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Interplanetary Overlay Network (ION)
Design and Operation

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1 Design

The Interplanetary Overlay Network (ION) software distribution is an implementation of Delay-Tolerant Networking (DTN) architecture as described in Internet RFC 4838. It is designed to enable inexpensive insertion of DTN functionality into embedded systems such as robotic spacecraft. The intent of ION deployment in space flight mission systems is to reduce cost and risk in mission communications by simplifying the construction and operation of automated digital data communication networks spanning space links, planetary surface links, and terrestrial links.

A comprehensive overview of DTN is beyond the scope of this document. Very briefly, though, DTN is a digital communication networking technology that enables data to be conveyed between two communicating entities automatically and reliably even if one or more of the network links in the end-to-end path between those entities is subject to very long signal propagation latency and/or prolonged intervals of unavailability.

The DTN architecture is much like the architecture of the Internet, except that it is one layer higher in the familiar ISO protocol "stack". The DTN analog to the Internet Protocol (IP), called "Bundle Protocol" (BP), is designed to function as an "overlay" network protocol that interconnects "internets" – including both Internet-structured networks and also data paths that utilize only space communication links as defined by the Consultative Committee for Space Data Systems (CCSDS) – in much the same way that IP interconnects "subnets" such as those built on Ethernet, SONET, etc. By implementing the DTN architecture, ION provides communication software configured as a protocol stack that looks like this:

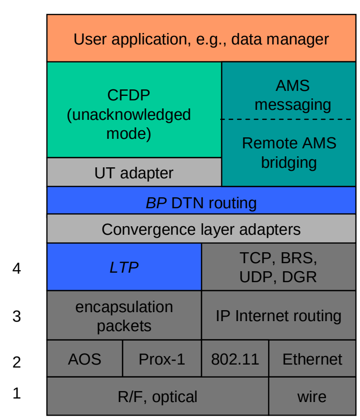


Figure 1 DTN protocol stack

Data traversing a DTN are conveyed in DTN *bundles* – which are functionally analogous to IP packets – between BP *endpoints* which are functionally analogous to sockets. Multiple BP endpoints may reside on the same computer – termed a *node* – just as multiple sockets may reside on the same computer (host or router) in the Internet.

BP endpoints are identified by Universal Record Identifiers (URIs), which are ASCII text strings of the general form:

scheme_name:*scheme_specific_part*

For example:

dtn://topquark.caltech.edu/mail

But for space flight communications this general textual representation might impose more transmission overhead than missions can afford. For this reason, ION is optimized for networks of endpoints whose IDs conform more narrowly to the following model:

ipn:*node_number*.*service_number*

This enables them to be abbreviated to pairs of unsigned binary integers via a technique called Compressed Bundle Header Encoding (CBHE). CBHE-conformant BP *endpoint IDs* (EIDs) are not only functionally similar to Internet socket addresses but also structurally similar: node numbers are roughly analogous to Internet node numbers (IP addresses), in that they typically identify the flight or ground data system computers on which network software executes, and service numbers are roughly analogous to TCP and UDP port numbers.

More generally, the node numbers in CBHE-conformant BP endpoint IDs are one manifestation of the fundamental ION notion of *network node number*: in the ION architecture there is a natural one-to-one mapping not only between node numbers and BP endpoint node numbers but also between node numbers and:

- LTP engine IDs
- AMS continuum numbers
- CFDP entity numbers

1.1 Structure and function

The ION distribution comprises the following software packages:

- ici (Interplanetary Communication Infrastructure), a set of general-purpose libraries providing common functionality to the other packages. The ici package includes a security policy component that supports the implementation of security mechanisms at multiple layers of the protocol stack.
- ltp (Licklider Transmission Protocol), a core DTN protocol that provides transmission reliability based on delay-tolerant acknowledgments, timeouts, and retransmissions.
- bp (Bundle Protocol), a core DTN protocol that provides delay-tolerant forwarding of data through a network in which continuous end-to-end connectivity is never assured, including support for delay-tolerant dynamic routing. The Bundle Protocol (BP) specification is defined in Internet RFC 5050.
- dgr (Datagram Retransmission), an alternative implementation of LTP that is designed for use in the Internet. Equipped with algorithms for TCP-like congestion control, DGR enables data to be transmitted via UDP with reliability

comparable to that provided by TCP. The dgr system is provided primarily for the conveyance of Meta-AMS (see below) protocol traffic in an Internet-like environment.

