Network, which is comprised of various international science orbiters employing standard relay capabilities, is proof of the value of standardization. The large volume of science data returned from Mars is due to the ability of

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the different orbiters to provide a standard communication service to the Mars surface. Each new mission to the surface can incorporate the standard in its design to take advantage of the orbiters, and any new orbiter carrying the standard capabilities adds additional communications opportunities for any surface user. The current standard services employed in the Mars Network are not network-layer services, however, and do not incorporate the advantages discussed in section 3.2.

3.2 DTN Enables Networked Communications

Use of DTN enables networked communications. The benefits from the use of a standard network-layer protocol are evident in terrestrial data communications. The Internet, which has transformed daily lives in so many ways, uses IP as a standard network-layer protocol. IP packets, or more generically, network data units, can be multiplexed and de-multiplexed together at various points along a communication path, allowing for maximum utilization of the path. At intermediate nodes along the path, individual network data units may be automatically forwarded to different nodes, based on information within the network data unit (typically, within the "header"), the node configurations, protocols in use, and policies. 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 a DTN architecture network communications are enabled by BP, which serves as the standard network-layer protocol, and the DTN bundle, which serves as the network data unit.

For the purposes of this study, the most relevant network-layer benefits are scalability, autonomy, and independent evolution of the application and the underlying infrastructure.

3.2.1 Scalability

Benefit Description: *DTN can facilitate the addition of a new node, link, or path to a communications network.*

Scalability is achieved when the difficulty of adding a new node, link, or path is minimized. As discussed in section 3.1.2, implementation of any interoperable standard reduces the difficulty of adding nodes or links. Inclusion of a network-layer function minimizes the difficulty of creating end-to-end paths by providing a standard way to move data across multiple links. A network layer enables paths to be changed at any intermediate node by using BP to route a network data unit from link to link.

In contrast, because today's missions do not use a network layer (other than across the terrestrial IP network portion), the end-to-end paths are formed by stitching together a series of point-to-point links using extensive design, operations planning, and scheduling processes. For example, in today's missions, an incoming piece of data does not include the source and destination addresses. Before any data can flow, each node involved in the data transfer must be configured so that it knows what data it is about to receive, where it should send that data, and what to do if any data is determined to be missing.

However, when a standard network-layer protocol is used, once a node is assigned an address and connected and the intermediate nodes are aware of possible routing paths, data can flow to and from that node. Since every intermediate node uses a standard approach to route data, no new implementations or tests are required. For example, in the current Mars Network, data from the Martian surface is destined for Earth and vice versa, so determining where to send incoming data is straightforward. Mission representatives agreed, however, that a standard network layer like DTN provides will be necessary to support future mission scenarios where data generated by systems on Mars could be destined for other surface systems, for a relay spacecraft itself, or for Earth. DTN would also enable multi-cast capabilities that would allow one lander to simultaneously communicate with multiple other space assets.

The automation of reliable end-to-end data delivery would also significantly impact scalability, since it would minimize the effort expended to identify missing data and initiate retransmissions. Such benefits are currently being realized by missions that use CFDP Class 2 for guaranteed file delivery, since no operator intervention is required to make sure files are completely delivered. As described in section 2.3, however, CFDP Class 2 alone does not provide the reliability across multiple hops that DTN does.

3.2.2 Autonomy

Benefit Description: Information embedded in the DTN bundle enables data-driven end-to-end data delivery across multiple hops.

Because it uses a network-layer protocol (BP), DTN enables automated end-to-end data delivery based on information in headers within the data stream. For current missions that do not employ DTN, not only do the links to the spacecraft need to be scheduled and configured a priori, the complete data path needs to be determined and configured before data transmission can commence.

The ability to simply address data to a destination at the time of data generation and have it routed automatically through the network to its final destination would allow a mission to generate different types of data for different destinations based on unpredictable events. For example, a mission could address and send information related to detection of a

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gamma-ray burst to a spaceborne observatory to enable measurement of that event. Even though the link to the observatory may still need to be scheduled, the mission can autonomously determine the data destination and the network will deliver the data.

