

# DTN Implementation and Utilization Options on the International Space Station

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The International Space Station (ISS) is in an operational configuration and nearing final assembly. With its maturity and diverse payloads onboard, the opportunity exists to extend the orbital lab into a facility to exercise and demonstrate Delay/Disruption Tolerant Networking (DTN). DTN is an end-to-end network service providing communications through environments characterized by intermittent connectivity, variable delays, high bit error rates, asymmetric links and simplex links. The DTN protocols, also known as bundle protocols, provide a store-and-forward capability to accommodate end-to-end network services. Key capabilities of the bundling protocols include the ability to cope with intermittent connectivity; the ability to take advantage of scheduled and opportunistic connectivity (in addition to 'always up' connectivity); Custody Transfer; and end-to-end security. Colorado University at Boulder (CU-Boulder) and the Huntsville Operations Support Center (HOSC) have been developing a DTN capability utilizing the Commercial Generic Bioprocessing Apparatus (CGBA) payload resources onboard the ISS, at the Boulder Payload Operations Center (POC) and at the HOSC. The DTN capability is in parallel with and designed to augment current capabilities. The architecture consists of DTN endpoint nodes on the ISS and at the Boulder POC, and a DTN node at the HOSC. The DTN network is composed of two implementations: the Interplanetary Overlay Network (ION) and the open source DTN2 implementation. This paper presents the architecture, implementation, and lessons learned. By being able to handle the types of environments described above, the DTN technology will be instrumental in extending networks into deep space to support future missions to other planets and other solar system points of interest. Thus, this paper also discusses how this technology will be applicable to these types of deep space exploration missions.

## I. Introduction

The ISS supporting ground system is a traditional, but embellished, ground system that supports manned space and research payloads that can be managed from the ground. Ground transport is over internet protocol (IP) networks and the space links are based on a Consultative Committee for Space Data Systems (CCSDS) silver standard. As illustrated in Fig. 1, users have uplink via S-band and two downlink paths: S- and Ku-bands. The S-

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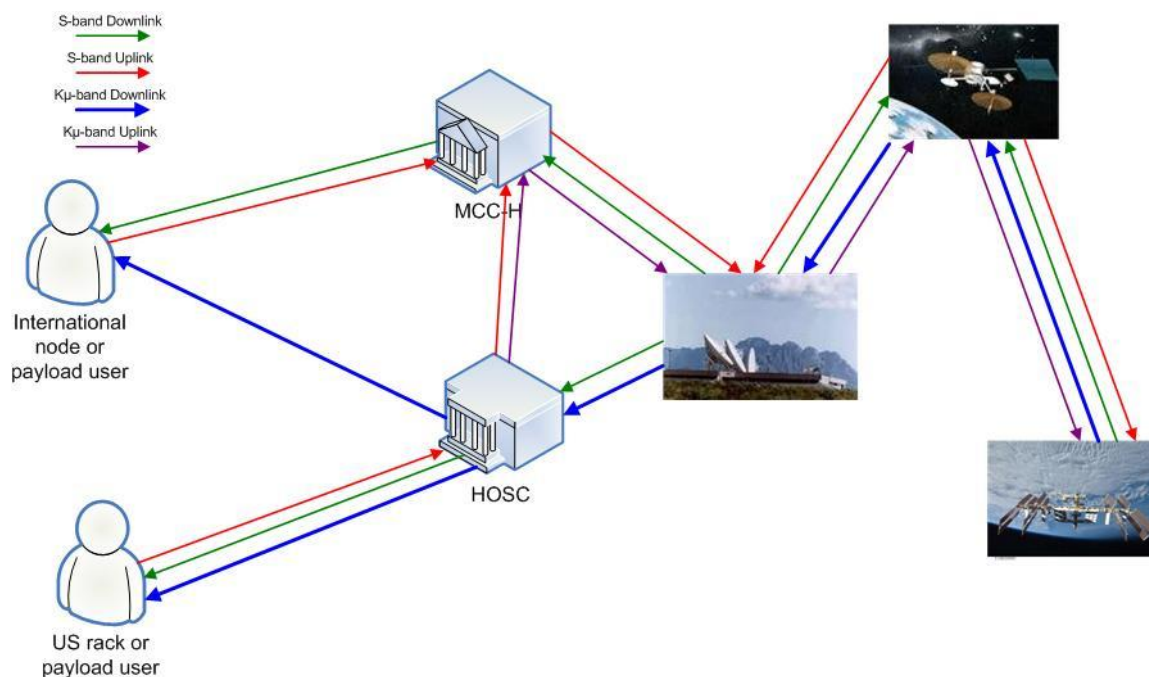
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band subsystem is viewed as the primary payload uplink and telemetry downlink path. It has a relatively low data



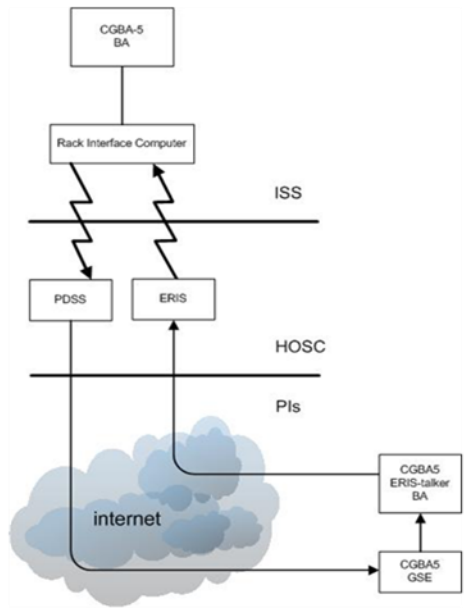
**Figure 1. ISS Traffic Flow.**

and command rate. That is to say much of the bandwidth and command slots are pre-allocated.

On the S-band uplink, the command rate is 8 commands per second, driven by an onboard 10 Hertz (Hz) clock. Each control center<sup>7</sup> is budgeted one time slot per second. The Mission Control Center-Houston (MCC-H) multiplexes the control centers' uplink data together for an approximate uplink rate of 38 Kilobits per second (Kbps). The uplink bandwidth is dynamically allocated, in that a user/facility may have varying size uplinks from zero to the maximum uplink size. A center does not have to use its time slot every time; MCC-H reserves the right to override any allocation based on operational necessity.

