The Deep Impact Network Experiment Operations Center

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Abstract—Delay/Disruption Tolerant Networking (DTN) promises solutions in solving space communications challenges arising from disconnections as orbiters lose line-of-sight with landers, long propagation delays over interplanetary links, and other phenomena. DTN has been identified as the basis for the future NASA space communications network backbone, and international standardization is progressing through both the Consultative Committee for Space Data Systems (CCSDS) and the Internet Engineering Task Force (IETF). JPL has developed an implementation of the DTN architecture, called the Interplanetary Overlay Network (ION). ION is specifically implemented for space use, including design for use in a real-time operating system environment and high processing efficiency. In order to raise the Technology Readiness Level of ION, the first deep space flight demonstration of DTN is underway, using the Deep Impact (DI) spacecraft. Called the Deep Impact Network (DINET), operations are planned for Fall 2008. An essential component of the DINET project is the Experiment Operations Center (EOC), which will generate and receive the test communications traffic as well as “out-of-DTN band” command and control of the DTN experiment, store DTN flight test information in a database, provide display systems for monitoring DTN operations status and statistics (e.g., bundle throughput), and support query and analyses of the data collected. This paper describes the DINET EOC and its value in the DTN flight experiment and potential for further DTN testing. The DINET EOC houses ground nodes that produce and consume “payload” data that is relayed through the DTN router on board the DI spacecraft. The EOC also controls the topology among the nodes, dynamically altering the connectivity to test DTN functionality. An additional node in the EOC acts to perform administrative functions, and contains the Monitor and Control System to collect and analyze the data delivery status and statistics, essential for the developers to view experiments and perform post-analyses. The software diagnostic messages and protocol diagnostic messages issued by network nodes are collected, analyzed, stored into a database in real-time. The DINET EOC is located within the JPL Protocol Test Lab (PTL). The PTL provides connectivity to other NASA centers and external entities, and is itself a node in the larger DTN Experiment Network (DEN). The DINET EOC is envisioned to become a general tool in this broader context of experimental testing of DTN across a geographically dispersed user community.

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1. DELAY/DISRUPTION TOLERANT NETWORKING OVERVIEW

Delay/Disruption Tolerant Networking (DTN) addresses extreme and performance-challenged environments where continuous end-to-end connectivity cannot be assumed. Recognition and interest in DTN has shown a rapid rise, with diverse applications ranging among such areas as battlefield communications, habitat and environmental sensor network monitoring systems, and mobile consumers having intermittent connectivity with the Internet. For example, the June 2008 IEEE Journal of Selected Areas of Communications [1] was dedicated to the DTN topic. Space communications represents a key application domain for DTN, arising from disconnections as orbiters lose line-of-sight communications with landers, long propagation delays over interplanetary links, and other phenomena. International standardization is progressing through both the CCSDS Space Internetworking Services (SIS) DTN Working Group (draft SIS-DTN Green Book [2]) and IETF (e.g., RFC 4838, “Delay-Tolerant Networking Architecture” [3]). Additional reference materials on DTN may be found on the Delay-Tolerant Networking Research Group (DTNRG) wiki [4].

DTN has been recognized as the basis for the future NASA space communications network backbone. JPL has developed an implementation of the DTN architecture, called the Interplanetary Overlay Network (ION) [5]. ION is specifically implemented for space use, including design for use in a real-time operating system environment and high processing efficiency.

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Key to the DTN architecture is the Bundle Protocol (BP). The BP performs routing and forwarding functions. The BP specification is provided in RFC 5050 [6]. Another element of DTN stack is the Licklider Transmission Protocol (LTP), which provides automated retransmission of data that was lost or corrupted in transit between two BP nodes. The LTP specification is provided in RFC 5326 [7] (see also RFC 5325 LTP Motivation and RFC 5327 LTP Security Extensions). BP and LTP are implemented in ION.

2. DEEP IMPACT NETWORK (DINET) FLIGHT EXPERIMENT

NASA is working to raise the Technology Readiness Level of DTN so that it may be infused into space exploration missions and supporting ground and space-based relay infrastructure. Several elements are envisioned in the overarching program of advancing DTN’s readiness, such as experiments on the International Space Station. A critical development milestone is the first demonstration of DTN in a spacecraft flying in deep space. This experiment is underway, known as the Deep Impact NETwork (DINET) flight experiment.

DINET makes use of the Deep Impact (DI) spacecraft. The DI prime mission successfully took place on July 4, 2005, in which a probe was released and impacted the Tempel 1 comet, producing a crater and ejecting material that was imaged by the DI spacecraft. On July 3rd, 2007, NASA approved the Extrasolar Planet Observation and Deep Impact Extended Investigation (EPOXI) mission. EPOXI is a mission of opportunity that continues operation of the DI (flyby) spacecraft, with objectives to objectives are to 1) conduct observations of stars known to have planets to photometrically detect extrasolar planets and to 2) encounter the Comet Hartley 2.