3.2.3 Independent Application and Link Evolution

Benefit Description: DTN allows the applications used to transport data to be decoupled from the underlying link infrastructure, facilitating upgrades to both elements.

One of the characteristics that enabled the rapid proliferation of the terrestrial internet is that the underlying infrastructure does not have to change to support new applications. The IP network-layer capability enables new software to be added to a computer without requiring any upgrades to the computer's operating system, network connection, or the entire network. Correspondingly, the underlying network infrastructure can be altered without the need to change application software. For example, in an IP network, the application software does not need to be modified when a new Ethernet or Wi-Fi adapter is added to a computer or a data connection is switched from a satellite service to an undersea cable. Because the applications are designed to operate using IP packets and the underlying infrastructure is designed to move IP packets, the standard network-layer interface allows both the applications and the infrastructure to evolve separately.

This capability has proven to be incredibly enabling. Because the network layer enables evolution of applications to be decoupled from that of infrastructure, developers can focus on innovative new applications that can immediately work on the existing network infrastructure. The network service providers do not need to know when a new application is running in user systems and no new hardware or software must be installed in the provider systems to support new applications.

If science missions were to implement DTN, any future file transfer applications beyond CFDP or any other application involving the exchange of data between spacecraft or between spacecraft and Earth would not require an updated communications infrastructure. If the network can deliver bundles, it is ready to support any DTN-based application.

This network-layer interface also allows a user to employ the same application across heterogeneous links. For example, if both TDRSS and Iridium supported bundle interfaces, a scientific balloon payload could use the same bundle-generating application to return data in DTN bundles over TDRSS links or Iridium links, despite the different underlying modulations and frequency bands used by the two systems. In a different case, a spacecraft could relay some DTN bundles over an optical link and later flow other DTN bundles over an RF link. Neither the spacecraft nor the MOC would need to change the respective applications they employ, regardless of the physical link used to accomplish the data transfer.

3.3 DTN's "Store-and-Forward" Communications Approach

In addition to the benefits realized by standardization and implementation of networked communications, there are several benefits that can be realized from DTN's "store-and-forward" approach to communications. The original purpose of the DTN protocols was to provide space communications scenarios with network-layer functionality similar to that provided by IP-based networks on Earth. Since space communications scenarios cannot be supported by the terrestrial IP protocol suite, a new solution had to be developed. BP provides basic network-layer functionality, but also provides storage capability, which enables networking benefits even with delays, disconnections, or rate mismatches. This ability to function when an end-to-end communication path is not available during the entire communication session allows DTN to provide network-based communications in space.

BP provides the potential for more efficient use of bandwidth and contact time. BP may also allow missions to avoid the use of files and file systems altogether, possibly simplifying flight system implementations and operations.

The benefits from DTN's "store and forward" approach to communications include provision of networking in scenarios involving delays, disconnections, and data rate mismatches, and more efficient use of bandwidth and contact time.

3.3.1 Networking with Delays

Benefit Description: *DTN enables data delivery across an end-to-end path based on destination address, even when the end-to-end path between source and destination includes extreme communication delays.*

The initial challenge for the originators of DTN was to find a way to provide networking when it could take minutes, hours, or more for signals to travel the distance between two nodes. The IP suite of protocols are inherently "chatty" and the handshake messages between nodes make using the full IP suite impossible for communications over extremely long distances. Any mission that requires or desires networked communications involving links with long delays will be dependent (if scalability is desired) on some network-layer functionality that can operate in the presence of delays. Examples of these types of missions are future planetary missions to Mars, Europa, or other destinations that may involve combinations of relays

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and multiple spacecraft—all of which are becoming feasible in the era of small spacecraft.

3.3.2 Networking with Disconnections

Benefit Description: *DTN enables data delivery across an end-to-end path based on destination address, even when a full bandwidth end-to-end path between source and destination does not always exist for the duration of a communication session.*

BP has proven to not only provide networking functionality over communications paths with delays, but also over those with disruptions or disconnections. Since a DTN architecture can provide storage at intermediate nodes, contemporaneous end-to-end paths are not required. The disconnections could occur for reasons ranging from typical link dropouts, to gaps in link availability or scheduling.