The HOSC is architected to provide command and control (C&C) and science data distribution in parallel. A payload such as CGBA sends commands to their payload via any of a number of applications. CGBA developed a LINUX based application called BioServe Communications Stack, BCS. C&C remote applications interface through a Programmatic Generic User Interface Design Document<sup>1</sup> (PGUIDD) defined interface to an Enhanced HOSC System (EHS) Remote Interface Service (ERIS) listener. From there, the commands are forwarded to the HOSC Command System Management (CSM). Based on a scheduled window, the HOSC forwards the commands to MCC-H. If uplink modulation is enabled, MCC-H forwards the command to the ISS. Once the ISS receives the data, it progresses through the C&C Multiplexer/Demultiplexer (MDM). Ideally, the Command and Control Software (CCS) is capable of receiving eight commands per second from the ground, whether they are commands to a device or "273 word" file transfer commands. However, actual experience and user needs have shown that the reality is something less. From there, the commands are sent to the Payload MDM and on to a specific payload, determined by its APplication IDentifier (APID). This process with CGBA is seen in Fig. 2. The ISS has allocated multiple APIDs per payload. One is allocated for command (forward) over S-band, and one is allocated for science downlink (return) over Ku-band. Health and status is provided by independent S and Ku-band APIDs, respectively.

<sup>7</sup> Control center refers to the Mission Control Center-Houston (MCC-H), Payload Operations Integration Center (POIC), European Space Agency (ESA), Japan Aerospace eXploration Agency (JAX), Russian Federal Space Agency (KKA), or Agenzia Spaziale Italiana (ASI).



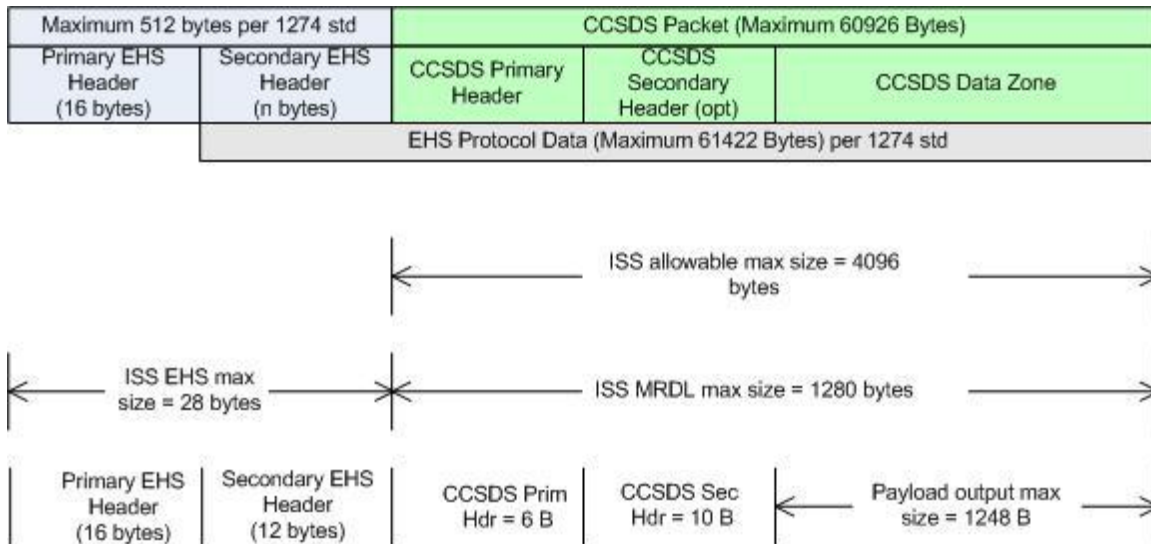
- CU-Boulder sends a bundle encapsulated in a command to EriS listener on an ePVT server.
- EriS forwards the command to the command server and the DTN command queue.
- After CSM requirements are met the command is forwarded to JSC and ultimately CGBA-5 on ISS.
- Acknowledgements are forwarded via Telemetry and Ku-Band
- Downlink science bundles are sent in CCSDS packets via Ku-Band to PDSS which forwards the data to CGBA-5.
- Acknowledgements to CGBA-5 are forwarded via S-band.

