SpaceOps-2023, ID # 673

NASA Delay Tolerant Networks: Operational, Evolving, and Ready for Expansion

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Abstract

The future of humanity's presence beyond Earth depends on the successful commercialization of space. For commercialization to succeed, companies need cost-efficient architectures to support their business models and minimize risks for human capital, design, development, and operations. An ongoing challenge to any space enterprise is the reality that terrestrial network technologies are insufficient to provide reliable communications between assets in space. Whether you need to ensure your valuable data is safely transmitted to the ground or reliably delivered between platforms in orbit, ensuring data integrity over intermittent communication links is a necessity. Current solutions to space communications rely heavily on manual recording, storing, and retrieval of data from spacecraft. The current standard in space communication protocols, Consultative Committee for Space Data Systems (CCSDS) Space Packet standard, is reliant on inflexible network architectures based around mission-critical infrastructure to ensure data delivery. However, by automating the recording, storing, retrieval, and verification of data with Delay Tolerant Networks (DTN), the operator is freed from the dependence on manual data management and expensive mission critical infrastructure.

NASA has been developing delay tolerant systems since the late 1990's. Multiple DTN implementations have been established during that time, each suited to different use cases. Most notably, the DTN deployment for the International Space Station (ISS) includes demonstration of two DTN technologies: Interplanetary Overlay Network (ION) and Delay Tolerant Network Marshall Enterprise (DTNME). Beyond ISS, there are even more NASA DTN deployments being considered. Now that DTN implementations are maturing, it is appropriate to reflect upon these decades of work, review the integration and performance of the existing ISS deployment, and explore the future possibilities for DTN deployment industry-wide.

The ISS DTN deployment is a complex architecture consisting of different DTN implementations for the onboard and ground network environments. The ION DTN implementation is being used in the on-board network. The Huntsville Operations Support Center (HOSC) DTN implementation, DTNME, is used by the ground network supporting ISS and will soon be a second onboard gateway too. The two implementations work cooperatively to provide high fidelity data services to flight operations users and payload developers across the globe. Though the two implementations yield a quality service, limitations are evident. Data rate, data storage, and device management are constrained by the services themselves and the complex nature of the deployment. Evolution of operations concepts will improve system capabilities and stability, but significant improvement will require additional development to the

implementations themselves and to the overall deployment architecture. Taking advantage of the ongoing development and operation of the ISS DTN service will be central to the success of the future evolutions of NASA DTN deployments while demonstrating the benefits of DTN's low-cost reliable data communication protocols for the growing commercial space industry.

A broad effort on DTN integration and support is necessary to promote expansion beyond existing applications. NASA is developing several useful DTN implementations across a number of different systems: ION, DTNME, High-Rate DTN (HDTN), Bundle Protocol Library (BPLib), and others. To prevent fragmentation, DTN implementation teams need to communicate, collaborate, and integrate with one another to build a solid operational foundation for new DTN deployments. The establishment of a group that can assist new DTN users with understanding the purpose of each DTN implementation, provide best practices, and serve as a general knowledge base is paramount. Potential use of DTN on Gateway and other future NASA missions further drives the need for streamlined communication between DTN implementation teams. A well-integrated and highly engaged NASA DTN working group should help provide system architects the best DTN solutions for future commercial space efforts.

This paper will first review the history of DTN implementations, explore the shortcoming of current space networking solutions given available limits in technology, and therefore establish the need for Delay Tolerant Networking in space communications. Secondly, the authors will explore NASA's array of DTN implementations and highlight their usefulness to space applications. Thirdly, this paper will establish general DTN implementation distinguishing factors. Fourthly, the authors will discuss attempts to create a generic DTN comparison matrix, and the authors will review potential future topics in DTN innovation and collaboration, highlighting several key future efforts. Finally, this paper will describe how the institution of a NASA DTN Working Group will benefit DTN adoption across the governmental and commercial space sector. The goal of this paper is to encourage enthusiasm for DTN, share strategies for improving DTN on both current and future applications, promote the collaboration of DTN implementation groups within the international space operations community, and open the conversations about DTN, priorities, complexities, and innovation to the wider spaceflight industry.