In 2008, the EPOXI mission was expanded to incorporate DINET, a technology validation experiment of experiment of JPL’s implementation of Delay-Tolerant Networking protocols. DINET will take place during otherwise quiescent duration between the EPOCh (Extrasolar Planet Observation and Characterization) and DIXI (Deep Impact eXtended Investigation) phases of the EPOXI mission. DINET consists of uploading JPL’s ION flight software onto one of the DI spacecraft’s flight computers. In addition, ION software will be configured on several computers on the ground. A virtual topology will be constructed, with the DI spacecraft acting as a DTN bundle relay node, with data being passed among the other nodes. Deep Space Network (DSN) tracking/communications passes have been scheduled with the EPOXI mission to support this experiment. A number of specific DTN technology validation metrics have been levied as requirements on the DINET mission. DINET operations will be conducted in Fall of 2008.

Figure 1 depicts the basic layout of the virtual topology of the experiment. The central node is the Deep Impact spacecraft which serves as a bundle router to pass the payload data from one space region to another space region. The three end nodes

The central node is the DI spacecraft, which does not generate source data but acts as a DTN bundle router and also implements the LTP retransmission protocol in response to induced lost bundles. The three end nodes simulate space regions, Earth, Mars, and Phobos, and produce and consume the payload data. These nodes are all computers on the ground, also implementing the ION DTN software. The ground node computers are contained within the Experiment Operations Center (EOC), which will be described in greater detail in the next section. The links (dashed lines) are intermittent depending on schedule.

Figure 1 – DINET virtual topology

The ground computers physically connect to the DI spacecraft via the Deep Space Network (DSN). The DSN operates three complexes that are geographically distributed over the Earth to ensure coverage may be maintained no matter where the spacecraft appears in the sky. To connect to these complexes, interface equipment is maintained and operated at the Jet Propulsion Laboratory (JPL). The intermediate interface system is referred to as DSOT (Data System Operations Team). An overview of the DINET system is depicted in Figure 2 below, divided into the primary components of the DI spacecraft, DSOT, and the EOC. As can be seen, additional nodes have been implemented beyond the simple diagram of Figure 1, in order to simplify integration and to enhance flexibility in operation. Also depicted in Figure 2 are the EOC Experiment Database and Load/Go elements.
In the network, “payload” data starts from one end node and is first routed to the ground system of that end node region, then to the Deep Impact spacecraft via RF links, then to the ground system of the destination region, and eventually arrives at the destination end node. The payload data are exchanged in the form of bundles. The source nodes produce and consume data in the EOC using the Asynchronous Message Service (AMS) [8] CCSDS draft standard publish & subscribe functions. Thus the EOC plays the role of exercising the data exchanges. The EOC also controls the topology among the nodes, dynamically altering the connectivity to test DTN functionality. In addition, the EOC monitors the delivery status among all end nodes. An additional node in the EOC acts to perform administrative functions, and contains the Monitor and Control System to collect and analyze the data delivery status and statistics, essential for the developers to view experiments and perform post-analyses. The software diagnostic messages and protocol diagnostic messages issued by network nodes are collected, analyzed, stored into a database in real-time. This application also provides a web interface for viewing the data in real-time and for interactive database queries. The messages include ION software status messages, ION bundle status report messages (BSRs), and node publish/subscription messages.

3. DINET EXPERIMENTAL OPERATIONS CENTER

An essential component of the DINET project is the Experiment Operations Center (EOC). The basic functions of the EOC are

1) Produce Experiment Payload Data
   - Input: JPEG image files
   - Single file per bundle
   - Mark bundle priority
   - Meter output to specified data rate
2) Consume Experiment Payload Data
   - Store in local file system at node upon reception
   - Display image upon reception
3) Consume Software Diagnostic Messages (ION logs)
   - ION will transmit log messages to EOC software via TCP/IP socket
- Received messages will be parsed & stored in a SQL database

4) Consume Protocol Diagnostic Messages (BSRs)
- ION will transmit bundle status reports (BSRs) to EOC software via the ION stack
- Received messages will be parsed & stored in a SQL database

5) EOC Bundle Network Configured / Monitored With GUI
- ION will transmit bundle status reports (BSRs) to EOC software via the ION stack
- Received messages will be parsed & stored in a SQL database

- Messages are displayed on the GUI in real time

The EOC will generate and receive the test communications traffic as well as “out-of-DTN band” command and control of the DTN experiment, store DTN flight test information in a database, provide display systems for monitoring DTN operations status and statistics (e.g., bundle throughput), and support query and analyses of the data collected.