**Figure 2. CGBA Command and Data Flow.**

## **II. How Current Payload Operations are Handled in the Non-DTN Environment**

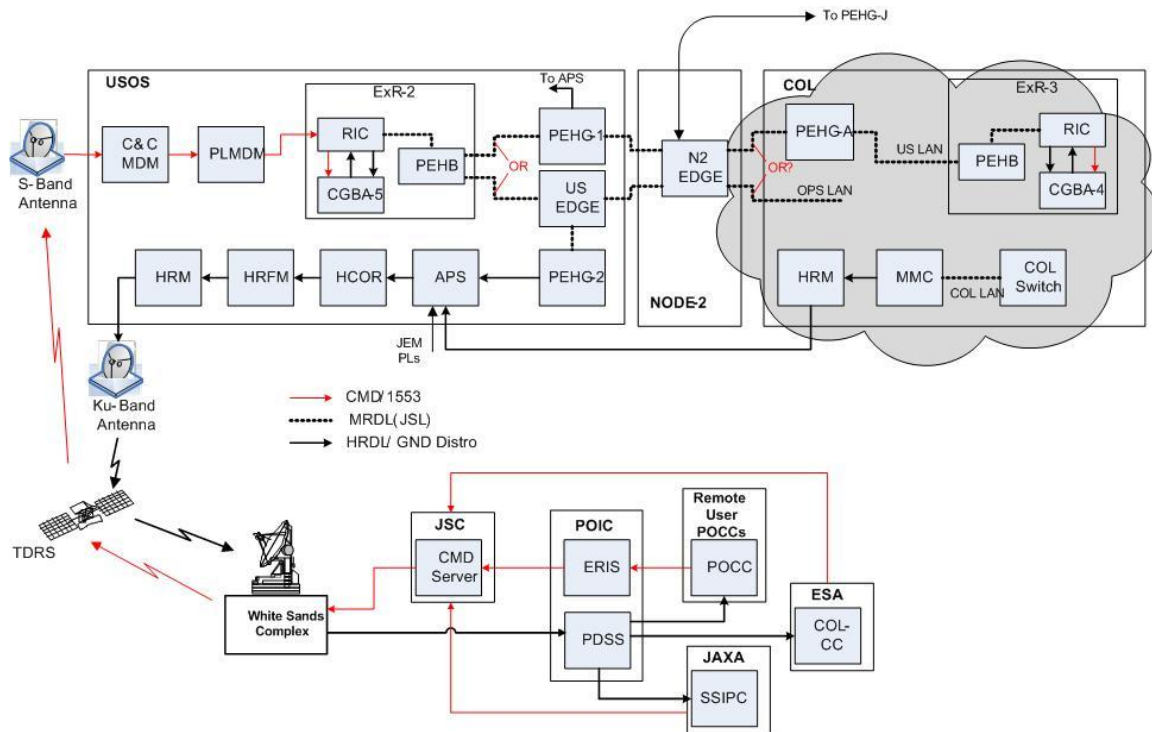
For the ISS, the HOSC primary goal is to support the Payload Investigators (PI) and the science associated with their payload. To meet this goal, tools and protocols have been utilized so that a PI can command and receive data any place in the world. Two core IP protocols are used, User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), with standard protocols such as “HTTPS” (Hypertext Transfer Protocol Secure), “RSH” (Remote Shell), and FTP (File Transfer Protocol). The HOSC has developed a number of protocols to support operations. For C&C applications, the protocols are TCP based and wrapped in the secure envelope of an IPsec compliant VPN (Virtual Private Network). Commanding for the ISS is primarily defined in three documents: the SSCC (Space Station Control Center) to HOSC ICD (Interface Control Document) (SSP-45001)<sup>2</sup>, the USOS (United State Onboard Segment) to USGS (United States Ground Segment) Command and Telemetry (S-Band ICD SSP-41154)<sup>3</sup>, and the USOS to International Ground System Segment(IGSS) Ku-Band Telemetry ICD (SSP-41158)<sup>4</sup>.

As stated previously, the HOSC C&C and Payload Data Services System (PDSS) operate in parallel. Science data is delivered by PDSS using UDP to the users designated by the PI. The data is down-linked in a CCSDS packet and encapsulated in an EHS header, as shown in Fig. 3. The down-linked CCSDS data is constrained to be less than the allowed CCSDS maximum packet size to 1280 bytes. The EHS header is prepended to expedite processing.



**Figure 3. Payload Science Data Packet.**

The downlink path is via CCSDS Standard 701.0-B-2. Fig 4 details the processing and data flow.



**Figure 4. Process and Data Flow.**

### III. Making the Case to Implement DTN into the Current Payload Science Operations Model

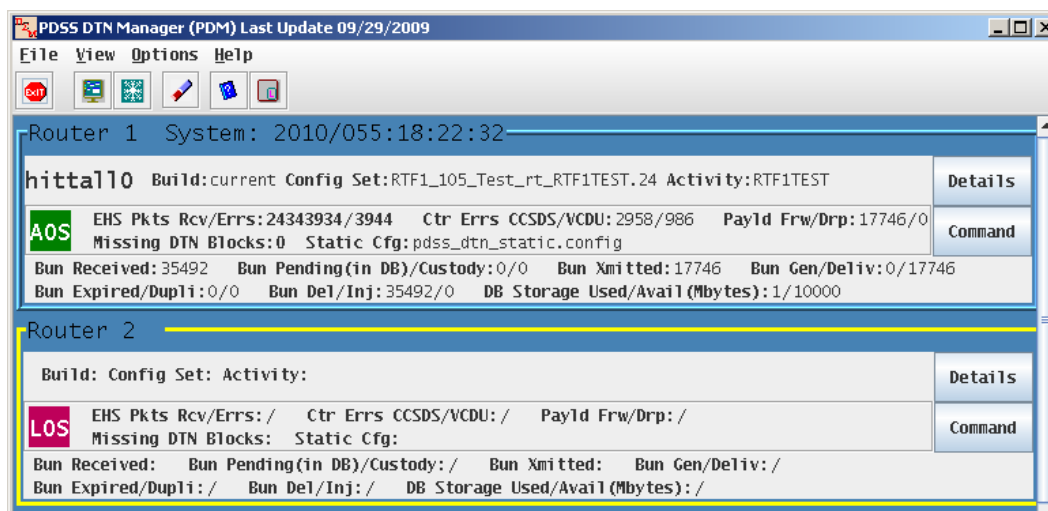
For an investigator, this methodology has pros and cons. It ensures access to data during scheduled Acquisition of Signal (AOS) (in view) and therefore, real-time evaluation of an experiment is possible. Onboard storage of data captured Loss of Signal (LOS) (out of view) is also available. However, the various communication legs are not without problems.

In the past, a PI had to accommodate spacecraft operations and the control center rhythms by building ground systems to accommodate the physics and engineering of space flight. With the use of DTN, access to payloads can be greatly simplified. A user need not be online continuously or request to fill-in missed data due to communication outages. Planning payload activities could become less contentious, because access to downlink or command opportunities would not be as critical.

Therefore, through the auspices of a Mission Operations Laboratory (MOL) Engineering Change Request and the NASA DTN working group, the HOSC, in concert with BioServe Space Technologies, proceeded to provide a prototypical DTN network between the ISS and CU-Boulder.

The HOSC design included a unique command interface to serve the needs of manned space and the implementation of a DTN router. Several important considerations were part of the design. First, the HOSC wanted to support the needs of our ever changing user base in some non-traditional ways. The HOSC model works best with a control center on a highly available network. However, the HOSC has many smaller centers and experimenters who do not staff their operations continuously. Therefore, a properly implemented DTN supports the need for on-demand services. A user need not be online to receive data. The user would pick it up when available and would be assured of 100 percent of their data received. Likewise, the user need not have a command path. He could command and be assured that delivery would happen when the opportunity arose. These capabilities are fundamental to a complete implementation.

