The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

CONCEPTS AND RATIONALE FOR STREAMING SERVICES OVER BUNDLE PROTOCOL

INFORMATIONAL REPORT

CCSDS 730.2-G-1

GREEN BOOK

September 2018

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this document is to discuss concepts and rationale for real-time video streaming services over Bundle Protocol. Previous testing of video streams over Bundle Protocol is documented. A common test configuration for continued testing and benchmarking of video (and other streaming data) is also documented.

1.2 REFERENCES

The following publications are referenced in this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

[1] *Digital Video Broadcasting (DVB); Measurement Guidelines for DVB Systems*. ETSI TR 101 290 V1.2.1 (2001-05). Sophia-Antipolis: ETSI, 2001.

[2] *Digital Motion Imagery*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 766.1-B-2. Washington, D.C.: CCSDS, August 2016.

[3] *Advanced Video Coding for Generic Audiovisual Services*. ITU-T H.264. Geneva: ITU, 2012.

[4] *CCSDS Bundle Protocol Specification*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 734.2-B-1. Washington, D.C.: CCSDS, September 2015.

[5] *Wireless Network Communications Overview for Space Mission Operations*. Issue 3. Report Concerning Space Data System Standards (Green Book), CCSDS 880.0-G-3. Washington, D.C.: CCSDS, May 2017.

[6] David Israel. "Disruption Tolerant Networking Experiments with Optical Communications." 20 December 2013. National Aeronautics and Space Administration. https://www.nasa.gov/directorates/heo/scan/news_DTN_Experiments_with_Optical_Communications.html.

[7] N. Spyropoulos. "UrtheCast: The System of Systems for Dynamic EO Monitoring Content." In *Prodeedings of the Symposium on International Safeguards: Linking Strategy, Implementation and People (20–24 October 2014, Vienna, Austria)*. IAEA-CN—220. Vienna: IAEA, March 2015.

[8] Sotirios-Angelos Lenas, Scott C. Burleigh, and Vassilis Tsaoussidis. “Bundle Streaming Service: Design, Implementation and Performance Evaluation.” *Transactions on Emerging Telecommunications Technologies* 26, no. 5 (May 2015): 905–917.

[9] *CCSDS File Delivery Protocol (CFDP)*. Issue 4. Recommendation for Space Data System Standards (Blue Book), CCSDS 727.0-B-4. Washington, D.C.: CCSDS, January 2007.

[10] S. Burleigh. *CBHE-Compatible Bundle Multicast*. Internet-Draft draft-burleigh-dtnrg-imc-00 [expired]. Reston, Virginia: ISOC, April 9, 2009.

[11] *Licklider Transmission Protocol (LTP) for CCSDS*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 734.1-B-1. Washington, D.C.: CCSDS, May 2015.

[12] *Space Communications Cross Support—Architecture Requirements Document*. Issue 1. Recommendation for Space Data System Practices (Magenta Book), CCSDS 901.1-M-1. Washington, D.C.: CCSDS, May 2015.

[13] D. Ellard, et al. *DTN IP Neighbor Discovery (IPND)*. Internet-Draft draft-irtf-dtnrg-ipnd-02 [expired]. Reston, Virginia: ISOC, November 8, 2012.

[14] “WANem: The Wide Area Network Emulator.” http://wanem.sourceforge.net/.

2 OVERVIEW

Previous testing and real-life experience with streaming video over networks indicates that video streams are particularly susceptible to network jitter and lost packets (see reference [1]). Video decoders typically buffer the incoming data stream to reconstitute the frames of video that were encoding using ‘group of pictures’ algorithms that combine frames or disassemble video frames into blocks of pixels. If enough data is missing, even with buffering, or the data arrives jumbled or out of order beyond the limits of the decoder’s buffering, the decoder will either freeze the last good frame of video and present it as live video output, or will simply default to a blank or colored screen.

It is likely that as humans endeavor to explore space beyond low Earth orbit, video will be included as important data transmitted back to Earth. Whether it is used for situational awareness, such as proximity of approaching spacecraft during docking and rendezvous, for monitoring an Extra Vehicular Activity (EVA), or for public use to allow people on Earth to ‘go along for the ride’, successful transmission and reception of video will become an important requirement for mission success. As these missions move beyond the Earth-Moon system, it is very likely the data communications will be over delay-tolerant networks.

This Green Book explores the requirements for video over bundle-streaming protocols and documents prototyping and testing of video over these protocols. Section 3 presents a number of use cases for video that motivate the requirements listed in section 4. Section 5 discusses the current experimental mechanisms to support streaming video services.

3 USE-CASE SCENARIOS

3.1 GENERAL USAGE SCENARIO

3.1.1 GENERAL

Depending upon the path(s) involved and overall latency/latencies, video transmitted over the Bundle Protocol (BP) can have many disruptions and severely out-of-order data packets, depending upon the path(s) involved and overall latency/latencies. In spite of this, there will almost always be a requirement for a best-effort video service that displays video as it is received at a mission control center while the entire set of video data is compiled. For this case, users should be able to view the 'newest' received video and to have awareness of the state of the stream (the time the current image was generated, the completeness of the stream archive, etc.). One possible scenario for providing this service is discussed below.

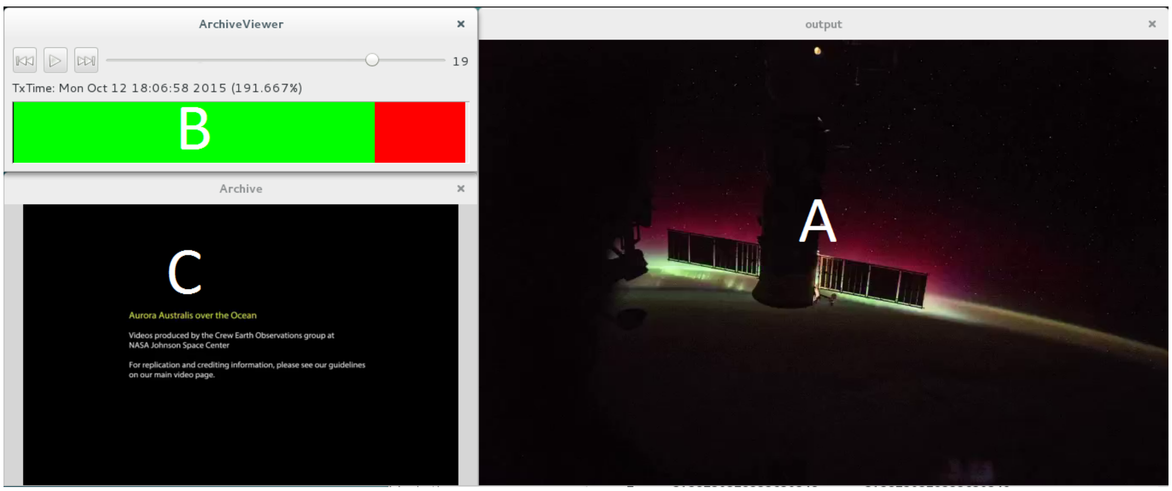

Figure 3-1: DTN Video System, Showing Both Real Time and Archived Playback

A typical end user would have a three-window display, as shown in figure 3-1. Window A is the real-time view from the spacecraft. Window B is a Graphic User Interface (GUI) comprising VCR-like control widgets for replaying the video stream. Window C is the replay video view, controlled from window B. In the above figure, the colors in window B are used to represent the state of the received video stream; green indicates that 100 percent of video for a given second was successfully archived, while red indicates that some or all of the video for a given second is still missing.

Window A shows the view from the spacecraft exactly as it was when it was transmitted. It will have a delay resulting from the latency of the transmission link for that distance. The video may freeze or break up once in a while because one or more video frames were lost or corrupted somewhere along the end-to-end Delay/Disruption Tolerant Networking (DTN) network path from the camera to the display. When there is such an outage, the missing frames never show up in this window; the displayed image simply remains unchanged until the next frame received in real time arrives. The view in this window is never delayed by any more than the one-way light time (plus processing), and it never regresses.

At the same time the real-time stream video is being displayed, the incoming data packets are being recorded and reassembled in the proper order, and stored on the local storage system.

The user controls the replay display from window B, commanding the replay view to start *N* seconds ago and then roll forward or perform other available playback features such as pause, rewind, roll backward, etc.

Window C shows the replay view. This may be no more than the frames that originally were displayed in window A just a few seconds or minutes ago. But in the event that there were some outages in the real-time view in window A, the replay may show more than what was originally displayed. That is because the replay view includes frames that arrived out of ascending bundle creation time order at the user's terminal, resulting from retransmission of lost/corrupt frames or from arrival on different length paths. So the replay view will always be at least as complete as the real-time view, and it may be more complete; moreover, by replaying a second time a while later, one may even find a more complete view may be available as late-arriving lost bundles (which perhaps were lost again) finally arrive.

It is this final compilation that will be used for distribution and archive. It is recommended the final compilation be archived without further processing. These files will be the closest to the original source video that will exist. While a decoded and processed video stream may be desirable for ease of use in most applications, keeping the original downlink data, in its most complete form, will allow the most options for further exploitation of the video asset in the future.

Video transmission can be divided into two major classes, with multiple use-case scenarios. The two classes are:

a) Interactive: Video transmission in which latency is sufficiently short to allow ground controllers to participate interactively in a real-time mode with the crew and spacecraft. For mission-critical operations, such as proximity operations/situational awareness, this is likely to be four seconds or less round-trip. Interactive video is being done in Low Earth Orbit (LEO) from ISS. Interactive video would be possible for lunar surface operations, and most cislunar situations. Non-mission-critical operations, such as personal video conferencing, medical conferencing, and most public affairs video could tolerate longer latency, perhaps as much as ten seconds round-trip. As one-way latency for transmission alone is approximately five seconds per 1.5 million km, interactive video would not be viable for a Mars Campaign.

b) Monitor: Video transmission in which latency is too long to allow interactive real-time communications and operations with the crew and spacecraft. As mentioned above, very shortly after leaving Earth/Moon proximity and flying to Mars, real-time communications and operations via video will cease. Video remains useful for communication, monitoring spacecraft routine operations, and for maintenance, but is no longer useful to ground controllers for making real-time changes.