The DINET EOC is located within the JPL Protocol Test Lab (PTL). The PTL provides connectivity to other NASA centers and external entities, and is itself a node in the larger DTN Experiment Network (DEN). The DINET EOC is envisioned to become a general tool in this broader context of experimental testing of DTN across a geographically dispersed user community. Figure 3 shows the PTL.

Figure 3 – Protocol Test Lab

EOC plays the role of exercising the data exchange and monitoring the delivery status among all end nodes. Three machines in PTL are designated to simulate the end nodes (“Earth”, “Mars” and “Phobos”) which publish and subscribe the data using the AMS (Asynchronous Message System) protocol over the ION network, where the data rate, DTN priority, and other transmission statistics are involved in the simulation and analysis. Another three machines in the PTL are used to simulate the routers in the space regions located between the end nodes and the ground systems. A seventh machine and two large screens in the PTL are employed as the administrative node and the visualization system to monitor and analyze the data delivery status and statistics for the DINET experiment. The execution of the Monitor and Control system in the administrative node helps researchers perform more informative and useful ION experiments. Figure 4 shows the software architecture of Monitor and Control System and the relationship with other DINET elements.
Software Modules of Monitor and Control System

The Monitor and Control System is designed as a multi-tier client-server web application. A middleware is used to service data requests between the user and the database. This hierarchical structure makes the application extensible and distributive. The framework of the Monitor and Control System in the EOC utilizes the technologies of Java, JavaScript, AJAX, JSP (JavaServer Page), and MySQL database to provide the means for the network administrator to monitor ION data delivery and operational status effectively. The devised infrastructure of the Monitor and Control system can be further extended to monitor the operation status, data transmission and the topology updates for other space mission simulations.

As shown in Figure 5, the Monitor and Control System in the EOC consists of four major executable pieces: DINETLogProcessor, DINETAdm, DINETQueryAdm, and DINETTopology. DINETLogProcessor sets up the TCP/IP socket connection to all simulated nodes to receive the ION status messages, parse and categorize the messages, and deposit the messages into the SQL database. DINETLogProcessor also sends signals to DINETAdm via TCP/IP socket to inform the arrival of status messages. DINETTopology is a topology description generator which dynamically updates the network topology description in xml format based on the ION network configuration, which is initialized prior to mission operation and updated during the course of mission operation. Similar to DINETLogProcessor, DINETTopology also notifies DINETAdm of any changes in the network topology via TCP/IP socket. DINETAdm is a web-based graphic display system which updates the display of the network topology and the ION status messages in real time based on notices from both DINETLogProcessor and DINETTopology units. DINETQueryAdm provides another web-based graphic display which interactively accepts and responses to users’ queries on ION status messages. Under the four major executables, there are five libraries constructed to support several specific functions. They are LibDatabase, LibLogProcessor, LibSocket, LibLogProvide and LibTopology. The functions of each library are described as follows:

- **LibDatabase**: manipulate and interface to the database, including setting connections to the database, creating tables in database, inserting data into the table, and querying table content.
- **LibLogProcessor**: build the database and the tables for the experiment, parse messages, classify messages, and store messages to the database.
- **LibSocket**: set the socket on the server side and receive messages from remote clients.
- **LibLogProvide**: interface to LibDatabase. Interpret the query sent issued from the application, send the query to the database, and return the query result to the application.
- **LibTopology**: parse the topology description in xml format and draw the network topology by the use of a Java applet.
The Monitor and Control System in EOC receives messages from all nodes in DINET during the mission operation via TCP/IP socket and ION stack. The messages include ION software status messages, ION Bundle Protocol status report messages, and publish/subscription messages. All messages are formatted in consistent plain text style prior to arriving to the processing unit of the destination, i.e. DINETLogProcessor at the administrative node of the EOC. Bundle Protocol status reports are issued by all nodes in the network and destined to the administration node in the form of DTN bundles via the ION stack, and those bundles which contain the status reports are further logged into plain text format, as are other ION status messages. Bundle status reports inform the deletion of any undelivered bundle and the administrative node may initiate some specific action to manipulate the happenings upon reception of the message. ION software status messages are logged by all nodes and programmatically redirected to a mechanism enabling them to be transmitted to the administrative node via TCP/IP, not via the ION stack. However, the message logged by the Deep Impact node will be encapsulated in EVR telemetry packets. As the ground system receives these packets, it will extract the encapsulated log messages and re-transmits the message to the administrative node via TCP/IP socket connection. ION status message are of five general types: informational message, warning message, diagnostic message, communication statistics message, and other status message. Informational messages mainly inform the occurrence of events that are nominal but significant. Warning messages inform the occurrence of events that are off-nominal but are likely due to configuration or operational error rather than software failure. Diagnostic messages inform the occurrence of events that are off-nominal and might be due to software errors. A communication statistics message provides network performance statistics over a stated interval. An “other status message” is seen in response to specific operator-initiated activity. The publish/subscription message denotes the publish and subscription status from the end nodes involving publish or subscription operations. All these status messages and statistics help the mission operations staff keep abreast of the network data flow and experiment status.