Second, the HOSC team considered it important to demonstrate the interoperability of a second implementation of DTN, specifically RFC 5050 – Bundle Protocol Specification<sup>5</sup>. The HOSC decided to use the current implementation of DTN: DTN2 as found at the “*sourceforge*” DTN project page. This was the starting point for the HOSC, and in collaboration with the University of Colorado at Boulder, we began our development and integration. This activity not only included DTN, but the integration into the HOSC mission management environment. Mission operations environments are extremely conservative. As a result, the management view of the DTN router was built as a web application with help from the operations team. Figure 5 is one such display illustrating the status of the router and traffic. Mission parameters such as AOS, LOS, and CCSDS/ Virtual Channel Data Unit (VCDU) error counters are included with bundle status.



**Figure 5. DTN Router Overall Status Display.**

Finally, the HOSC viewed the use of DTN protocols as a profound change because it tied the ground segment closer to flight segment as interoperable entities. The current users of the internet, including PIs, are familiar with four basic assumptions<sup>6</sup>:

- 1) Near continuous bi-directional path end-to-end.
- 2) Short and nearly equivalent (consistent) round trip times to send data and receive ACKnowledgments (ACK).
- 3) Relatively symmetric and equivalent data rates in both directions.
- 4) Low loss or corruption of data.

Access to spacecraft/payloads from a control center is via CCSDS packets. Therefore, even though a user may be local to a control center or remote and using IP protocols, access may be severely constrained or proxied. The physics and logistics of access to space re-write the four basic assumptions as:

- 1) Intermittent path defined by geometry and load.
- 2) Long round trip times which may have varying times by segment. The times may increase or decrease.
- 3) Uplink and downlink rates are almost never symmetric between entities. The exceptions are usually peer relationships; e.g., Extra-Vehicular Activity (EVA)-EVA.
- 4) Loss or corruption of data has the potential to be greater due to the harsh environment, device degradation, inaccuracies in pointing, etc.

#### **IV. Phase I DTN Operations: Early Implementation with BioServe's CGBA Payload**

The harsh environment of space presents a new set of problems that traditional IP networks on the ground do not typically experience. This harsh environment is characterized by disruptions due to occultation, solar flares, or scheduling issues associated with sharing downlink with other spacecraft. The spacecraft must be able to handle interruptions in connectivity due to these events and be able to handle the data losses associated with them. DTN is an emerging technology that was designed to handle these types of harsh networking environments. CU-Boulder is the first payload developer to be an early adopter of this technology. They have implemented DTN protocols on their ground side network at their Payload Operations Center (POC), and onboard the ISS using their CGBA payload. CGBA is primarily an environmental control chamber for life science, but it also provides an embedded computational /communications platform that the payload developer used to implement the DTN protocols. The payload is remotely monitored from the POC located in Boulder, CO. The payload developer can send commands to CGBA from their POC, or an onboard ISS crew member can issue commands locally to CGBA. Prior to CU-Boulder implementing DTN on CGBA, payload operations required CGBA commanding sessions to be scheduled days or weeks in advance. The commanding uplink is very limited as discussed earlier; typical sessions might include five or fewer commands. Another limiting factor of this command uplink is that it cannot be used to provide any communications feedback, so the telemetry downlink from CGBA must be used for this purpose. This downlink path is subjected to interruptions due to losses in connectivity between the ISS and Earth due to normal Tracking and Data Relay Satellite System (TDRSS) handovers, and losses due to the unreliable UDP network protocol used to transmit the telemetry over a congested internet between the HOSC, located in Huntsville, AL, and the CU-Boulder POC. To compensate for these losses between the ISS and the ground station, a playback system downlinks the newest telemetry files first and uses the remaining bandwidth to repeat older files. To compensate for losses without a true communications feedback path, the telemetry files may be replayed hundreds or thousands of times. This can lead to a sizable overhead of useless retransmission of files for which the first attempt was successful.

The S-band uplink path is tightly controlled by ground operators at the HOSC due to the safety risk and bandwidth limitations involved in sending ISS payload commands. The ground operator responsible for managing the payload user's command interface to their payloads onboard the ISS is called the PRO (Payload Rack Officer). Payload users are allocated windows of opportunity during AOS periods to send their commands; these commanding sessions are typically planned out days in advance. The command windows are tracked by an overall daily schedule that breaks the good uplink times into planned windows. A payload user is required to come online before the opening of their window and check in with the PRO to let them know he/she is online and ready to command. The PRO then enables that user's account for commanding. When that specific window ends, the PRO then disables the user's account, the next payload user calls in, and the process starts over. It is apparent that this is a very involved and intensively scheduled resource, requiring extensive effort to map out. Also, at some point after a particular command session has expired, the payload user may discover that an additional command needs to be sent in response to an unexpected event the previous command may have caused. This requires that user to call the PRO position and request another command window to send any additional commands. This interaction was established for safety reasons, so that the PRO is aware of what type of commanding is being done by individual payload users.

DTN has shown great potential in drastically improving this process. In a DTN environment, the users are only being required to log into their systems once and select a series of commands that are needed for the day. As the resource becomes available, the commands are sent up to the payloads. If there is a need to send a follow up command, the user simply initiates the command and it will be uplinked when the resource becomes available. To integrate the DTN features with manned operations and provide a level of "safe" command autonomy, the HOSC extended its systems to support a new class of commands for feedback acknowledgments. This enables DTN operations to have a simple form of automatic repeat request (ARQ) that is delay and disruption tolerant. Thus, the

downlink can be used much more efficiently because the system is now able to preserve reliability and therefore permit higher fidelity science operations. Development was done at the HOSC to flag these types of commands as DTN commands and allow them to be queued up and transmitted without PRO intervention. This was accomplished by implementing a priority queue that collects DTN commands and uplinks them when there is an available opportunity. This does not make the HOSC a true DTN node because the priority queue is limited and does not allow for custody transfer or other features of the Bundle protocol. This approach permitted CU-Boulder to take the first step and verify that DTN worked between their payload and ground system before making future enhancements to the HOSC to support DTN.