Regardless of the primary mission, the use cases detailed in subsection 3.4 of the Motion Imagery Applications Blue Book (reference [2]) are applicable. These include

1) personal video conferencing;
2) medical conferencing;
3) proximity operations/situational awareness;
4) public affairs;
5) high resolution imaging; and
6) crew training/instruction.

There are other use cases, which are detailed in the appropriate section. Priorities of usage are dependent on mission requirements.

3.1.2 PRIORITIZATION OF VIDEO

Video may not be the highest mission priority at any given point in time, but for real-time viewing, it typically requires the highest network priority. For certain missions, LEO for example, this is not a concern, as there is typically sufficient bandwidth to handle all signals requiring transmission, regardless of priority. For other missions, however, bandwidth will be limited. In these cases, mission planners will have to balance mission priorities with the desire for Earth-based controllers to watch video as close to real time as possible.

To efficiently utilize the available space-to-ground bandwidth, video encoding parameters must be carefully set. For example, some videos may be encoded twice with different relative qualities, or individual frames may have different priorities. In the first example, the lower quality video can continuously be transmitted with a high priority, while the higher quality video is sent with a low priority but a higher time to live. If the bandwidth is available, the high-quality video may be transmitted. In general, video that will be viewed in real time will be prioritized over other high-bandwidth traffic, such as file transfers. In a DTN network, prioritization of video can be used as a mechanism to reduce jitter and out-of-order arrivals, and allows for a reduction of buffer sizes in receiver applications.

In some cases, it may be possible to use the results of image processing as a metric to provide automated priority determination. This method allows the cameras and/or encoders to set their own relative priority or flow label based upon image rules. For example, an external camera pointed at a spacecraft should not see small ‘clouds’ of particulate, which may indicate a Micro Meteoroid Orbital Debris (MMOD) strike. Therefore, a rule should be implemented, stipulating that one object, the spacecraft, must be tracked. If the velocity of that object increases by 200 percent over a time of 1 second, then ‘Increase Transmission Priority’ may be processed by the encoder. A simplistic implementation of this method induces a significant increase in the CPU utilization of the (on-or-off camera) encoder, because of the additional image processing required. Techniques exist to lower the burden and/or combine it with other processes, such as the motion estimation step of H.264 encoding (reference [3]).

The logic used for priority determination may be based upon the number of discrete tracked items as well as the size and/or speed of these items. Each of these values may be uniquely weighted; the exact weights must be determined on a per-mission and/or per-camera basis. Therefore any common encoder or processor must support the entry of unique and discrete values targets and algorithms.

The weights of different parameters will be vastly different for interior and exterior cameras. For example, the sudden presence of a large cluster of small, quickly moving objects may be a cause for extreme alarm on an external camera, whereas the same event seen on an interior camera of a manned vehicle may be indicative of a spill near the camera.

While beyond the scope of this document, it may be helpful for developers and integrators to develop or adopt cameras with image-processing capability that could provide an ancillary capability to act as a sensor. The output of tracking algorithms may be used as input to automated Fault Detection, Isolation, and Recovery (FDIR) systems.

3.2 THE EMERGENCY SCENARIO

The ability of the Bundle Protocol to transport critical data, even over disrupted networks, is a special advantage in a scenario in which there is an emergency or malfunction that disrupts communications. Consider a scenario in which a major fault, or even an explosion, has disabled many surface (lunar or Mars) systems, but there are several surface DTN nodes storing bundles that include the last few video frames before the anomaly. As relay satellites pass overhead, there can be multiple routes to deliver those last few video frames or continued live anomaly video from those DTN nodes to mission control. The resulting imagery may be key evidence for an accident investigation to determine the cause of the event. Such a capability is enabled because of the disruption-tolerant, store-and-forward capabilities of the streaming service over the Bundle Protocol.

When utilizing DTN for emergency video, the specifics of video encoding should be considered. In catastrophic emergencies, the amount of telemetry will increase, while the available bandwidth will likely decrease. Changing the priority of specific frames of video is one way to increase the likelihood that video will get to the emergency teams. This priority increase can either be based upon their importance with regards to the decoding of the stream (such as I-Frames, provided that the codec utilizes them), or in specific time-ranges (immediately prior to and after the off-nominal or emergency event).

A particularly simple and secure way to immediately, comprehensively, and automatically revise the priority of a given subset of video frame bundles is to

– use the Bundle Protocol Extended Class of Service block (reference [4]) to attach a content-indicating ‘flow label’ to each bundle;

– add the ability for BP implementations to configure bundle-forwarding to associate priority levels with flow labels; and

– upon occurrence of a priority-altering event, simply revise the priority associated with the affected video flow.

3.3 LOW EARTH ORBIT

Low Earth Orbit (LEO) involves either direct transmission and reception to and from ground stations or the use of an orbiting satellite relay such as the Tracking Data Relay Satellite System (TDRSS). Latency is low enough to maintain real-time interactive communication. The Bundle Protocol still brings enormous advantages to automating the reassembly of transmissions that are disrupted, for example, by Acquisition Of Signal/Loss Of Signal (AOS/LOS) handovers, unplanned signal disruptions, or relaying and assembling data along different downlink paths. Because of these features DTN protocols should be utilized even though many of their advantages for communication over very long distances are not utilized. Unless stated otherwise, this subsection refers to mission elements that implement the Space User Node guidelines, subsection 5.2.3.4 of reference [12], *Space Communications Cross Support—Architecture Requirements Document*.

While it is likely there will always be multiple channels of video in a LEO mission, there may be priorities that will cause one or more channels to be more important to the immediate task and might need additional bandwidth; mission rules should dictate priorities. Typically, proximity operations/situational awareness and emergency medical will have the highest priority. Video surveillance systems that are triggered by events such as leaks or debris strikes would also have a high priority.

In some scenarios, video may be buffered and sent later if required to complete a sequence of events, such as a debris strike or subtle changes in exterior conditions of the spacecraft. During emergencies, such as crew egress, multiple-video-feed downlink would be critical to verify the location of each crew member. In such a case, video that had been considered low priority might become the highest priority with little or no warning.

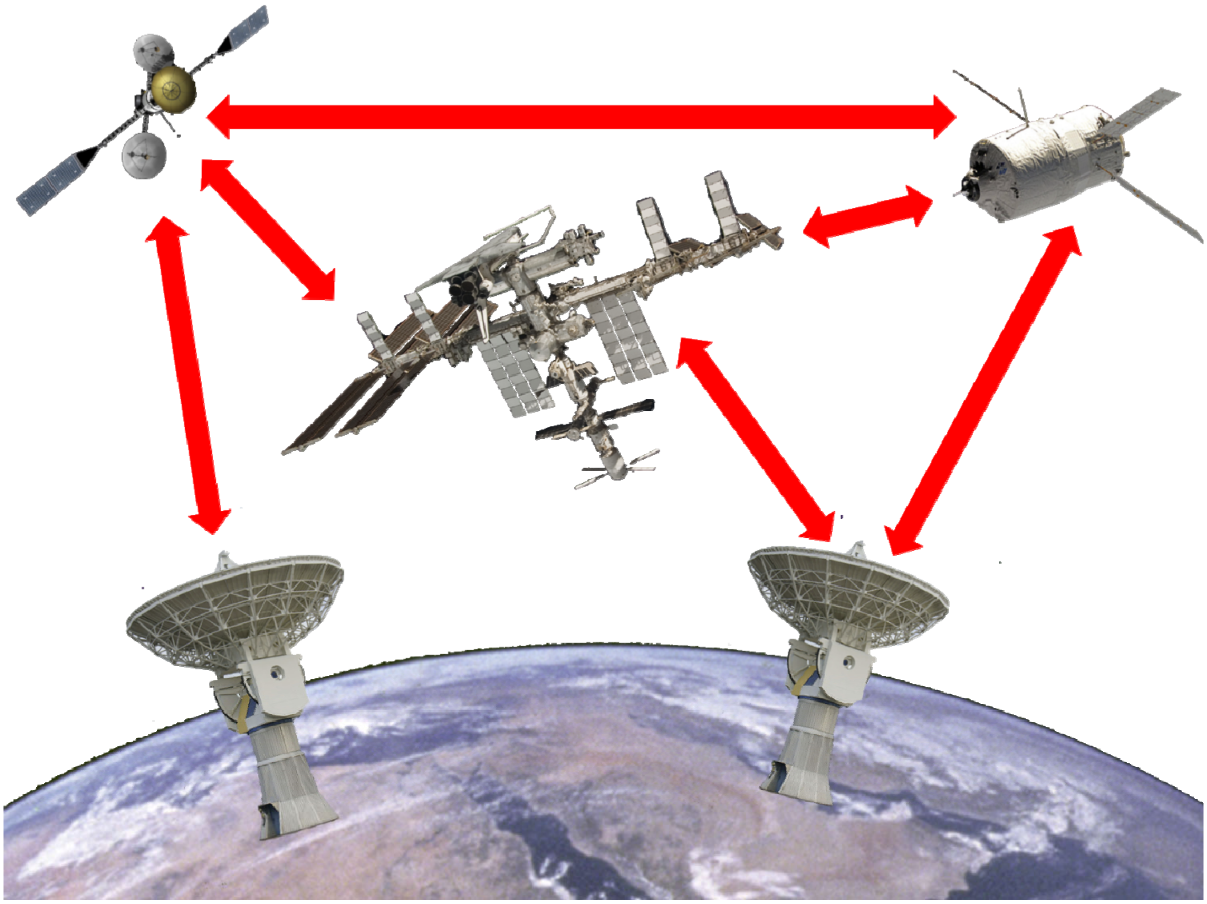

Figure 3-2: Configuration for Visiting Vehicles

A common scenario in which priorities may rapidly change because of the natural sequence of events is visiting-vehicle docking. Docking-related video may be generated by both the docking vehicle (e.g., Soyuz) and the vehicle providing the dock, such as the Space Station. In this case, both vehicles are SSI Space User Nodes, as outlined in figure 3-2. Many different parties are interested in the video acquired during docking video events, including the astronauts, vehicle support teams, and mission operation teams. In standard operations, video would be transmitted directly between the two vehicles involved in the docking operation, before being relayed to the ground. However, communication failures may occur resulting in the use of relay satellites or other intermediate nodes. The combination of multiple routes and multiple endpoints showcases the combined functional advantages of the Bundle Protocol and multicast, which is explained further in 5.4.