Acronyms/Abbreviations

AMP	Asynchronous Management Protocol
BARD	Bundle Architectural Restaging Daemon
BP	Bundle Protocol
BPLib	Bundle Protocol Library
BPv6	Bundle Protocol version 6
BPv7	Bundle Protocol version 7
CCSDS	Consultative Committee for Space Data Systems
DINET	Deep Impact NETworking
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Space Agency)
DTN	Delay-Tolerant Networks
DTNME	Delay Tolerant Network Marshall Enterprise
ESA	European Space Agency
GB	Gigabytes
Gbps	Gigabit per second
GSFC	Goddard Space Flight Center
GUI	Graphic User Interface
GW	Gateway
HDTN	High-rate Delay Tolerant Network
HOSC	Huntsville Operations Support Center
IETF	Internet Engineering Task Force
ION	Interplanetary Overlay Network
IP	Internet Protocol
IPN	Interplanetary Internet
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Lower Earth Orbit
LFN	Long Fat Network
Mbps	Megabits per second
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NTRS	NASA Technical Reports Server
RTP	Real-time Transport Protocol
RTT	Round Trip time
SCAN	Space Communications and Navigations
SSI	Solar System Internetwork
TB	Terabytes
TCP	Transmission Control Protocol
TTL	Time To Live
UDP	User Datagram Protocol

1. **Introduction:** *The Need for DTN*

The future of humanity's presence beyond Earth depends on the successful commercialization of space. An ongoing challenge to any space enterprise is the reality that terrestrial network technologies are insufficient to provide reliable communications between assets. Whether you need to ensure your valuable data is safely transmitted to the ground or reliably delivered between platforms in orbit, ensuring data integrity over intermittent communication links is a necessity. Current solutions to space communications rely heavily on manual recording, storing, and retrieval of data from spacecraft. The current standard in space communication protocols, the Consultative Committee for Space Data Systems (CCSDS) Space Packet, is reliant on inflexible network architectures based around mission-critical infrastructure to ensure data delivery. However, by automating the recording, storing, retrieval, and verification of data with Delay/Disruption Tolerant Networks (DTN), the operator is freed from the dependence on manual data management and expensive mission critical infrastructure.

NASA has been pioneering DTN technology for well over a decade and has years of operational experience to share with the communications and space industries on the subject. One of NASA's biggest communications challenges is sending data to and from distant assets due to gaps in the communications links between them. For example, just to get to the International Space Station (ISS) in low Earth orbit, you roughly need the following things: a control center, a ground network from the control center to the ground site, the ground site itself, line of sight to a satellite, a functioning satellite, line of site to the ISS, and a functioning ISS. If you're using Internet Protocol (IP) or CCSDS packets, which is common in the space community, the failure of just one of these segments will result in zero data flow between the control center and vehicle. The ISS has enough redundancy that extended gaps in communication are rare, but the realities of geometry and physics results in gaps that even the ISS can't afford to close. Smaller organizations and missions away from Earth don't even have the option for affordable round the clock coverage. DTN solves this problem by providing a relatively inexpensive way to move data from A to B even though the network between A and B is unreliable.

Completely reliable networks are expensive and add significant complexity to system architectures losing a piece of the network can be easy: higher priority users may come along, line of sight can be lost, scheduled and unscheduled maintenance has to happen, hardware fails, someone unplugs the wrong thing, or a backhoe digs in the wrong place. Instead, organizations should be designing systems to handle failures in such a way that data flow is merely delayed rather than entirely stopped or lost. The most robust systems have mitigation in the form of complex data recording solutions. Such solutions try and prevent data loss through either manual intervention or automatic analysis and playback. These approaches, while ensuring data is captured, are expensive and add unnecessarily burden to already busy networks. DTN technologies address the shortcomings of more traditional solutions while also providing efficient data delivery, simple to integration, and relatively low upfront and sustaining costs.