The ability to automatically deliver data following a link outage was demonstrated in 2013 during a demonstration of DTN using the Lunar Laser Communications Demonstration (LLCD) optical links [7]. As LLCD was communicating by laser from lunar orbit onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, clouds temporarily disrupted the links. When the clouds passed, the DTN protocols automatically retransmitted the missing data without requiring any operator actions.

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) instrument is currently operating onboard the International Space Station (ISS) and the ISS DTN services are being used to transport data from onboard the ISS to the ECOSTRESS Ground Data System (GDS). Though the project experienced some early difficulties due to unexpected configuration changes after installation, ISS DTN services enable complete data delivery by automatically retransmitting data that could not be received during data disconnections along the path between the ISS and the GDS.

DTN's ability to support communications with delays can also enable certain mission scenarios. In a DTN architecture, two nodes that may never be connected to the network at the same time can still exchange data. For example, a radio astronomy instrument on the far side of the moon could relay data to a lunar relay, which would then relay the data to Earth as its orbit comes back into view of Earth.

3.3.3 Networking with Data Rate Mismatches

Benefit Description: DTN enables data delivery across an end-to-end path based on destination address, even when sequential nodes on the path transmit data at different rates.

The store-and-forward approach of the Bundle Protocol also provides for automated rate buffering. The data rate supported by the link to Earth is often much higher than the rate on the link from the ground station back to a mission operations center. BP automatically provides the buffer mechanisms to support communications for both of these links (as described earlier in section 2). Even though the costs for high-rate data lines between ground stations and MOCs may decrease, the data rates from space links could still increase such that data rate mismatches continue. For example, NASA is planning to demonstrate a >100 Gbps optical downlink from LEO [11]. The intention is to deliver the data directly to a scientist's low-cost optical ground station located on a rooftop. However, at least some of the time, clouds will interfere with data transmission to this location, and the data will have to be delivered to a backup location elsewhere. It is highly unlikely that there will be a >100 Gbps data line from a backup location to the scientist, so a data rate mismatch will exist.

In addition, the ECOSTRESS instrument on ISS has been able to continue to accrue data independently of any communications link status. When a link at a rate greater than the data generation rate becomes available, DTN transmits the data from storage back to the ECOSTRESS GDS. The need to accumulate data onboard while waiting for an available link is common to almost all missions.

3.3.4 More Efficient Use of Bandwidth and Contact Time

Benefit Description: DTN's ability to provide data delivery across an end-to-end path even when the full bandwidth end-to-end path between source and destination does not always exist enables efficient use of bandwidth and contact time.

In cases when the complete end-to-end path is available only part of the time, a DTN architecture may deliver data to the end destination sooner than presently used communication schemes, since DTN can move the data along the path hop by hop without waiting for all nodes along the path to be available simultaneously. The following examples also illustrate how DTN would help a mission maximize its communications resources, by either allowing for the delivery of more data in the same amount of time or by reducing the total amount of time communications links are required.

In a future planetary relay scenario in which multiple surface users are seeking to communicate not just with Earth, but also with each other, DTN would enable a transmitting surface user to take advantage of the contact time with the relay to send all data on its way, whether or not the relay has a link available simultaneously with the Earth or the other surface user. If the transmitting user had to wait until the full path was available to each individual destination, the user

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would not be able to offload as much data during its contacts with the relay. Using DTN, the data can incrementally travel to its destination as the next hops become available, which may be sooner than the next time the full path is available.

In multiple current mission designs, the transmission of files is managed to ensure that no partial files are delivered to any single ground station. This arrangement must be made because the current approaches that use CFDP to deliver the files to the ground station must retransmit the whole file at the beginning of the next pass if the next pass employs a different ground station. If CFDP were implemented as an application transmitting and receiving bundles, the reliability enabled by using data units smaller than a file could allow the transfer of files to span multiple contacts or data paths. Required retransmissions would involve the retransmission of lost bundles instead of the retransmission of the whole file. The end result would be more efficient use of bandwidth and contact time, since pieces of files could continue to be sent until the very end of a pass without concern for how much of a file is left unsent.