In some cases, ultra-high-resolution or high-framerate cameras may be used. These cameras typically do not output their video in any standard video format, but instead rely upon on-board file recording capabilities. The files produced may become many hundreds of gigabytes and may not be playable until the entirety of the file has been received. For these cases, a robust file-transfer method that can gracefully recover from AOS/LOS and multi-path relay events is required, and the use of CFDP-over-DTN is recommended. This technique is covered in 5.3.

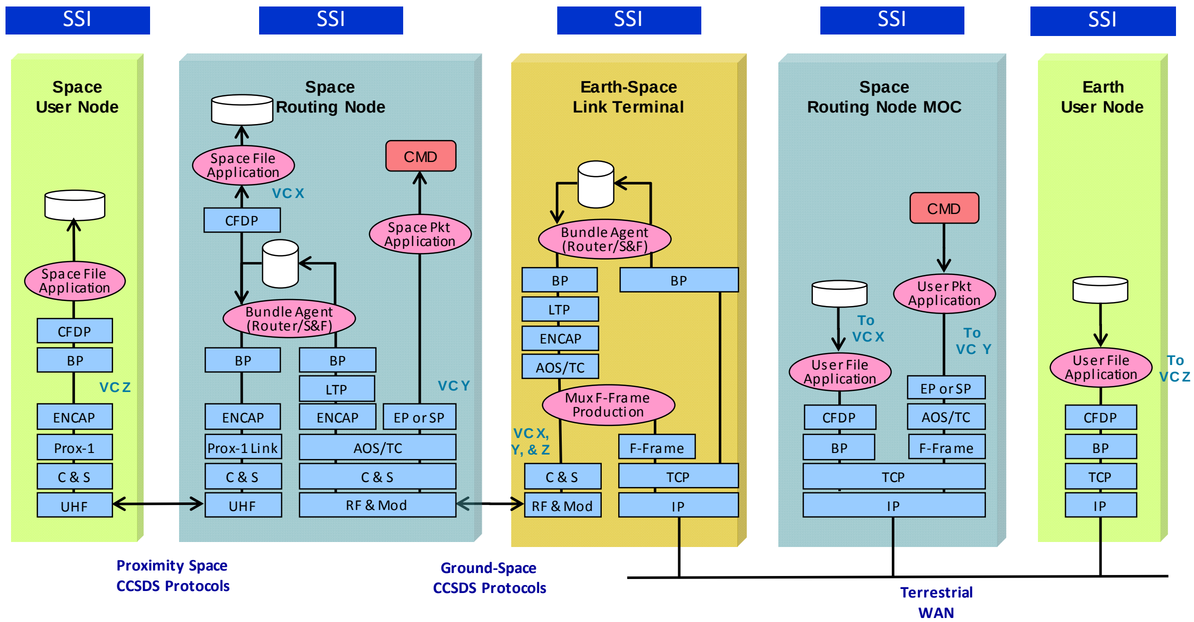

Figure 3-3: DTN Protocol Building Blocks[1]

Forward (ground-to-space) video may be requested for operational or crew-morale purposes, implementing the forward stack described in subsection 6.2.3 of reference [12], and shown in figure 3-3. Operational video, such as training procedures, may be transmitted via files and stored on-board until it is required, while crew-morale video may be sent via streams or files. Streaming video may be used for constant and low-priority video, such as television programming, while video messages from family, etc., may be sent as files and replayed when appropriate.

[1] From subsection 7.3.1 of reference [12].

3.4 CISLUNAR

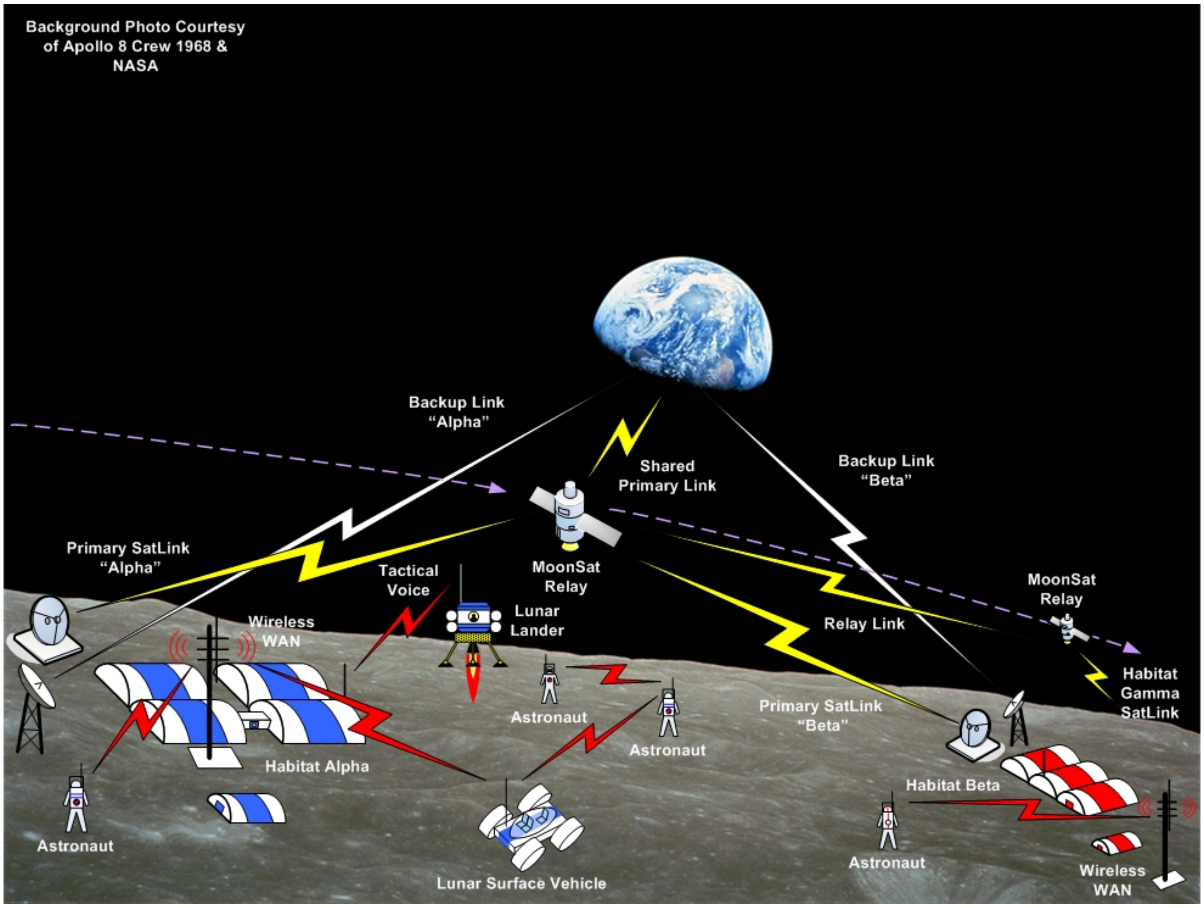

Figure 3-4: Representative Depiction of Potential Communications Links Needed for Lunar Surface Operations

Cislunar operations should, for the most part, fall under the category of interactive video. Round-trip-communications latency of 2.5 seconds, on average, falls within the latency constraints for ground controllers to use video for active control of mission events, therefore freeing the astronaut to perform hands-on tasks that cannot be performed from the ground. Certain cislunar operations, such as a lunar orbiting mission with very a high apogee from the moon, might stretch the limits of interactive video usage. It is expected there will be many more video sources, as well as much longer loss-of-signal periods, so all DTN-aware relay nodes must have additional storage in order to cope with this. Unless stated otherwise, this subsection refers to mission elements that implement the Space User Node guidelines from subsection 5.2.3.4 of reference [12].

As one-way transmission delays increase, the importance of scheduled routing increases. Some routing methods for DTN are dependent upon the usage of beacon packets or neighbor discovery. These methods are suboptimal for DTN networks, which are negatively affected by long delays between proximate nodes, as the period between the transmission of the beacon or neighbor discovery packet and its reception by the spacecraft will cause a loss of valuable space-to-ground utilization time. This leads to a desire for schedulable routing algorithms, such as Schedule-Aware Bundle Routing (SABR). These routing algorithms allow a node to begin transmission based upon a predefined schedule. This schedule also provides hints to nodes that may not have direct access to the space-to-ground link. These nodes may refer to this schedule in order to determine the optimal proximate node for transmission to the ultimate bundle destination.

At the same time, opportunistic discovery of available nodes that can support communications may also be of great value, especially if the nodes are all using DTN along with common discovery and hailing mechanisms, but are not all under the control of a single management entity. Bundle Protocol routing is still an active topic of research, and, by the time a DTN-reliant mission is developed, opportunistic discovery of contacts may be a mature feature of the architecture.

It is essential that the mission designer take these considerations into account in the development of the network, in order to maximize the total throughput.

An additional use-case scenario for a spacecraft in cislunar orbit will likely be extended monitoring with the spacecraft uninhabited. One mission profile would be to have a larger spacecraft in cislunar orbit that serves as a waypoint for surface missions. It would not need to be crewed continuously. Video would be a valuable tool for ground controllers to monitor the spacecraft between crewed periods. This would also be true of prepositioned assets on the surface prior to manned operations. For this usage, the automated priority determination described in 3.1.2 may be of interest.

The use-case scenarios listed in 3.1.1 are all valid for cislunar orbital operations. However, if lunar landing is involved, there will be additional use cases, such as

a) lander spacecraft video feeds from descent, from the surface, and during ascent;

b) surface EVA from the astronaut/cosmonaut perspective as well as fixed deployed cameras and rover cameras; and/or

c) prepositioning of surface assets prior to human inhabitation.