For terrestrial communication applications, systems designers generally use two main protocols, Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). TCP is used in more than 90% of communications, with UDP serving as a protocol of choice in many other applications where some packet loss is acceptable. TCP works best over communication links with low latency. Unfortunately for the space industry, space communication links that extend beyond Low Earth Orbit (LEO) start to experience latency that restricts the efficiency of TCP. The majority of the terrestrial networks have 20-100ms latency. The current networks to ISS provide communication with latency (Round Trip Time) of about 700ms. Further improvements in data processing and communications links could at most save another 20-30ms in latency, however that becomes insignificant when the Round Trip time (RTT) grows beyond one second. To move beyond Low Earth Orbit and maintain communications reliability, the industry must move beyond TCP. A solution begins to emerge with UDP, with its high tolerance for latency. However, there is no guarantee of delivery or reliability. Therefore, a solution that brings reliability and guarantee of delivery to UDP is required. That solution is DTN.

The value of DTN is easy to see, but when one decides to begin using DTN, things get a bit cloudy. The current DTN landscape is poorly understood, and sometimes poorly defined, within the space community. Half a dozen solutions, each with advantages and disadvantages, make it confusing for those wanting to adopt the technology to understand the options and which version is best for their system. NASA currently has two operational solutions within the ISS program, a third version being readied for deployment. Some implementations are baseline DTN versions while others are improvements on those baselines. When the new CCSDS Bundle Protocol version 7 (BPv7) is released, there will be several non-NASA DTN implementations to choose from. The spaceflight community needs a way to understand the various versions of DTN, how to select an implementation which is right for them, and experts they can speak to when they have questions about using DTN in their systems. Without a structure to support the incorporation of DTN into new spaceflight systems, the space industry will fail to achieve widespread DTN adoption and will be stuck in the limitations of the current generation of communications technology.

The most useful DTN implementations to look at are the ones which are already being used in an operational capability. These implementations have an established track record of performance and have demonstrated the ability to integrate into a complex legacy communications architecture. They have had been reviewed, approved by operations teams, tested by experts, failed, recovered, updated, and overcome any number of other hurdles which come with the ongoing maintenance and support of an operational capability. If one wanted to add DTN to a communications network, looking at what is already being used is the first place to start. However, before we discuss where we are, we'll review how we arrived at the current state.

2. **Background:** *The Origins of DTN*

The roots of DTN begin with the development of Interplanetary Internet (IPN), led by internet pioneer Vint Cerf (developer of TCP). In 1998, Vint Cerf, and one of the co-founders of CCSDS, Adrian Hooke, would commence the work on the Interplanetary Internet in the labs of NASA's Jet Propulsion Laboratory (JPL). In 2002 Kevin Fall would coin the term Delayed -Tolerant-Networking (DTN) after he started implementing IPN designs to the terrestrial networks with higher latency [4]. Around this time, Marshal Space Flight Center (MSFC) became heavily involved in the development of both DTN and Bundle Protocol (BP)[5] through the center's involvement with CCSDS. In 2008, NASA JPL successfully tested the DTN protocol by utilizing the Deep Impact Networking (DINET) experiment onboard the Deep Impact spacecraft. The DINET implementation of DTN was the first use of the Interplanetary Overlay Network (ION) implementation, which was developed under the leadership of Scott Burleigh (JPL) and Dr. Keith Scott (MITRE). DTN as a whole is summed up in the words of Scott Burleigh, "DTN is NASA's solution for reliable, automated "network" communication for space missions". The most significant aspect of this initial DTN capability is automation. Operators had always been able to manually move data across space, manually assess missing data, manually command retransmission of missing data, and merge and manage the final data delivery to the end-user. DTN took all that manual effort and made it one seamless automated communications stream. The development of ION began the first generation of operational DTN implementation. A year after DINET, in May of 2009, the first payload using DTN was deployed on ISS using a customized version of ION [3]. Around 2012, Marshall deployed a DTN Gateway, based on DTN2 (an implementation developed with NASA contribution), as a ground gateway to support ISS payload operations. Then in 2016, the ISS program deployed an ION DTN gateway on ISS for payload use. With an ION gateway onboard and a DTN gateway on the ground, the ISS program DTN implementation proved interoperability between the two DTN implementations and became NASA's first multi-gateway DTN system.