Ground team operators at the HOSC still have the ability to disable or enable these DTN acknowledgements without advance notice, if the uplink bandwidth is needed for other higher priority commands that need to be sent to another payload. With these modifications in place at the HOSC to support the feedback link, enhancements to payload software allow monitoring of the DTN software and new telemetry software adapted to the DTN model. The payload developers at CU-Boulder used the interplanetary overlay network software (ION) to develop DTN capabilities that are used in their payload and ground software.

The first DTN experiments were conducted on July 10, 2009, after the CGBA payload was configured with the new DTN software. This first experiment involved down-linking images from a previous CGBA experiment where a metal salt was added to a silicate solution to produce insoluble silicates. A frame of this experiment was sliced into smaller pieces that were down-linked over a disrupted space to ground link during a TDRSS handover. (The TDRSS handover causes the link to experience disruptions on the order of several minutes.) The payload was able to respond to these disruptions and resume the downlink where it had been previously interrupted. After CU-Boulder finished this preliminary experiment with DTN, they conducted more experiments to test how DTN would respond to unattended operations. The payload down-linked its status telemetry files via both a non-DTN environment and a DTN environment for comparison. During this time, 14 files per hour were generated. The non-DTN scheme yielded an average of 3504 redundant receptions per file. The DTN scheme performed much better, with an average of 0.06 redundant receptions per file<sup>7</sup>.

The early DTN demonstrations proved that the technology could have far reaching applicability in terms of the ISS operations model. CU-Boulder has been very instrumental in taking the first steps toward implementing DTN on the ISS and showing its usefulness to other potential ISS users. As a result, it was decided that a more end-to-end DTN concept should be developed that involved deploying a true DTN gateway at the HOSC and examining areas to upgrade some of the onboard ISS infrastructure to support DTN.

## **V. Phase II DTN Operations: The HOSC DTN Gateway**

The K-band parallel downlink leg with an intermediate node is implemented by the HOSC. The DTN2 node at the HOSC is wedged between the ION node onboard and the ION node operated by BioServe. The implementation is being conducted in five phases.

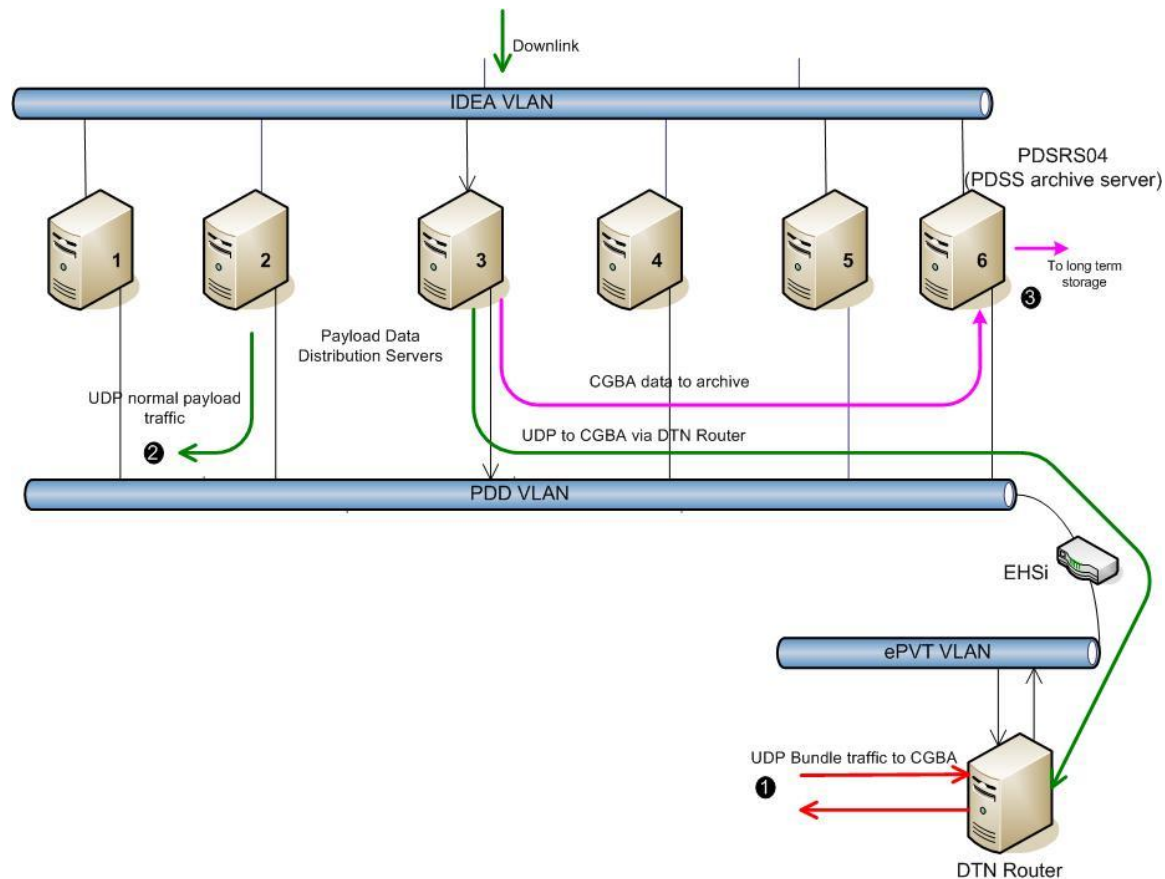
1. Initial development and evaluation.
2. DTN Engineering Network (DEN) testing in support of Phase 0 DTN support.
3. DEN testing with CGBA and recorded data.
4. IV&V testing with recorded and live data.
5. Operational data flow.

Initial development began with the download and subsequent building of a DTN2 instance. This was conducted in a pure development model with standalone testing between two DTN2 instances. During this activity, discussions with BioServe were conducted to understand the implementation details between the CGBA and the onboard Express Rack<sup>8</sup>. Eventually, source listings were provided to ensure an exact understanding of the CGBA encoding. However, once complete, testing moved to the DEN, a research testing network setup between NASA DTN entities to ensure compatibility between DTN components.