There will likely be multiple communication paths for imagery, depending upon what imagery is in use. The lander spacecraft should have communication to the orbiting spacecraft, orbiting relay satellites, and slower direct links to Earth for backup and emergency communications, functionally acting as an SSI planet node, as described in subsection 5.3.3.3 of reference [12]. The fixed EVA cameras may be hardwired to the lander, but may use wireless communications to the other nodes in the network, subject to mission requirements. The EVA suit cameras will certainly need wireless communication links to the lander spacecraft as well as any rover that might be used. The rover will require communications to the lander, orbiting spacecraft, and Earth. There will also be a need for multiple simultaneous video transmissions from any surface operations. Details relating to the implementation of wireless networks for space applications can be found in *Wireless Network Communications Overview for Space Mission Operations* (reference [5]), produced by the Spacecraft Onboard Interface Services (SOIS) Onboard Wireless Working Group.

Much more than in LEO operations, differing communication paths will provide for an extremely wide range of possible throughputs. The correct usage of priorities and time-to-live values must be decided based on mission requirements and operational constraints.

The multitude of communication links and endpoints will also lead to the widespread usage of bundle multicast, as described in 5.4. For example, EVA cameras may be of interest to the astronauts in the habitat, as well as the mission control teams. It may be that no single point may simultaneously be in communication with all interested parties. Delay-tolerant bundle multicast is uniquely able to sustain such non-concurrent multicast transmission.

It is assumed there will be forward and return video links to any spacecraft in cislunar orbit, as those are expected to be longer-duration missions. For extended surface operations missions, it will be a requirement as well. The surface operations habitat for that type of mission requires a full communication suite, effectively being a spacecraft on the ground.

As also described in 3.3, proximity operations and situational awareness video will likely have highest priority. During complex phases of missions involving lunar landers, rovers, and EVA crew, it is likely the amount of video streams will exceed the downlink capacity of available bandwidth to Earth stations. In these cases, video may need to be buffered and sent sequentially based on predetermined prioritization. Crew in an orbiter may need to monitor in real time video that is not downlinked to Earth, or video that will be downlinked later. Therefore for nearby spacecraft it may be necessary to have a prioritization scheme that is different from that used for downlinks to ground stations. Again, applying prioritization indirectly by flow labeling and router configuration will help make such scenarios manageable and secure.

Cislunar scenarios will be similar to LEO (3.3) for emergency scenarios and for large files from high-resolution cameras.

3.5 MARS CAMPAIGN

A Mars campaign with surface operations will be a virtually identical situation to a cislunar mission with surface operations. The same variety of communication between orbiting spacecraft, satellite relays, surface habitats, EVA suits, and rovers will be required. However, Earth ground controllers will not be able to work interactively using video, putting Mission Control in a monitor mode as far as downlinked video is concerned. After only a few days of flight, one-way transmission time will reach 5 seconds, rendering interactive use of video essentially useless for the mission. Transmission time, on average, from Mars is 11.65 minutes, one way. It can be as high as 20.76 minutes and, in certain years in which Mars and Earth are the closest, as low as 3.25 minutes. This puts the burden upon the crew or automated systems to make immediate decisions without the help of Earth-bound mission controllers. Unless stated otherwise, this subsection refers to mission elements that implement the Space User Node guidelines from subsection 5.2.3.4 of reference [12].

For Mars missions, link disruptions will be more frequent and more severe, putting strain on the Bundle Protocol while using all the capabilities of BP within DTN to ensure successful data delivery to Earth and other, proximate assets. There will be links from orbiting spacecraft and ground operations. Even with 100-percent coverage between surface operations to orbiting spacecraft, there will still be significant LOS time periods when Earth and Mars are in opposition to each other around the sun. To overcome this would require a DTN node located in a position to allow both the Earth and Mars to ‘see’ the spacecraft at all times, no matter the relative positions of Earth, Mars, and the Sun. The exact positioning and number of such satellites is beyond the scope of this document, a subject of separate studies, and dependent upon agency and mission requirements. It should be noted that DTN can address such LOS outages automatically, retaining data in suitably sized buffers while waiting for the orbiting relay assets and planets’ orbital motion to eventually restore a data path.

A Mars campaign will also likely pre-position supplies on the surface for the crews. This will happen before the crewed flights leave for Mars. Video capability from the surface would start with the landing of these components, necessary to insure a safe environment for the crew before its arrival.

Forward video will also be an important factor as these missions must be greater than two years in duration because of the realities of orbital mechanics. While bandwidth concerns are certainly more of a factor because of distance, a multiple-channel video system is envisioned for Mars campaigns as well. Video streaming as well as file transfer will be employed. It will be necessary to get some video scenes from Mars sent to Earth in a real-time mode in order to get the earliest confirmation of certain events. However, much of the video from a Mars campaign can be treated as file transfers, as it is not time critical. Regardless of the transmission mechanism, it should be expected that much of this data will be used as soon as it is received, in part or full.

4 OPERATIONAL CONSIDERATIONS

Regardless of the mission profile, a number of operational considerations for video streaming services should be kept in mind.

Certain spacecraft-to-spacecraft video will also need to be downlinked for proximity operations/situational awareness. This will require cross-links between spacecraft and likely additional relay or DTE links to the ground.

Spacecraft communications systems will need a data store-and-forward capability to store video for downlink while the spacecraft is in a LOS situation. When the spacecraft cannot communicate directly to a ground station, it will require on-board recording and storage of video that cannot be transmitted. When communication is restored, those files can be downlinked via CFDP. For files transmitted via CFDP, there are no special considerations beyond those required for any other data file transfer. In order to deal with high-data-rate video streams, the capacities of DTN data management that support store and forward operations must be adequately sized.

However, during live streaming of video or playback in real time as though it were live, mission designers must carefully consider the amount of storage available to all DTN nodes on the path. For live streaming, it is generally anticipated the video encoder will not buffer the data beyond what is required for MPEG stream construction. However, if video is played back in a streamed fashion, the mission designers must be acutely aware of the potential for data duplication between the video file and DTN buffer.

Individual DTN implementations have implementation-specific mechanisms to prevent duplication; the designers and engineers need to ensure that they are aware of these mechanisms and utilize them when appropriate. These problems are not unique to video and/or streaming media applications; they apply to all DTN-enabled relay nodes that may transfer files. An on-board video implementation must not attempt to pause streaming during LOS periods, as it cannot be expected that the proximate DTN node has an accurate overview of AOS/LOS periods.

In the case that a spacecraft possesses multiple data pathways (such as S and Ku bands, or Ku and optical) with differing throughputs and error rates (see reference [6]), the lower-throughput pathway may be utilized for file transfer via CFDP, leaving the higher-throughput pathway for real-time video. This increases the maximum possible video bitrate (and resolution), allowing for higher-quality video transmission. If a certain real-time video stream is mission critical, the more reliable pathway needs to be used, provided that the end-to-end throughput of the link is more than that of the video.

For LEO missions, receiving video at multiple MOCs may be required to enhance mission functions, or for easier routing. Regardless, communications links between ground facilities are needed to distribute video to all participating agencies.

Under the assumption that there will always be a requirement for obtaining imagery in higher resolutions than will be transmitted in real time, video systems will need access to a file transfer system in order to get that imagery to the ground. A current analog is the use of the Digital Cinema Camera or high-resolution imagery from UrtheCast (reference [7]). These systems generate file sizes that are not conducive to real-time downlink. They are recorded and then downlinked as file transfers with CFDP providing the complete, in-order, delivery.

Many of the streaming video techniques specified here rely upon or are enhanced by the modification of priority levels for different activities. Therefore the video system should allow for a change of priority levels from an external interface or telecommand. This may be implemented directly upon a DTN-aware video encoder, or upon an encapsulation system farther in the avionics pipeline. Again, indirectly revising bundle priorities by revising the priorities associated with video flow labels in forwarding nodes may be more effective than attempting to revise individual bundles' embedded priorities directly.

If real-time decoding is desired, a video encoding bitrate that is less than the worst-case end-to-end throughput needs to be selected. While the Bundle Protocol and Licklider Transmission Protocol (LTP—reference [11]; see also figure 3-3), if operated with red parts, are tolerant of high bit error rates, the loss and subsequent retransmission of bundles or LTP segments may cause out-of-order arrival data. Therefore a video system must be prepared for the arrival of such data. The simplest mitigation for out-of-order arrival is the use of large decoding buffers, which may be tuned to be at least three times the One Way Light Time (OWLT) of the end-to-end link, in order to provide padding for the additional delay of retransmission. This simple mechanism is not robust; more elaborate networks will have to use robust buffer-resizing mechanisms. Alternatively, the relevant buffers may be calculated by the mission designer. However, the calculation methodology for buffer sizing is beyond the scope of this document. For example, it may be necessary to factor the buffer size based upon the upper end of the historical end-to-end delay.

When using file-based cameras and CFDP downlink, a repository needs to be provided for camera data in a location that has sufficient storage and is available for a CFDP agent. Best practices for the usage of CFDP are beyond the scope of this document.

For medical or otherwise confidential video, the BP Security Protocol (BPSP) needs to be utilized.[2]

Based on the use-case scenarios listed, the following are considerations for video transmission over space-based internet services:

a) A disruptive networking situation for a deep-space mission will require DTN.

b) The network will be based on Bundle Protocol (reference [4]).

c) SABR and opportunistic routing will be required for use of DTN during cislunar and Mars missions.

d) Schemes to determine the relative priority of video will have to be developed.

e) Priority mapping must be able to be changed in real time.

[2] At the publication time of this document, the Recommended Standard outlining SBSP has not been finalized.

f) Encryption/private communication capability needs to be validated to meet agency and user requirements.

g) Multicast communication will be needed, utilizing some sort of bundle-based multicast mechanism, such as CBHE-Compatible Bundle Multicast (see reference [10]), as outlined in 5.4.

h) If the same video data is available from multiple paths, a capability is required for proper ordering and de-duplication video data.

i) The video system must be able to handle variations in latency and/or throughput in the same video data stream.

j) All of the DTN BPA nodes must be adequately sized to handle the impact of latency, OWLT delays, and LOS events.

5 METHODS FOR TRANSMISSION OF VIDEO OVER THE BUNDLE PROTOCOL

5.1 BUNDLE STREAMING SERVICE

5.1.1 GENERAL

Bundle Streaming Service (BSS—see reference [8]) and Bundle Streaming Service Protocol (see reference [8]) are proposed mechanisms for reliable transmission and acquisition of streaming video data over delayed and/or disrupted links. While these mechanisms remain experimental and are not yet documented in formal specifications, the concepts they realize seem potentially useful. The two components are the BSS Database Library (5.1.2) and the BSS Protocol (5.1.3).