Installation and Execution of the Monitor and Control System in the PTL

In the PTL, the Monitor and Control software package is installed on a Linux workstation with two large screens which serves as the administrative node and visualization system in EOC development. One screen is used to display the main page of the Monitor and Control System GUI, and the other screen shows the GUI query page and x-term...
consoles of other nodes in EOC. Figure 6 is an example shot of the main GUI page. In the page, either an existing experiment name or a new experiment name is selected for executing the operation. There are 11 tables on the page which display live messages respectively received from DINET nodes. The message display is started by selecting the “start/update” button and temporarily paused by selecting the “paused” button. Moreover, all messages received and stored in the database can be dumped into a text file as the “save” button is selected and a file name is entered. On the top and middle of the page shows the network topology which is updated dynamically as the network connectivity changes.

Figure 6 – Monitor and Control System GUI main page

Figure 7 shows an example of the GUI query page. In order to query the messages stored in the database, an experiment name is specified and the message type, the message source node, number of messages, the message creation time period are optionally selected, and then the “query” button is clicked. The messages stored in the data which meet the query criterion are shown on the table of the query page, and those resultant messages can also be dumped into a text file by clicking the “save” button and entering a file name. The table content and topology display on both web GUI page are locally and dynamically updated without interfering the display of the entire page by the usage of Ajax and Java servlet techniques.

Figure 7 – Monitor and Control System GUI query page
4. CONCLUSIONS

This paper has briefly described the JPL Deep Impact Network (DINET) Delay/Disruption Networking (DTN) technology experiment, intended to increase the technical readiness DTN for space missions and supporting ground and space-based relay infrastructure. This represents the first deep space implementation of DTN in flight and ground software, and paves the way for future space networks. DINET demonstrates the Interplanetary Overlay Network (ION) implementation of DTN, which incorporates the Bundle Protocol and LTP retransmission protocol. We have described the DINET Experiment Operations Center (EOC) and its functions in accomplishing this experiment. The DINET EOC starts all ION processes, experiment data sources, status message receiver processes and display processes. The ION-based Monitor and Control System is an innovative, intranet-based software application which receives status messages and displays live results from the DINET network. With this Monitor and Control application, the ION software and protocol diagnostic messages issued by network nodes are collected, analyzed, stored into a database in real-time. This application also provides a web interface for viewing the data in real-time and for interactive database queries.

5. ACKNOWLEDGEMENTS

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BIOGRAPHY

J. Leigh Torgerson leads development and operation of spacecraft systems, with emphasis on end-to-end communications system technology. He has over 25 years of experience in team management, aerospace system design, digital & RF electronic system integration and flight test. He has been with Jet Propulsion Laboratory since, and is currently a member of the Communications Networks Group. He obtained an M.S. in Aeronautical System Engineering from the University of West Florida, and an B.S. in Engineering, EE/CS emphasis, from UCLA.
Loren Clare is the supervisor for the Communications Networks Group at the Jet Propulsion Laboratory. He obtained the Ph.D. in System Science from the University of California, Los Angeles in 1983. His research interests include wireless communications protocols, self-organizing systems, network systems design, modeling and analysis, and distributed control systems. Prior to joining JPL in May 2000, he was a senior research scientist at the Rockwell Science Center, where he acquired extensive experience in distributed sensor networks, satellite networking, and communications protocols for realtime networks supporting industrial automation.

Shin-Ywan (Cindy) Wang is a senior member of the Communications Networks Group at JPL. She has over 20 years experience of technology development, system analysis, and software engineering in the fields of document image processing, mission scenario and operation analysis, and telecommunications. Cindy’s recent work supports the development of Monitor and Control System for DTN experiments, link budget analysis for tasks of Constellation program’s DSIL SCaN simulation/emulation and TFPC, Telecom Forecaster Predictor C, and Remote Asynchronous Message Service (RAMS) of AMS protocol. She has a B.S. in Electronics Engineering from National Chiao-Tung University, Taiwan, and M.S. and Ph.D. in Electrical and Computer Engineering from the University of California, Irvine.