Building on the foundation of the ION implementation and these first generation DTN deployments, NASA continued DTN development. In 2019, MSFC completed the initial development of DTN Marshall Enterprise (DTNME), NASA's first second-generation DTN implementation, and deployed it to the HOSC ISS ground system as a replacement for DTN2. Around this same time, development on HDTN began through NASA's SCAN program. DTNME has now been installed on the ISS as a second onboard DTN gateway and the program hopes to deploy HDTN on ISS in the coming years. ION and DTNME, combined, have over a decade of operational experience, proving their effectiveness and reliability. HDTN will hopefully soon join ION and DTNME in the lineup of NASA's premier DTN implementations.

2.1 Overview of NASA Premier DTN Implementations

ION [6] pioneered the basic principles of DTN and Bundle Protocol (BP) through the demonstration of three core DTN technologies: "store and forward", convergence layer utilization, and custody signals. Firstly, "store and forward" capability store bundles (data + metadata) in non-volatile memory where the DTN system can retrieve and then transfer it as soon as the link to the next node is available. Secondly, the bundle protocol allows the DTN bundles to travel across a communications link regardless of the convergence layer used. Finally, Custody Signals enables nodes to re-transmit bundles in case of a dropped packet along the network path. ION also provides the capability to run multiple ION nodes on the same computer. ION has proved very effective on ISS in handling limited data rates, especially given the limited onboard hardware supporting the system. ION was, and is, a proven and useful DTN implementation.

DTNME (DTN Marshal Enterprise – DTNME [2] is the Marshal Space Flight implementation of DTN Based on DTN2. Built with years of experience from operating ION and DTN 2 on ISS, and under the vision and skill of Robert L. Pitts, David Zoller, and Joshua Deaton, DTNME brings a host of new capabilities and features. In the way of major advancements, the MSFC solution supports the latest Bundle Protocol version (BPv7), Bundle Architectural Restaging Daemon (BARD), Asynchronous Management Protocol (AMP), video streaming over DTN (RTP over DTN), and more. Firstly, DTNME is fully prepared to take advantage of the soon-to-be released CCSDS Bundle Protocol version 7 standard, while still providing backwards compatibility for BPv6 DTN sources. Given the inherent lack of compatibility between BPv6 and BPv7, DTNME's bridging of the two standards is particularly useful in the environment of the ISS where many payloads remain active for a decade or more without updates. Secondly, the BARD capability allows DTNME to enhance the reliability of the DTN system by offloading stored packets to secondary storage for later restaging and retrieval. The authors have learned that this ability is important to ensure the reliability of a DTN system with multiple users and high throughput. Thirdly, the AMP capability allows for streamlined management of the DTN system, which reduces operational costs and lessens risk. Finally, the implementation of CCSDS's Real time streaming protocol over DTN brings a streaming video capability to the DTN community. Video is an important scientific, safety, and general operations capability for any space mission. Therefore, it's an important feature for a successful modern DTN implementation. Beyond these major capabilities, other smaller improvements and fixes have been applied over the years to make DTNME truly unique in NASA's mission operations. Testing has shown success with devices as small as a raspberry PI and as powerful as a full server class resource. DTNME is a powerful DTN implementation and still under active development with more important features, such as a web interface and improved GUIs, planned for completion by the end of 2023. The authors can strongly recommend DTNME for almost any application where DTN is needed.