BSS is not a video service per se: unlike the Deutsches Zentrum für Luft- und Raumfahrt (DLR) technologies for video over DTN, discussed later in 5.2, it is not specifically tuned for video transmission. By the same token, it is not limited to video transmission: the general character of BSS data delivery can be applied to one-way voice transmission, to 'real-time' telemetry, or to any other continuous data stream that can be transported by bundles. Good video display quality will always require application-layer data conditioning such as is performed by transparent gateways (as discussed later) and direct H.264 systems. BSS, in contrast, focuses on transport resilience and buffer management.

5.1.2 BSS DATABASE LIBRARY

At the receiver of the streamed transmission, the BSS database library is integrated into a user-defined Bundle Protocol application that acquires bundle payloads, Application Data Units (ADUs) such as video frames, intended for a designated BP endpoint. The acquired ADUs can be in any format that is meaningful to the application, as their content is opaque to the BSS library. The sender of those ADUs can be any application.

The receiving application in the endpoint node delegates to the BSS library the job of receiving these ADUs upon delivery from the Bundle Protocol Agent (BPA). The BSS library function inspects the bundle creation times of the bundles that transported the delivered ADUs and dispatches the application data in one of two ways:

– If the bundle creation time of the ADU's carrier bundle is greater than that of any previously received ADU from the same sender, then the content of the ADU is deemed 'in order' and is passed to a 'real-time' presentation function that must be provided by the application. The ADU content is also written to a database designed for very-high-speed access, for future replay.

– Otherwise, the ADU content is deemed to have been delayed in transmission, possibly because it had to be retransmitted. Since it has arrived out of order, it must not be passed to the application's real-time presentation function; if the data were video frames, for example, to do so would scramble the video display. Instead, the ADU content is only written to the database. ADU content in the database is ordered by transmission time, so over the course of the transmission, the in-order and out-of-order data are merged in time sequence into a single uninterrupted stream, so that a higher-quality display of previously presented data can be viewed in replay.

5.1.3 BSS PROTOCOL

The other component of the Bundle Streaming Service is the Bundle Streaming Service Protocol (BSSP), an experimental BP 'convergence layer' protocol. While no formal specification of BSSP exists yet, an informal description of the protocol is provided here for informational purposes.

Like all convergence layer protocols, BSSP manages the transmission of bundles directly from one BP node to some other, network-accessible, BP node. To do so, it operates two concurrent transmission channels, one unreliable, the other reliable. The implementations of these channels are opaque to BSSP and are established by node configuration: one BSSP engine might use UDP/IP for the unreliable channel and TCP/IP for the reliable channel, while another might use LTP 'green' transmission for the unreliable channel and LTP 'red' transmission for the reliable channel. These underlying channels are analogous to the 'link service' protocols underlying LTP. Just as the LTP protocol engine transmits data using an underlying link service and performs specific timing and data accounting procedures to recover from failures in that link service protocol, so does the BSSP engine transmit data using two underlying transmission channels and perform specific timing and data accounting procedures to recover from failures in those channels.

When a bundle is presented to BSSP for transmission, the protocol inspects the bundle's creation time and dispatches the application data in one of two ways:

– If the bundle creation time is greater than that of any previously presented bundle from the same sender, with the same destination, then the bundle is transmitted using the unreliable channel. That is, data presented in order is forwarded in order over the unreliable channel, to minimize end-to-end delivery latency.

– Otherwise, since the bundle has been determined to be out-of-order, the bundle is transmitted over the reliable channel in which it is subject to automatic retransmission upon detection of data loss. It will arrive somewhat later than the in-order data, but its eventual end-to-end delivery is virtually assured.

Upon reception of a bundle sent on the reliable channel, the receiving BSSP engine simply passes the bundle up to the BPA for delivery or further forwarding.

Upon reception of a bundle sent on the unreliable channel, the receiving BSSP engine passes the bundle up to the BPA in the same way, but it also sends an acknowledgment back to the sending BSSP engine.

When the sending BSSP engine receives a BSSP acknowledgment for some forwarded bundle, its transmission of that bundle is deemed complete. But if no such acknowledgment is received prior to expiration of a per-bundle timer that was set at the moment of transmission on the unreliable channel, then transmission on the unreliable channel is deemed to have failed. At that point, the bundle is re-dispatched on the reliable channel exactly as if its creation time had been out of order when originally presented.

5.1.4 SOME NOTES ON BSS

The two components of BSS (database library and protocol) are complementary, but neither is reliant on the other; each can be used by itself if that is desirable in a given deployment configuration.

A key advantage of the BSSP design is that, because it operates at the convergence layer underneath BP, it can support bundle multicast. Bundle multicast functions by sending copies of a given bundle to multiple topological neighbors; each such copy is conveyed separately by the applicable convergence-layer protocol, and any retransmission that is required in the course of that conveyance is managed privately by that convergence layer adapter without any impact on transmission to any other neighbor. BSSP enables streaming application data presented to BP to be efficiently forwarded to an unlimited number of final-destination applications with minimal end-to-end latency in a virtually error-free manner.

5.2 ENCODING AND ENCAPSULATION OF VIDEO VIA DTN

5.2.1 GENERAL

DLR has developed two systems for video transmission via DTN networks. The first is a transparent gateway that aims to provide a simple transport for UDP-based media protocols that are inherently unusable over high-latency/high-jitter networks (including the lunar and deep-space communication environments), and is agnostic to the protocol running above it. The second is a more advanced encoder that integrates directly with an H.264 video encoder and decoder and is designed to function natively with DTN.

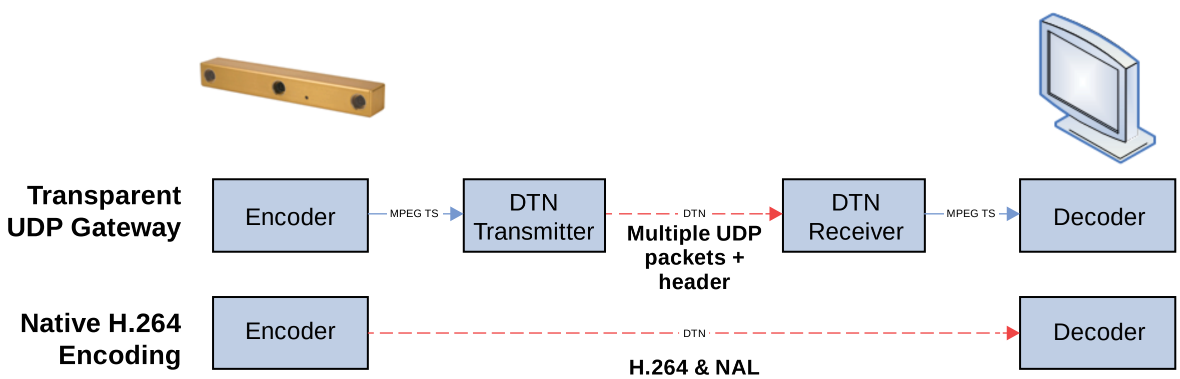

Figure 5-1: Implementation Overview

5.2.2 TRANSPARENT GATEWAY

The transparent gateway is a set of applications that encapsulate/de-encapsulate UDP data into DTN bundles while maintaining the timing information that is important to video transmission. This technique is primarily used for MPEG Transport Streams. The gateway will ingest a user-configurable number of UDP packets directed toward it and add additional metadata, comprising a size and a nanosecond-resolution timestamp, generated as a delta between UDP packet reception at the gateway. Once the given number of packets have been received, they are serialized. A header containing a count of packets and a sequence number is prefixed to the serialized data. The gateway can be utilized as a drop-in replacement for existing Data Link Layer protocols, as shown in figure 5-1. Other multimedia protocols such as Real-time Transport Protocol (RTP) have been successfully tested with the gateway.

The gateway implementation was complicated by the interleaving inherent in Moving Pictures Experts Group Transport Stream (MPEG TS) data, as well as the 4-bit MPEG TS sequence counter. The 4-bit counter overruns quickly, and will not typically (at higher bitrates) lend itself to the resequencing of data, even when that data is occurring within the same one-second DTN timestamp. The gateway receiver aims to prevent this by utilizing the sequence number to reorder packets before outputting them at a rate based upon the reception delta value, located in the header. By tuning the input buffer size, a user can reduce the visual impact of out-of-order packets. The structure of a gateway-generated bundle is shown in figure 5-2.

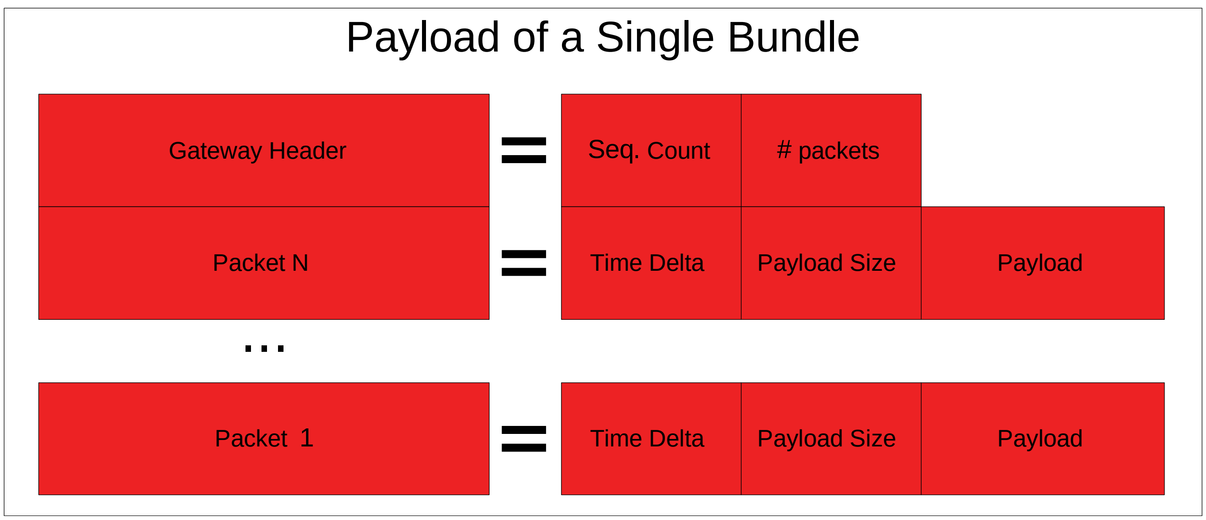

Figure 5-2: Payload of a Bundle from a Transparent Gateway

5.2.3 DIRECT H.264 TRANSMISSION

In the process of testing the transparent gateway, it was quickly discovered that DTN provides a greater advantage and requires less overhead when utilized with larger bundles, hence the addition of the ability to aggregate multiple UDP packets described above. It was also noticed that there is functional redundancy between MPEG TS and the Bundle Protocol (alongside associated protocols); MPEG TS specifies a packetizer and container for temporally redundant media data, such as audio and video, as well as providing forward error coding. The Bundle Protocol specifies a container, while lower-level protocols such as LTP provide reliable transport. It was decided to remove the redundancy of the MPEG TS in the hopes of reducing end-to-end bitrate and providing a protocol that is compatible with DTN best practices.