In the DEN, testing was conducted to ensure interoperability between the DTN2 implementation and the ION<sup>9</sup> implementation which was developed at the Jet Propulsion Laboratory. A testing configuration was established between BioServe operation at CU-Boulder and the HOSC. Actual recorded downlink data was used in the test scenarios. Testing included DTN capabilities for the TCP and UDP Convergence Layer Application (CLA) and the inclusion of a Bundle Application to support the CGBA Rack Interface Computer (RIC) implementation.



The HOSC is currently beginning its Independent Validation and Verification (IV&V) testing phase with recorded data. Transport will be across the wide-open internet as shown in Fig 6. The items to be tested and reconfirmed include data flows, either from the PDSRS ③ servers that have been previously recorded or live data from the Payload Data servers. For real-time data, the HOSC will execute in a failsafe mode by archiving ③ payload



**Figure 6. IV&V Data Flow.**

data in parallel with transmission directly ① ② to the user or to the HOSC DTN router.

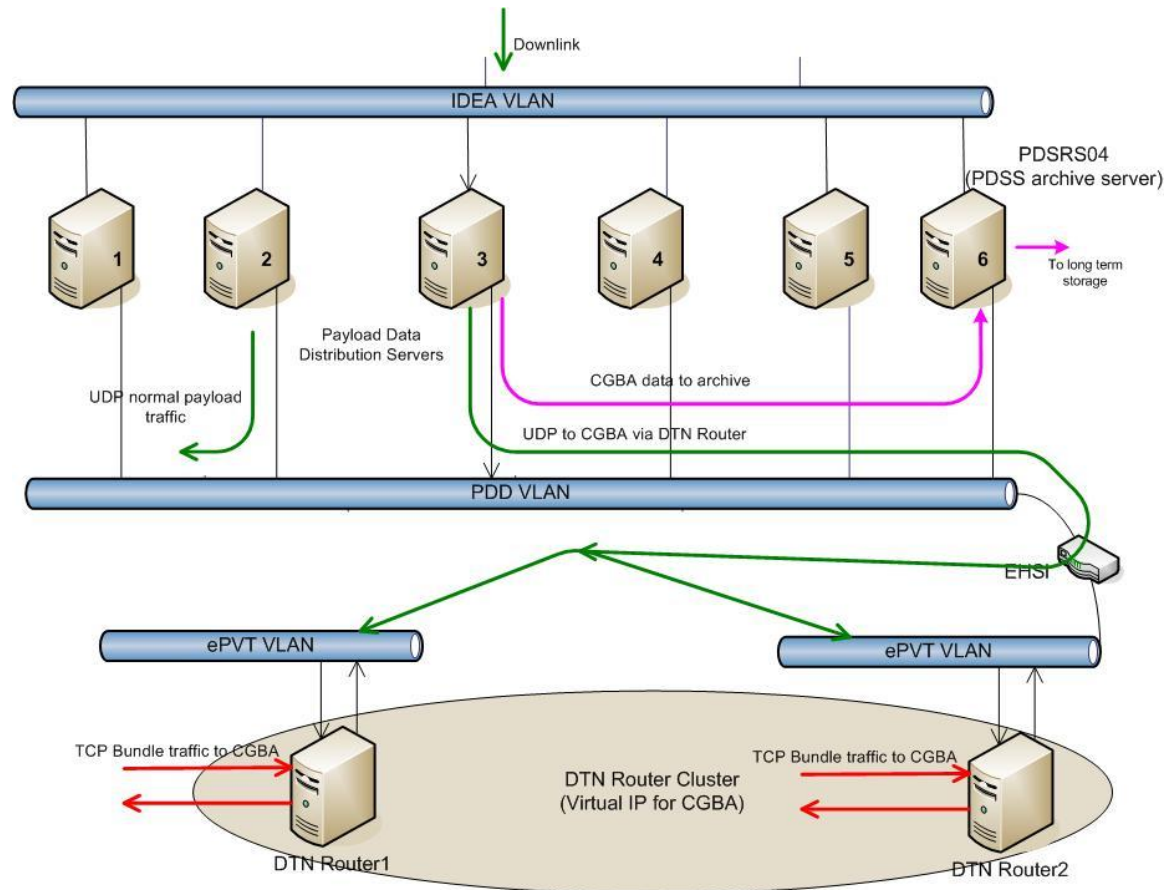
Packets from PDSS are composed of APID 941 for the BioServe payload CGBA-5. Real-time data will be simultaneously routed to BioServe at CU-Boulder, the HOSC science archive, and to the HOSC DTN Router. The packets will conform to PGUIDD standards and encapsulate the BioServe RIC channel packets. A custom CLA of the DTN2 daemon identifies and extracts the embedded BioServe RIC channel packets and then extracts the Bundle Protocol (BP) bundle set. The BioServe packets are then processed by the DTN2 daemon for bundle separation, forwarding, custody transfers, and any other processing.

The HOSC router implementation maintains and displays packet statistics on EHS PDSS packets received by source APID. The router also displays information returned from the DTN2 daemon including: individual link statistics, bundle statistics for all links and a listing of individual bundles by source and destination for individual bundle removal if required. The interface for router command and control is a JAVA applet that is similar to the Front End Processors (FEP) used to acquire the data from the downlink. The router and the DTN2 daemon are configured and controlled via this interface, including audible alarms for critical events such as low availability of bundle storage space. The DTN2 daemon is controlled by a C++ application remotely, allowing single control but multiple views. The HOSC operational model supports up to 8 distinct and separate routers in a prime and backup configuration, with each pair processing data in parallel. Only the Prime router forwards these packets to the DTN2 daemon for bundle extraction and processing. This allows the backup router to at least show positive status for flows from PDSS and connectivity of the remote destination's links. Testing has demonstrated the aforementioned capabilities and the custom BP application is being modified to be a custom CLA of the DTN2 daemon. Custody



transfers have been tested between the router and Colorado for the extracted bundles, but custody transfers between the HOSC and the ISS CGBA payload are still to be tested. This is anticipated in the next phase of testing.