High-Rate DTN (HDTN), a project based at NASA's Glenn Research Center, aims to build upon the first generation of DTN implementations and create a DTN solution that prioritizes high rate data transfer through the use of distributed architectures and cognitive networking. HDTN is focusing on several key concepts, including bundle prioritization, bundle fragmentation, multi-path data transmissions, end-to-end advanced routing, and neighbor discovery[1]. These features will add significant new capabilities for to the array of DTN implementations, particularly for an environment where many DTN nodes are all working in the same system, as one might imagine in lunar or martian space. HDTN is currently in the testing and development phase. In laboratory testing with the ISS program, DTNME and HDTN successfully exchanged a file at the rate of 950Mbps at a link latency 4 of seconds with 100% delivery. This testing was limited by the network interfaces, otherwise higher rates could have been achieved. Another significant factor of this testing is that succeeded in a latency environment that far exceeded that which would be expected for lunar operations (2.56s RTT). The authors are very encouraged by this testing and the promise for interoperability and DTN advancement. As the second of the NASA second generation DTN implementations, HDTN promises top-tier-performance and smart network integration to deliver a highly effective DTN implementation.

3. Assessing DTN Implementations

In the example of the International Space Station deployment, the current architecture featuring ION onboard with DTNME on the ground was not the product of simple convenience, familiarity, or happenstance. The ISS teams at Johnson Space Center (JSC) and Marshall Space Flight Center (MSFC) jointly assessed this configuration as the best solution given available DTN implementations. The reasons for selecting each of these implementations are complex, especially given the role of the space station as a platform for technology demonstration, but broadly, it comes down to the fact that the onboard environment imposes different constraints from the ground environment, and thus a different solution made sense. The decision was simplified by the limited options for operational DTN systems available at the time, but ultimately, a thorough assessment was the deciding factor. As with many systems, a reliable assessment begins with consideration of the operational constraints: available computing resources, required data rates, payload constraints and requirements, mission criticality, and more. The constraints will drive requirements and give the system designer a useful valuation of the key DTN implementation distinguishing factors. The operational constraints can also be used to validate the final implementation selection by ensuring all the constraints are met by the final solution.

Identifying operational constraints for a system is the important first step, however the true assessment begins with the consideration of the key DTN implementation distinguishing factors. Based on our experience, we believe the key factors to consider are as follows: performance, available system resources, features, interoperability, reliability, availability of support, architectural flexibility, and user-friendliness. Each factor is described below:

- **Performance:** The assessment of how much data, given a system with appropriate resources, can the implemented DTN system transmit from one node to another each. With the data demands from spacecraft continuing to increase as larger and more advanced platforms are launched, the value of high-bandwidth DTN implementations increases.
- **System Resources:** The assessment of the amount of computing hardware/software required to achieve the desired level of performance. Some DTN implementations can be run at full capacity on a small spacecraft, while others require laptop-like performance, and others may be most comfortable in an enterprise computing environment. Missions with more computing resources will have greater flexibility in selecting a DTN implementation.
- **Features:** The individual capabilities of each DTN implementation vary widely. The ability to elegantly offload bundles from a node's storage media to secondary storage might be invaluable to the operators. Do you want to be able to use AMP for operational management of your DTN node? If you plan to send video over your DTN link, then you'll want the capability to stream RTP over DTN. Do you need an implementation that can transmit each bundle to multiple nodes simultaneously? Do you need to optimize the number of nodes and the transmission path? Each DTN implementation has something unique to offer.
- **Interoperability:** CCSDS is regularly updating and improving upon the DTN standards. What DTN systems will you need to interface with and which version of the standard is it running on? Bundle Protocol Version 7 will soon be the latest DTN bundle protocol standard version, but it's not yet been widely adopted.
- **Reliability:** An assessment of needed reliability and robustness for a DTN system. Will your system tolerate downtime from a DTN node, or do you need to ensure every node is always available and resilient to operational impacts.

- **Support:** Does the implementation have a team behind it that can add new capabilities, ensure the software maintains compliance, respond to user problem reports, stay engaged in the greater DTN community, and have a reliable source of funding and expertise.
- **Architectural flexibility:** An assessment of how many different scenarios a given implementation can cover. Ideally, each organization would be able to use the same implementation across all the DTN nodes in the system, which could require an implementation that allows for extensive configuration, for example modules that could be added or removed to suit the situation.
- **User-Friendliness:** Assessment of how much technical skill is required to implement a given implementation. Some implementations have more robust operations user interfaces and support documentation.