- ams (Asynchronous Message Service), an application-layer service that is not part of the DTN architecture but utilizes underlying DTN protocols. AMS comprises three protocols supporting the distribution of brief messages within a network:
    - The core AAMS (Application AMS) protocol, which does message distribution on both the publish/subscribe model and the client/server model, as required by the application.
    - The MAMS (Meta-AMS) protocol, which distributes control information enabling the operation of the Application AMS protocol.
    - The RAMS (Remote AMS) protocol, which performs aggregated message distribution to end nodes that may be numerous and/or accessible only over very expensive links, using an aggregation tree structure similar to the distribution trees used by Internet multicast technologies.
- cfdp (CCSDS File Delivery Protocol), another application-layer service that is not part of the DTN architecture but utilizes underlying DTN protocols. CFDP performs the segmentation, transmission, reception, reassembly, and delivery of files in a delay-tolerant manner. ION's implementation of CFDP conforms to the "class 1" definition of the protocol in the CFDP standard, utilizing DTN (BP, nominally over LTP) as its "unitdata transport" layer.

Taken together, the packages included in the ION software distribution constitute a communication capability characterized by the following operational features:

- Reliable conveyance of data over a delay-tolerant network (*dtnet*), i.e., a network in which it might never be possible for any node to have reliable information about the detailed current state of any other node.
- Built on this capability, reliable file delivery and reliable distribution of short messages to multiple recipients (subscribers) residing in such a network.
- Management of traffic through such a network, taking into consideration:
    - requirements for data security
    - scheduled times and durations of communication opportunities
    - fluctuating limits on data storage and transmission resources
    - data rate asymmetry
    - the sizes of application data units
    - and user-specified final destination, priority, and useful lifetime for those data units.
- Facilities for monitoring the performance of the network.
- Robustness against node failure.

- Portability across heterogeneous computing platforms.
- High speed with low overhead.
- Easy integration with heterogeneous underlying communication infrastructure, ranging from Internet to dedicated spacecraft communication links.

1.2 Constraints on the Design

A DTN implementation intended to function in an interplanetary network environment – specifically, aboard interplanetary research spacecraft separated from Earth and one another by vast distances – must operate successfully within two general classes of design constraints: link constraints and processor constraints.

1.2.1 Link constraints

All communications among interplanetary spacecraft are, obviously, wireless. Less obviously, those wireless links are generally slow and are usually asymmetric.

The electrical power provided to on-board radios is limited and antennae are relatively small, so signals are weak. This limits the speed at which data can be transmitted intelligibly from an interplanetary spacecraft to Earth, usually to some rate on the order of 256 Kbps to 6 Mbps.

The electrical power provided to transmitters on Earth is certainly much greater, but the sensitivity of receivers on spacecraft is again constrained by limited power and antenna mass allowances. Because historically the volume of command traffic that had to be sent to spacecraft was far less than the volume of telemetry the spacecraft were expected to return, spacecraft receivers have historically been engineered for even lower data rates from Earth to the spacecraft, on the order of 1 to 2 Kbps.

As a result, the cost per octet of data transmission or reception is high and the links are heavily subscribed. Economical use of transmission and reception opportunities is therefore important, and transmission is designed to enable useful information to be obtained from brief communication opportunities: units of transmission are typically small, and the immediate delivery of even a small part (carefully delimited) of a large data object may be preferable to deferring delivery of the entire object until all parts have been acquired.

1.2.2 Processor constraints

The computing capability aboard a robotic interplanetary spacecraft is typically quite different from that provided by an engineering workstation on Earth. In part this is due, again, to the limited available electrical power and limited mass allowance within which a flight computer must operate. But these factors are exacerbated by the often intense radiation environment of deep space. In order to minimize errors in computation and storage, flight processors must be radiation-hardened and both dynamic memory and non-volatile storage (typically flash memory) must be radiation-tolerant. The additional engineering required for these adaptations takes time and is not inexpensive, and the market for radiation-hardened spacecraft computers is relatively small; for these reasons, the latest advances in processing technology are typically not available for use on interplanetary spacecraft, so flight computers are invariably slower than their Earth-bound counterparts. As a result, the cost per processing cycle is high and processors are heavily subscribed; economical use of processing resources is very important.

The nature of interplanetary spacecraft operations imposes a further constraint. These spacecraft are wholly robotic and are far beyond the reach of mission technicians; hands-on repairs are out of the question. Therefore the processing performed by the flight computer must be highly reliable, which in turn generally means that it must be highly predictable. Flight software is typically required to meet "hard" real-time processing deadlines, for which purpose it must be run within a hard real-time operating system (RTOS).

One other implication of the requirement for high reliability in flight software is that the dynamic allocation of system memory may be prohibited except in certain well-understood states, such as at system start-up. Unrestrained dynamic allocation of system memory introduces a degree of unpredictability into the overall flight system that can threaten the reliability of the computing environment and jeopardize the health of the vehicle.

1.3 Design Principles

The design of the ION software distribution reflects several core principles that are intended to address these constraints.