For a mission such as Kepler/K2, where science data collection needed to be halted during communications links, employing an approach such as DTN that could minimize the amount of communications time required would directly lead to an increase in science collection. Even for missions that can continue science data collection during communications events, reducing the required communications time reduces potential conflicts involving bandwidth and ground station scheduling.

3.3.5 Simplified Flight and Ground System Implementations and Operations

Benefit Description: DTN enables simpler solutions to meet mission requirements.

Each DTN bundle is a complete data storage unit and network data unit. When a node confirms that a bundle has been delivered to the next node, the original node may consider the data "delivered" and delete its local copy even if the delivery all the way to the final destination has not yet occurred. In this manner, the source or intermediate node sending the data has the option to free up storage sooner than if it had to await final data delivery to the destination node. Because DTN ensures reliable data delivery in this manner, it enables missions to store data in bundles instead of files. In many current missions, the decision to use files was not made because the end user scientist wants specific data grouped into a file. Rather, files are used for data accounting and to ensure reliable data delivery. Flight systems and mission ground systems have developed various methods of maintaining file directory structures and allocation tables. If these systems were not necessary, the flight and ground system designs could be simplified.

To transmit data in files over high data rates, flight hardware and software systems are required to maintain lists of all files and the states of all pieces of files in transit. Implementing this capability was a challenge for LRO. Other missions have chosen to include operational constraints, adjust file sizes, and increase RF link requirements to ensure that no bit errors occur during the transmission of a complete file—all to avoid having to implement the reliable file transfer protocol CFDP Class 2. DTN implementation would eliminate the need for these complex methods to ensure data transmission.

NASA's scientific balloon platforms support multiple instruments per flight. Onboard instruments may be using IP-based applications for their data flows, but the applications need to be adjusted to ensure that no instrument overflows the available bandwidth from the balloon to the ground. The balloon platform also needs to manage the storage usage for each instrument. Since the data volume capacity for the communications throughout the mission can be lower than the science accumulated during the flight, some instrument data must remain in storage to be retrieved following the completion of the mission and recovery of the platform. DTN's networking functionalities to multiplex/de-multiplex and prioritize user data flows, combined with its ability to manage the data in storage, may provide balloon platforms with a more efficient and standardized approach for instrument data handling and delivery.

4. Conclusions

During this study, representatives across the NASA science mission community validated numerous DTN benefits. There is agreement that DTN can benefit any mission type—from missions in low Earth orbit to complex future missions that could include multiple landers and relay orbiters, human exploration efforts involving numerous assets on the Moon and Mars, swarms of spacecraft, and scenarios where every spacecraft may communicate with every other spacecraft.

Discussions with mission representatives also enabled the study team to identify the following topics and issues that must be addressed to implement DTN in science missions:

1. *Security:* What is needed to ensure DTN meets security requirements? What impact does DTN have on the security posture of future missions?
2. *Navigation*: Does the use of DTN impact navigation performance and if so, how are those impacts mitigated?
3. *Overhead*: How much additional data overhead occurs through the use of DTN?

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4. *Incentives*: What types of incentives would encourage mission adoption of DTN?
5. *Provider Availability*: Will there be a DTN network provider to support DTN missions?
6. *Adherence to Standards*: How can standardization be enforced? How will customization be discouraged?
7. *Technology Readiness Level (TRL) Advancement:* What technologies require TRL advancement? What is needed to make those advancements?
8. *Network Management*: How will the DTN network be managed?

Investigating and resolving the above challenges will be vital to the next phase in this study, which involves determining the current DTN status, defining the desired end state and identifying the gaps, and determining strategic options to implement DTN.

Just as IP allowed the Internet to transform terrestrial science, DTN will enable networked-based communications to revolutionize space-based science, potentially yielding unprecedented scientific results.

Acknowledgements

The study team appreciates the time and expertise that representatives from NASA missions and Agency space communications experts dedicated to this effort. These study participants provided crucial information that ensured the accuracy of study results.

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