The relative value of each factor depends on the operational constraints of the system, how important/difficult the system designer finds it to meet each constraint, and the cost of relaxing the operational constraints. These values, once established, can be used as part of a standard engineering trade study (as metrics to determine the weighting of each category) to determine which DTN implementation is most appropriate for a given system. Note that the cost of the software is not necessarily a factor as the NASA DTN implementations are available at no cost.

Ideally, one could show a direct comparison of each implementation in a quality table which would allow one to understand the general quality, or comparative "strength", of a given implementation. Such a table would, in general, indicate which DTN versions are likely to be useful to the spaceflight community and help separate the mature DTN implementations from the immature. However, development of such a table has proven relatively difficult. A straightforward ranking of implementations is challenging or impossible given the complexities and breadth of use cases. No baseline DTN reference model exists to compare against, and the subjective value of the key factors means any such published table would only be applicable to a narrow segment of the spaceflight community. It's meaningless to perform a trade study against a nonrepresentative architecture. As an example, the closest the authors came to a meaningful comparison for three theoretical implementations can be seen in Table 1, Universal DTN Implementation Comparison (Rejected), and Table 2, Universal DTN Implementation Scoring (Rejected).

Table 1: Universal DTN Implementation Comparison (Rejected)

Weight	**DTN Technical Capability**	**Implementation 1**	**Implementation 2**	**Implementation 3**
5	**System Resources**	Server	Desktop	Embedded
3	**Architectural Flexibility**	Special System	Widely Available System	Multi-System
2	**Features**	High	Low	Low
3	**Reliability**	Moderate	High	Low
5	**Performance**	<1Gbps	>1Gbps	>10Gbps
2	**Required User Proficiency**	Expert	Intermediate	Entry

Table 2: Universal DTN Implementation Scoring (Rejected)

A	B	C	D
18 (Points)	**17-13 (Points)**	**12-9 (Points)**	**<9 (Points)**
Ideal technical DTN implementation for most applications	**Strong technical DTN implementation. May require research to ensure appropriate choice for a given application**	**Useful, but research to make sure appropriate for a given application**	**May not be most appropriate for a given application**

Table 1 consists of capabilities (which each implementation would be scored against), three theoretical implementation examples with random characteristics, and weightings (indicating the value of each factor as determined by the system operational constraints). Table 2 contains the target cumulative scores (which describe the overall strength of an implementation) and an associated letter grade. Each factor receives a score of 1-3 based on how "good" each implementation is for the given capability. Each score is multiplied by the weight column and then summed with the other capability scores to determine the cumulative score, similar to how a trade study would be scored. The authors hoped this approach would provide a generic comparison score for DTN implementations.

Ultimately, the authors rejected this generic approach for the following reasons. First, both the selection of relevant capabilities and the determination of what is a "good" implementation proves inaccurate when applied to the broad range of users and use cases. Second, although the authors assigned weights to each capability based on their own expert assessment, they ultimately decided any weighting would only be valid for a minority of use cases. Finally, while the concept of a general strength comparison was deemed interesting, the added complexity was not offset by an equal increase in understanding. The authors hope that in conjunction with additional efforts to establish formal baseline DTN use cases, a similar table could be generated for each use case and provide the needed structure to make sense of this comparison approach. The authors do note, however, that informally, a rough estimate of NASA's three leading DTN implementations, ION, DTNME, and HDTN, all fell within the B ranking described in Table 2, in an informal assessment of the ISS-like use case (details of which have been withheld due to lack of robustness).