The direct H.264 DTN encoder does not attempt to interleave data, instead relying on the underlying DTN stack to perform that task. Instead, the encoder outputs individual compressed frames as single bundles. Minimal metadata is added in Concise Binary Object Representation (CBOR) format and is largely composed of width, height, and frame-rate, all of which are requirements for the initialization of the H.264 decoder. Frames are encoded in the packet-oriented H.264 Network Abstraction Layer (NAL) format. The decoder simply initializes a decoder and decodes the data provided in the bundles before finally displaying them.

The native H.264 transmitter is extremely robust to interruption and packet loss. As LTP Red provides retransmission and fragmentation capability and will not present a bundle to the Bundle Protocol implementation before transmission has completed successfully, each bundle can be assumed to be intact. As such, each frame can be assumed to be intact as well. The order of packets is maintained via the timestamp from within the Bundle Protocol as well as a per-second count of frames. Any packet that contains a timestamp less than the current ‘running’ timestamp is assumed to have arrived out-of-order and is archived. Once the one-second frame count is equal to the framerate from the metadata, the video for that second is assumed to be 100-percent retrieved. The disadvantage of this system is the uniqueness of its implementation. The encoder and decoder are built using the FFmpeg libraries but are otherwise self-contained. It is technically possible to integrate it with other IP-based encoders and decoders by creating a new and functionally identical MPEG TS output. It must be noted that the encoder must use a codec that supports frame-based output, such as H.264, motion JPEG2000, or H.265. CCSDS 706.1-G-2, *Motion Imagery and Applications* (Green Book, Issue 2, May 2015) and CCSDS 766.1-B-2, *Digital Motion Imagery* (Blue Book, Issue 2, August 2016) should be consulted for further information on various video codecs.

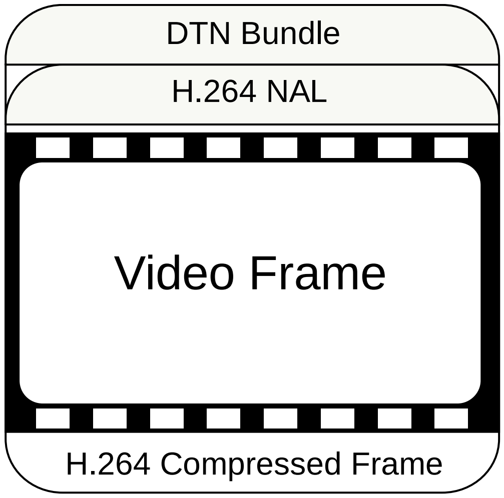

Figure 5-3: Single Video Frame As Generated by Encoder

5.2.4 DTN VIDEO APPLICATION DEMONSTRATOR USING EPIDEMIC ROUTING (D-VADER)

As an alternative to the direct H.264 transmission system, a second experimental implementation of H.264 functionality was developed. This second implementation utilized two different implementations of Bundle Protocol—one, named ‘ION’, developed by NASA, and a second, named ‘IBR-DTN’, developed by Technische Universität Braunschweig—together with an Android smart phone (as the video source) and the same video decoder application that was employed in the direct H.264 demonstration.

The D-VADER application is written in Java and uses the H.264 encoder available in the Android operating system directly to generate compressed frames of video from the on-board camera of the phone. This data was formatted following the conventions mentioned in 5.2.3, and sent via 802.11n using the TCP convergence layer of IBR-DTN to another IBR node, located on a laptop. The IBR instance situated on the laptop relayed the video-bundles to an ION node, which ran the same application as utilized for direct H.264 transmission. Figure 5-3 provides an overview of the D-VADER system.

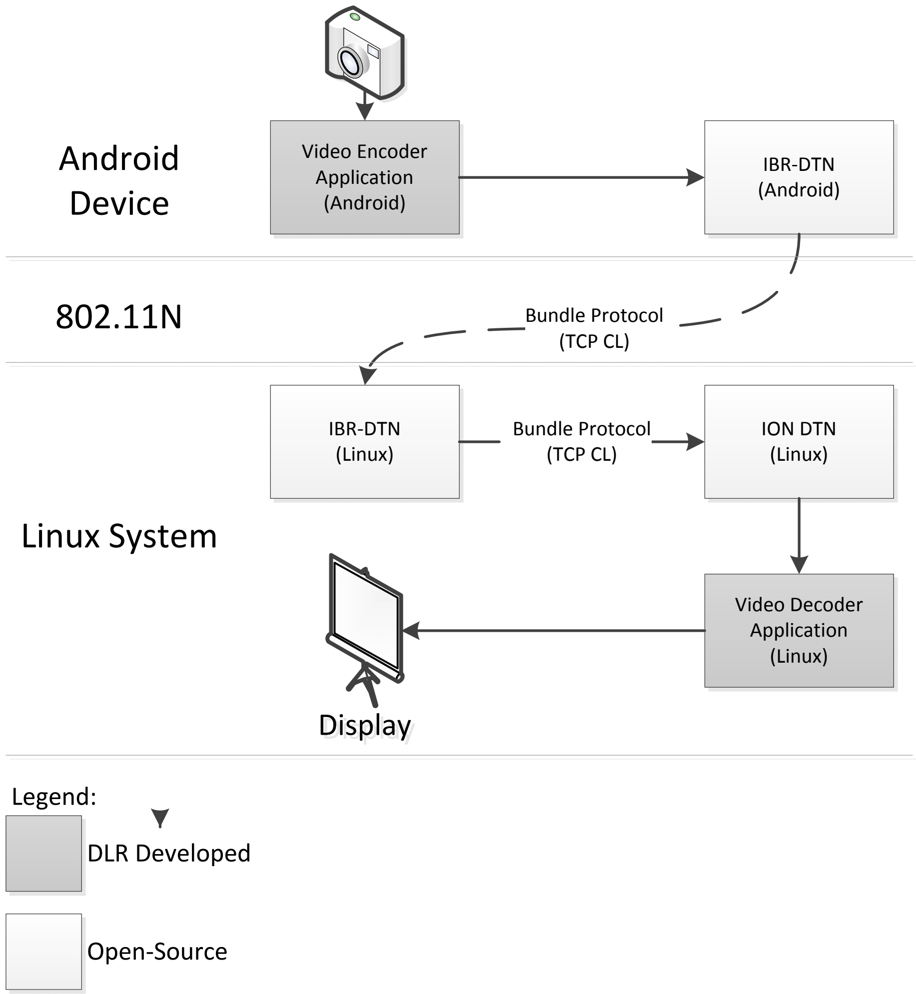

Figure 5-4: Overview of D-VADER Architecture

There were several major differences between this test and other video-over-DTN tests that have been conducted, the largest of which being the usage of dynamic neighbor discovery and routing. The Android application was seen to be a surrogate for a mobile camera (such as an EVA helmet camera). The inherent unpredictability of communication links for such a camera created a requirement to avoid the use of static routing. Instead, the IP Neighbor Discovery (IPND) protocol (reference [13]) was used to allow the Android device to determine its available neighbors for forwarding. The Android node did not possess knowledge of an end-to-end route toward the final ION node, so it attempted to forward via the neighbor of which it did have knowledge. IPND is implicitly designed for IP-based networks; future work may be required in order to create a neighbor-discovery protocol that is applicable to Proximity-1 and/or other CCSDS links.

5.3 CFDP-OVER-DTN

While the primary focus of this Informational Report is real-time streaming video applications, the use of files as a transfer medium cannot be ignored. For these applications, the use of the CCSDS File Delivery Protocol (CFDP) over DTN should be investigated. CFDP, specified in CCSDS standard 727.0-B-4 (reference [9]), provides a reliable, complete, bidirectional file transfer system designed for spacecraft applications. CFDP may run over space data link protocols (such as CCSDS Advanced Orbiting Systems [AOS]) as well as the Bundle Protocol, but in the context of this book, exclusive focus is on the Bundle Protocol transport.

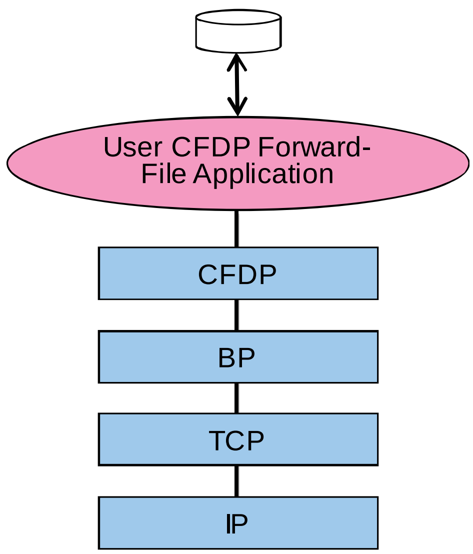

Figure 5-5: CFDP Protocol Stack[3]

5.4 MULTICAST VIDEO TRANSMISSION VIA BUNDLE PROTOCOL

The ION BP implementation provides facilities for Interplanetary MultiCast (IMC) via the 'CBHE-Compatible Bundle Multicast' mechanism, defined in the Internet Draft burleigh-dtnrg-imc-00 (reference [10]). This document specifies methods that allow for reliable BP-based multicast over bundles encoded with Compressed Bundle Header Encoding (CBHE). IMC works in conjunction with reliable convergence layer adapters (such as TCP on terrestrial links or LTP on space links) in order to provide a high order of reliability for multicast bundles.