The operational configuration will include a highly available implementation, as shown in Fig 7. It will support multiple routers in a prime-backup mode. The use of shared Redundant Array of Independent Disks (RAID) or a global file system will ensure no loss of data. When this configuration is in place, the HOSC can support end-to-end



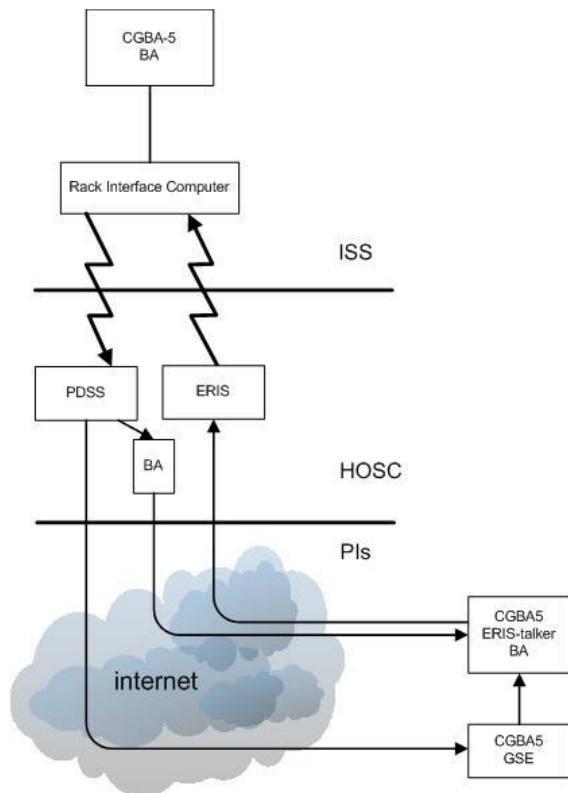
**Figure 7. Highly Available DTN Configuration.**

DTN traffic from CGBA.

This operational configuration preserves the separation between science data downlink and the S-band command and telemetry path. Therefore, the next HOSC goal is to support custody transfers between CGBA on the ISS and CU-Boulder and break the separation. This will be accomplished in two phases. The first phase will provide acknowledgement via a route to CU-Boulder as shown in Fig. 8. The CLA on the HOSC DTN implementation will inspect CGBA-5 downlink APIDs. The HOSC can provide the capability to:

1. Encapsulate the APID and forward with a custody transfer or
2. Pull out the bundle and perform a custody transfer.

Option 2 is preferred and the direction the HOSC is pursuing with BioServe. Option 1 is being preserved for those who do not have a spaceborne DTN implementation but, nevertheless desire the benefits of DTN, such as store and forward.

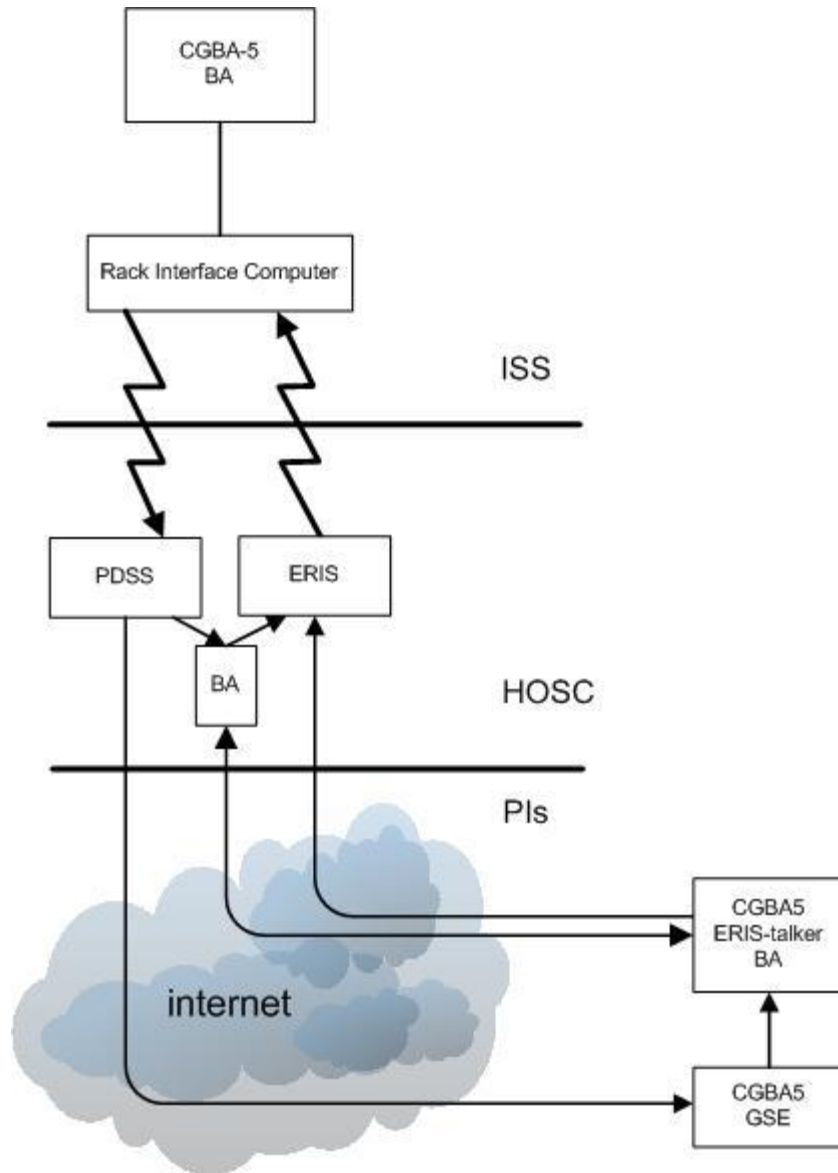


**Figure 8. Acknowledgement for Custody Transfer.**

With option 2, a complete end-to-end DTN network is available between the ISS and a ground user. The HOSC will forward acknowledgement of Bundle reception to the ISS/CGBA via a path to BioServe. BioServe will forward the acknowledgement to the ISS which is routed back to a HOSC ERIS server and on to the ISS via MCC-H. Two purposes are served by this method. First, the network is fully exercised if somewhat circuitously. Second, issues of command authority and privilege are bypassed since BioServe will be responding to its own experiment over an APID which it controls. This APID is not the downlink APID. The downlink APID is all that the DTN router is aware of.