Despite the inability of the authors, within the scope of this paper, to provide a meaningful generic comparison, the approach to assessing DTN implementations, as explained above, remains particularly useful. Assessment of the key factors serves as both a validated engineering approach and as a helpful introduction for new DTN users into some of the central considerations for selecting a DTN implementation. When assessing operational constraints, the key factors can help guide the investigation and formulation of system resource limits by reminding the designer of which limits must be truly understood. Much like how development of a concept of operations is an essential step in the systems engineering process as it provides validation for the final engineering design, the identification of operations constraints provide validation to selection of the DTN implementation. Therefore, the authors strongly encourage the reader to understand their system constraints and to understand the relationship of the constraints to the key DTN implementation distinguishing factors so that the use of DTN in a space system provides the maximum value and capability to the reader.

4. Future Collaboration:

Future collaboration in the DTN community should include the establishment of one, or several, baseline reference DTN implementations which can be used to generate performance metrics for all DTN implementations. Such a baseline reference would be exceedingly beneficial to the community on its own, but simplifying the complexities of implementation use-cases, configuration options, and environments will go even further to enabling meaningful metrics and comparisons. Additionally, the actual development and execution of DTN implementation testing to develop those metrics would be a valuable addition to the DTN and space operations community. Further collaboration with CCSDS groups and publications is also encouraged. CCSDS has published the Solar System Internetwork (SSI) Architecture Green Book, which contains an approach for the classification of various space systems. The authors believe there is value in using the SSI framework in establishing DTN categorizations. Beyond the ISS implementations, other missions are beginning to incorporate DTN systems as part of their communications architectures. NASA's Lunar Gateway program included a DTN capability and the Korean Pathfinder Lunar Orbiter, which launched in 2022 and incorporates an ION DTN node on their spacecraft. Broader adoption should follow. There's also strong potential to include DTN as part of commercial space platforms, or even to incorporate DTN to terrestrial communication networks which experience frequent drops in connectivity. For example, a DTN node at a mission ground site could replace extensive custom data management and routing equipment, while allowing greater automation and less expensive non-mission-critical ground circuits. Further expansion of DTN implementation into the space sector is highly desirable and would be advantageous for the advancement of space communications capabilities and operations. NASA is wholly committed to collaborating with commercial partners on DTN use-cases, lessons learned, and best practices. The authors continue to push for greater adoption by the space industry and other commercial sectors. This technology is revolutionary and is a key enabling technology for the future of spaceflight. We want to help as many people as possible benefit from it and realize the promises of Delay Tolerant Networking.

No future collaboration would be complete nor effective without the ability to centralize the conversation. An effectively managed and centralized organization is necessary to provide a one-stop-shop for the space community for any questions about standards, solutions, implementations, or support for DTN. Responsibility for these tasks is currently sprawled across multiple groups, agencies, and environments with overlapping areas of interests. A one-stop-shop DTN group spearheaded by NASA would take the burden of providing the commercial and international community a centralized source of DTN-related information, advice, and expertise for distribution to the various professionals engaged in DTN efforts around the world. NASAs Space Communications and Navigations (SCAN) working group is uniquely positioned to lead such an effort and the authors encourage this group to expand their DTN integration and outreach efforts. The timing for the expansion of a centralized DTN effort has never been greater.

5. Conclusion:

The second generation of DTN implementations are here, and with these second-generation solutions come new and exciting capabilities, efficiencies, and possibilities for space operations. ION and DTNME are already proving themselves as tried and tested implementations. HDTN will soon join their ranks. While it is still difficult to present a generic quantitative comparison between the three leading NASA DTN solutions, the authors provide a qualitative comparison and affirm mission-specific quantitative assessments. The tools and knowledge to implement DTN are available to the space industry and robust enough for operations and integration into spacecraft systems. We now need industry to recognize the empowering potential of DTN, come alongside NASA to learn from our experience, and begin including DTN implementations into their own missions. DTN is a critical capability for the future of spaceflight communications and the commercialization of space. Now is the time to get it onboard your space system.

Acknowledgments

The authors would like to thank the NASA Huntsville Operations and Support Services (HOSC) Engineering and Development teams, and in particular Robert Lee Pitts and David Zoller for their leadership and support over the past decades. Lee and David have been instrumental in the CCSDS and DTN development and implementation. Their contributions pave the road for future DTN development and space exploration.

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