In IMC, multicast networks are built as limited overlays on a spanning tree, which in turn overlays all nodes in a given IMC domain (DTN network). Each IMC-aware node that receives a multicast bundle must distribute it to all 'kin' (parent and all children, within the spanning tree) that are interested in that specific multicast. If the forwarding node is also interested in the specific multicast, it must also present the node to local applications.

[3] From subsection 6.2.3 of reference [12].

6 DEMONSTRATION SCENARIOS FOR FUTURE STUDY

6.1 TESTING TO DATE

Because of the complexity of video, the Bundle Protocol, and the interactions between the two, care must be taken to avoid unintentionally changing multiple variables that may affect the outcome of the tests. These may be parameters from within the DTN stack (such as the selection of CLAs, as well as the parameters required by each CLA) or those within the video transmission system (such as bitrate, I-frame interval, etc.).

DLR has performed tests that focused on both video-encoding parameters and transmission methods (specified in 5.2.2 and 5.2.3), while separately testing for DTN-related parameters. These tests used LTP or UDP as the convergence layer. Custody transfer would be used in parallel with either CLA. Initial testing found that the performance of the ION TCP convergence layer was unsuitable for video-related tasks. More recently, the DLR tests that utilized D-VADER (5.2.4) also used TCP as a CLA, and performed well at bitrates from 1–4 Mb/s. For video-related tests, Ericsson encoders (CE-XH 40) and decoders (RX-1290) were used. For other tests, as well as for the implementation of the native H.264-based solution, FFmpeg was used as an encoder and decoder, and VLC was used as a player for the transparent gateway. The native solution used includes a decoder and viewer, so the use of VLC was unnecessary. Some tests were performed using H.265 using x265 and MP4box. It was noted that the CPU requirements for H.265 compression were extremely high, so it was decided to perform further testing at a later date when encoding is more efficient.

In general, it was found that the native H.264 system provides higher video quality, although the integration between that system and the rest of a video pipeline is complex. The transparent gateway was simple to install and integrate, but was less robust to failure.

The native transmission system running over LTP with a 25-frame buffer (one second at PAL rates), with an 8 Mb/s encoding bitrate (chosen to match the ISS on-board encoding parameters) has been found to be resistant to extremely high bit error rates without visual degradation, provided that the system runs without the addition of delays. If the OWLT delay is short enough, it is possible for any LTP retransmissions to occur before the next frame is due to be displayed. If the delay is longer than one second, there may be some visual impact, but it will appear as dropped frames and eventually wind up in the archive. The time to archive can be shortened by using Bundle Streaming Service, though DLR has opted not to implement it. Higher error rates will cause the abortion of LTP sessions, resulting in significant losses of video with the visual impact increasing accordingly. Tuning of the I-frame interval may minimize the duration of this video loss.

The transparent gateway running over LTP with a two-second buffer has been shown to handle 8-Mb/s H.264 transport streams and allow for some packet loss with no visual degradation. Running with a smaller buffer demands a ‘perfect’ connection, in which even a small packet loss may cause a momentary disruption of audio or video.

6.2 PROOF OF CONCEPT DEMONSTRATIONS

6.2.1 GENERAL

Discussed in this section are three future demonstrations that will be performed to validate the concepts in section 5. These demonstrations will allow variables to be introduced to stress the network. The demonstrations will also provide valuable metrics of video quality in different BP configurations and network impairments.

In proof-of-concept testing for video, one of the main goals, besides determining if BP is applicable for video applications, will be to assess video quality of the transmitted video. A Picture Quality Analysis (PQA) system will be utilized. A PQA utilizes software developed to mimic the human vision model and measures video quality. It uses a measurement system referred to as Just Noticeable Difference (JND), originally developed by Sarnoff (RCA) Laboratories, and is an internationally accepted method of providing objective measurements of video quality based on human perception. It has been used for numerous benchmark comparisons and equipment comparisons in industry and by NASA.

The PQA used in this case is made by Tektronix Corporation. It works by comparing a reference video scene from its library to the same scene processed through whatever encoder/decoder systems and networks will make up the video transmission path. As encoded video quality video is different depending upon the complexity of the scene to be encoded, different scenes with varying amounts of spatial and temporal resolution are used. This presents scenes to the encoder that are easy to encode and scenes that will stress any encoder.

The PQA generates mean opinion scores, Picture Quality Ratings (PQRs) (equivalent to JND), and absolute comparisons of each pixel in a frame from the reference to the test video. The absolute measurement is called the Peak Signal-To-Noise Ratio (PSNR) of the scene. These are the most commonly used measures of video quality. When HDTV systems were being developed, PQR measurements were done by statistical analysis of scores generated by ‘golden eyes’ viewers. These people were quality reviewers specially trained to note the slightest impairments to a video image. The PQA performs the same function as the golden eyes but with complete objectivity and repeatability.

Three demonstrations are proposed to show the applicability of BSS to video transmission, described below.

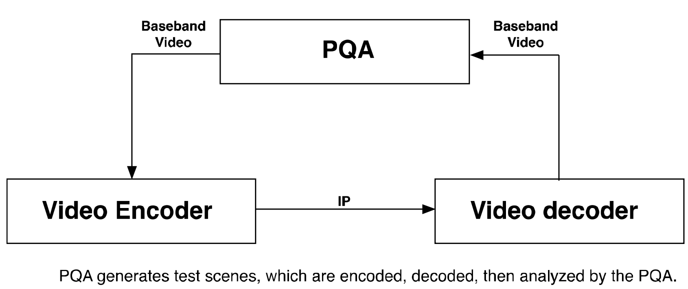

Figure 6-1: Benchmark Video Test

6.2.2 DEMONSTRATION 1

This demonstration will benchmark the encoder and decoder to be used for subsequent tests. The system will be set up with no network impairments. It will essentially be a direct connection from the H.264/H.265 encoder to the decoder, the configuration of which is shown in table 6-1. In the selection of the decoder, the implementer must ensure that it can decode the required formats and encapsulations. Otherwise, decoder configuration is automatically inferred from signaling information contained within the MPEG2 Transport Stream. Selected reference scenes will be run through the system and the decoded output used as test scenes for the PQA. More than one data rate for video will be utilized, with 4, 8, and 12 Mb/s suggested. The scores obtained from this demonstration will serve as the benchmark for comparison with all subsequent demonstrations.

Table 6-1: Encoder Configuration

Bitrate	Codec	Encapsulation	Notes
2 mbps	H.265	MPEG-TS over RTP	*Optional*
4 mbps	H.264	MPEG-TS	
8 mbps	H.264	MPEG-TS	
12 mbps	H.264	MPEG-TS	

6.2.3 DEMONSTRATION 2

This demonstration will use the same encoder, decoder, and video data rates as the first demonstration. A BSSP convergence layer will be utilized as the underlying CLA within DTN. The initial part of the demonstration will be to transmit video over BSS with the lowest latency and no network impairments. As in the first demonstration, the output of the decoder will serve to provide the test scenes for comparisons to the reference scenes using the PQA and provide a first set of scores to compare to the benchmark to determine if BSS inherently adds errors that impact video quality. From there, various network impairments will be added to determine their effect on video quality.

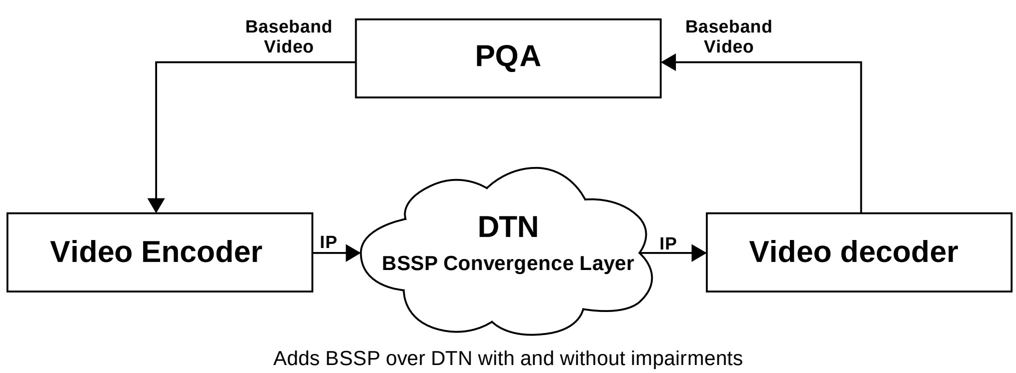

Figure 6-2: Video Utilizing BSSP

6.2.4 DEMONSTRATION 3

Demonstration 3 will utilize experience from DLR using Android operating-system devices working as DTN devices, using the direct H.264 transmission method outlined in 5.2.3. Again, the initial setup will provide the best network performance with subsequent setups adding various network impairments. As in the first two demonstrations, video scenes output from the decoder will be used for PQA testing. In this case, the video decoder application will provide a file of the transmitted video. In the previous two demonstrations, a standalone hardware decoder is used. This decoder is used in these cases because the video transmission is considered to be real time, and this would be a standard configuration for that scenario. The limitations of using current Android devices require an encoded file to be prepared for test transmissions and a file to be produced at the end of the process. Standard decoders do not accept files. The PQA, however, can accept an encoded file and decode it for analysis. While this is a change from the first two demonstrations, MPEG encoding is a standard, so the results will be the same as using a hardware decoder. The same video data rates will be utilized as with the other demonstrations.