Phase 2 includes the DTN router at the HOSC which provides acknowledgements to the preceding node, specifically CGBA on the ISS. Figure 9 depicts the flow of commands and data. As can be seen, custody transfers occur via the DTN2 BP layer for bundles sent between the HOSC and Colorado. Custody transfers will occur for the bundles received by the HOSC from the CGBA payload via direct acknowledgement. Finally, the DTN router will forward Bundles to CU-Boulder and receive acknowledgements completing the end-to-end transfer.

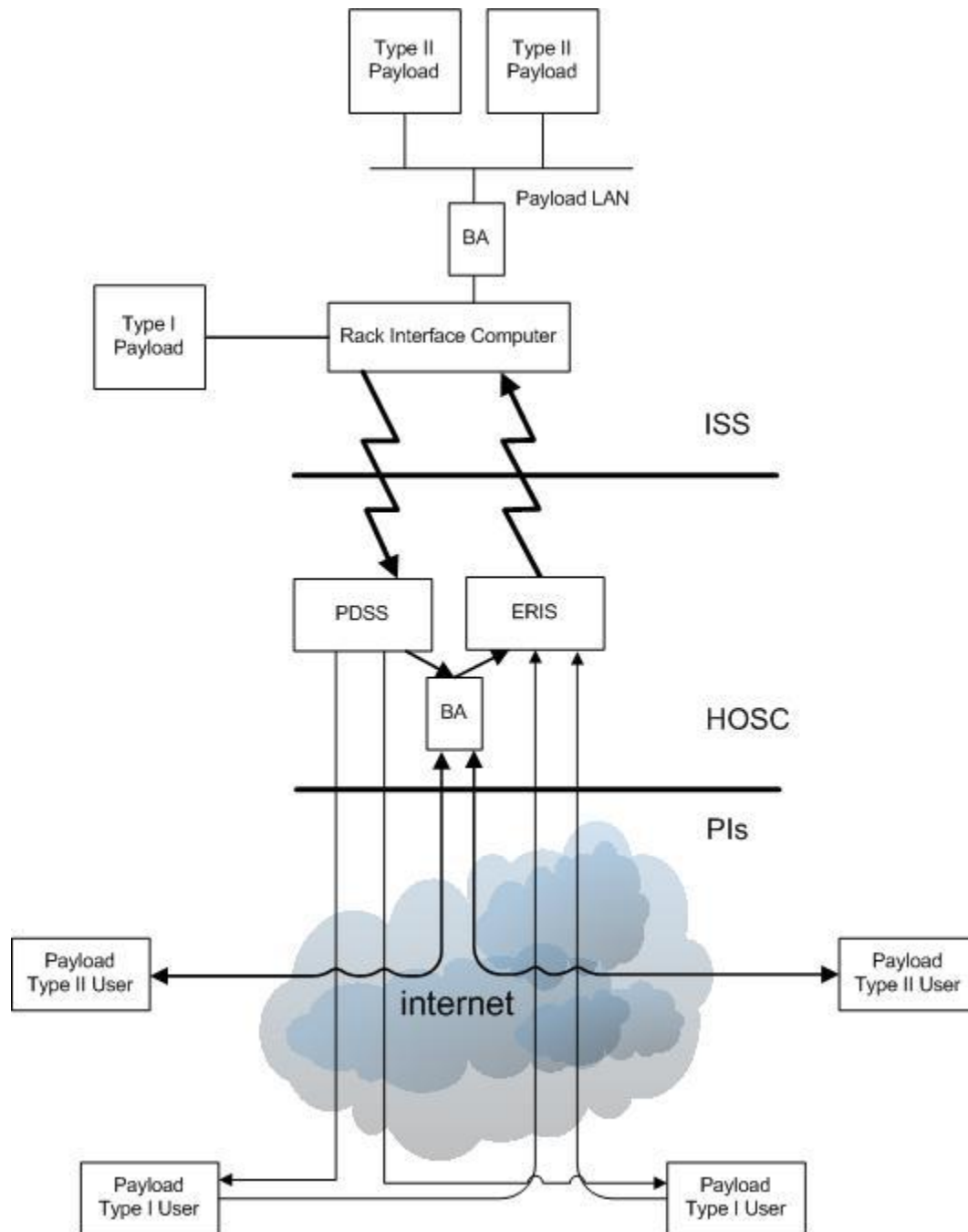
- A Convergence Layer Application (CLA) on a DTN2 implementation will inspect CGBA-5 downlink APIDs and extract bundle data.
- The HOSC can
  1. Encapsulate the APID and forward or
  2. Pull out the bundle and do a custody transfer
- Both options are desirable in that it makes the HOSC a full DTN node
  - Provides for custody transfers
  - Supports an End-to-END DTN network
- BioServe acts as an intermediary to provide Ack/Nak commanding to the payload



**Figure 9. Phase II Ack/Nak.**

## VI. Conclusion

DTN has proven to be an effective technology that can simplify the current operations concept involved with payload commanding and telemetry receipt. CU-Boulder played an important part by becoming the first DTN enabled payload onboard the ISS. They were able to run experiments and compare the results with previous experiments that had been conducted in a non-DTN environment. The results clearly indicated that the DTN technology reduced the number of retransmissions, allowing them to start changing their operations concept to allow for autonomous operations. The success of these first DTN experiments with CGBA has allowed the HOSC to pursue a more robust architecture by infusing more DTN technology into the ground system. This work has started with the on-going development of the HOSC DTN router. This router will make the HOSC an actual DTN node between CU-Boulder and their payload onboard the ISS, which will allow for a more robust end-to-end DTN path. This will also allow other interested payload users to benefit from DTN in the future. Figure 10 shows an integrated architecture that will support both non-DTN users (Type I) and DTN users (Type II). Future work will continue with more DTN infusion onboard the ISS's infrastructure. This should coincide with current ISS communications upgrade projects that are already in work.



**Figure 10. Integrated configuration to support both DTN and non-DTN users.**

## **Acknowledgments**

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