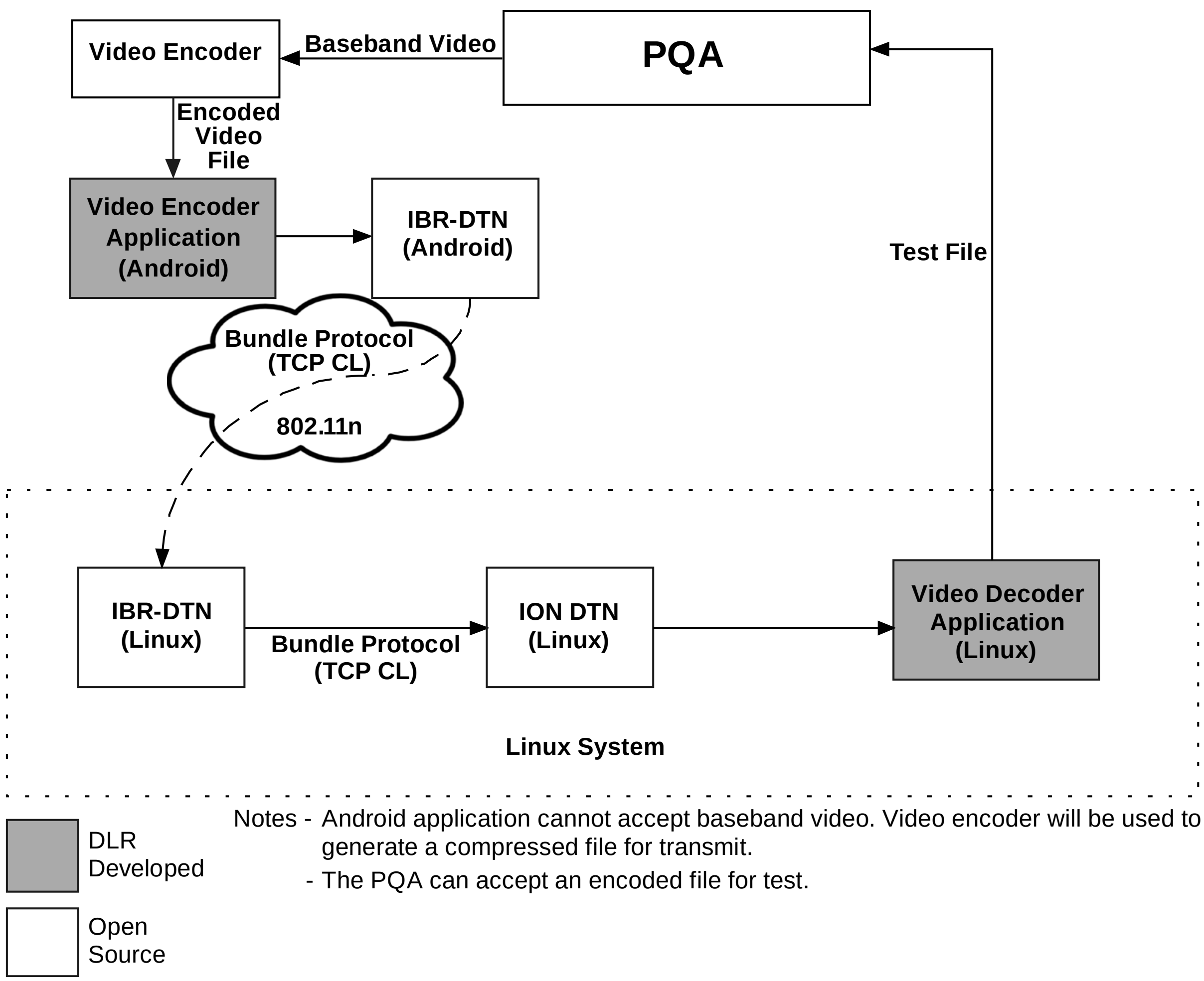

Figure 6-3: Android Devices Utilized for Video Transmission

6.2.5 INDUCED IMPAIRMENTS

No data network is perfect. There are a number of impairments that will be present in any configuration other than two devices directly connected to each other. As part of demonstrations 2 and 3, these impairments will be added until network performance is degraded to the point of real-time video transmission being unusable. Real-time video will be deemed unusable when the output of the decoder cannot be used to discern any significant information about the reference scene.

The most common network impairments are

– packet loss;

– excessive bit error rate;

– jitter; and

– packet misordering.

Adding these impairments one at a time will provide useful data as to what impairments affect video and to what degree as the impairments are worsened. However, all of these are present to some degree in virtually every network. As a test more representative of real-world scenarios, all of these impairments will be increased to the equivalent level of typical space-to-ground links, as a baseline. The parameters for the test will be taken from CCSDS 880.0-G-3, *Wireless Network Communications Overview for Space Mission Operations* (Green Book, Issue 3, May 2017), table G-1. The test scenes will be run again to determine if typical operating conditions add degradation to the video quality. Each of the impairments listed above will be increased one at a time until the video is unusable. Then all of these impairments will be increased together to determine at what point the cumulative effects of the impairments make the video unusable.

In addition to the impairments listed above, space-based networks are subject to disruptions in the signal path not common in ground-based networks as well as variable latency, and both of these factors will be added into the demonstrations as well. A variety of tools may be used to induce these impairments, such as WANem (reference [14]), an open-source WAN emulator. This tool allows the user to add various types of OSI Layer 3 impairments, such as delay, jitter, and/or packet loss, and is available as a Linux-based virtual machine image. WANem provides a Web interface, which allows the user to modify the network impairments in near real time, as can be seen in figure 6-4.

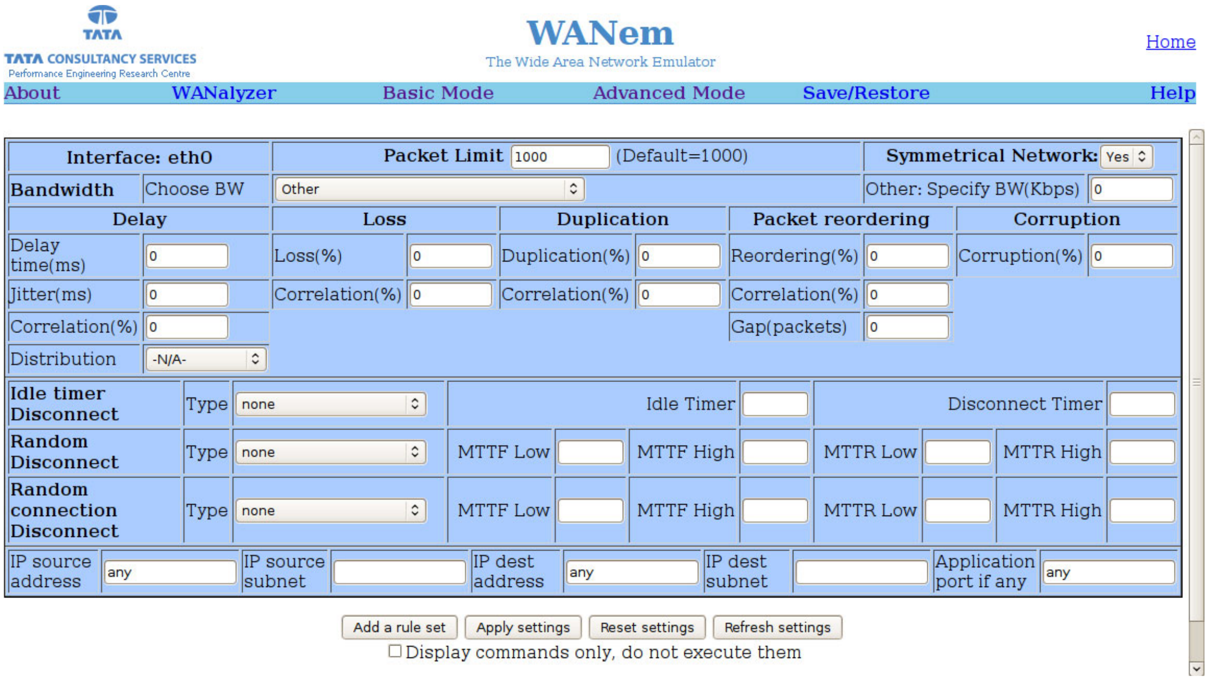

Figure 6-4: WANem Screenshot

More specific to DTN will be signal prioritization. Both demonstrations 2 and 3 will incorporate a prioritization scheme to determine the effect on video. Data sources for 2 will be utilized on the same DTN link. One source will be video data; the other source will be random data representing other mission data flow. This could be telemetry data or file transfer. One scenario will be for the video signal to have priority with the data rate of the second source raised until it is in contention with the video. If the prioritization scheme is set up properly, the second data source should stop adding bandwidth when it starts trying to use the bandwidth of the video signal. The video signal data rate should remain constant.

A second test will involve a constant bit rate for the video with the second data channel bursting data periodically. This would simulate potential conditions during an emergency.

ANNEX A

ABBREVIATIONS

Term	Meaning
ADU	application data unit
AOS	acquisition of signal; Advanced Orbiting Systems
bpSec	BP Security Protocol
BP	Bundle Protocol
BSS	Bundle Streaming Service
BSSP	Bundle Streaming Service Protocol
CBHE	Compressed Bundle Header Encoding
CBOR	concise binary object representation
CFDP	CCSDS File Delivery Protocol
CLA	convergence layer adapter
CPU	central processing unit
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTN	Delay/Disruption-Tolerant Networking
FDIR	fault detection, isolation, and recovery
HDTV	high definition television
IBR	Institut für Betriebssysteme und Rechnerverbund
IMC	Interplanetary Multicast
ION	Interplanetary Overlay Network
IP	Internet Protocol
ISS	International Space Station
JPEG	Joint Photographic Experts Group
LOS	loss of signal
LTP	Licklider Transmission Protocol
MMOD	micrometeoroid orbital debris
MOC	mission operations center
MPEG TS	MPEG Transport Stream
MPEG	Moving Pictures Experts Group
NAL	Network Abstraction Layer

Term	Meaning
OWLT	one way light time
PAL	Phase Alternating Line
PQA	picture quality analysis
PQR	picture quality ratings
PSNR	peak signal-to-noise ratio
RTP	Real-time Transport Protocol
SABR	Schedule-Aware Bundle Routing
SOIS	Spacecraft Onboard Interface Services
SSI	Solar System Internet
TDRSS	Tracking Data Relay Satellite System
UDP	User Datagram Protocol
VLC	VLC media player developed by the VideoLAN project