1.3.1 Shared memory

Since ION must run on flight processors, it had to be designed to function successfully within an RTOS. Many real-time operating systems improve processing determinism by omitting the support for protected-memory models that is provided by Unix-like operating systems: all tasks have direct access to all regions of system memory. (In effect, all tasks operate in kernel mode rather than in user mode.) ION therefore had to be designed with no expectation of memory protection.

But universally shared access to all memory can be viewed not only as a hazard but also as an opportunity. Placing a data object in shared memory is an extremely efficient means of passing data from one software task to another.

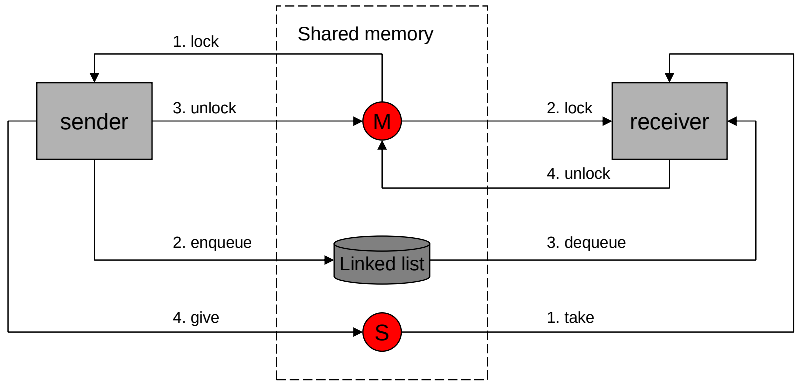


Figure 2 ION inter-task communication

ION is designed to exploit this opportunity as fully as possible. In particular, virtually all inter-task communication in ION follows this model:

- The sending task takes a mutual exclusion semaphore (mutex) protecting a linked list in shared memory (either DRAM or non-volatile memory), appends a data item to the list, releases the mutex, and gives a “signal” semaphore associated with the list to announce that the list is now non-empty.
- The receiving task, which is already pended on the linked list’s associated signal semaphore, resumes execution when the semaphore is given. It takes the associated mutex, extracts the next data item from the list, releases the mutex, and proceeds to operate on the data item from the sending task.

Semaphore operations are typically extremely fast, as is the storage and retrieval of data in memory, so this inter-task communication model is suitably efficient for flight software.

1.3.2 Zero-copy procedures

Given ION’s orientation toward the shared memory model, a further strategy for processing efficiency offers itself: if the data item appended to a linked list is merely a pointer to a large data object, rather than a copy, then we can further reduce processing overhead by eliminating the cost of byte-for-byte copying of large objects.

Moreover, in the event that multiple software elements need to access the same large object at the same time, we can provide each such software element with a pointer to the object rather than its own copy (maintaining a count of references to assure that the object is not destroyed until all elements have relinquished their pointers). This serves to reduce somewhat the amount of memory needed for ION operations.

1.3.3 Highly distributed processing

The efficiency of inter-task communications based on shared memory makes it practical to distribute ION processing among multiple relatively simple pipelined tasks rather than localize it in a single, somewhat more complex daemon. This strategy has a number of advantages:

- The simplicity of each task reduces the sizes of the software modules, making them easier to understand and maintain, and thus it can somewhat reduce the incidence of errors.
- The scope of the ION operating stack can be adjusted incrementally at run time, by spawning or terminating instances of configurable software elements, without increasing the size or complexity of any single task and without requiring that the stack as a whole be halted and restarted in a new configuration. In theory, a module could even be upgraded with new functionality and integrated into the stack without interrupting operations.
- The clear interfaces between tasks simplify the implementation of flow control measures to prevent uncontrolled resource consumption.

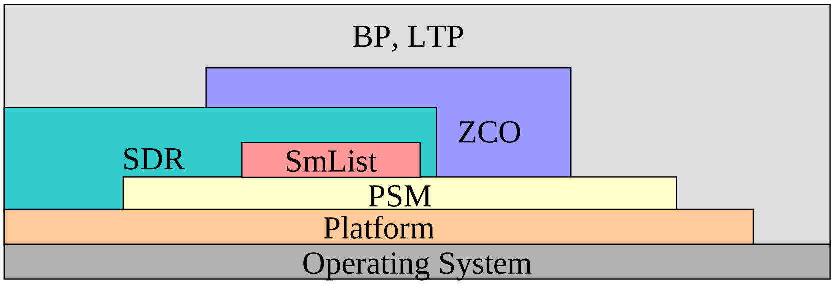
1.3.4 Portability

Designs based on these kinds of principles are foreign to many software developers, who may be far more comfortable in development environments supported by protected memory. It is typically much easier, for example, to develop software in a Linux environment than in VxWorks 5.4. However, the Linux environment is not the only one in which ION software must ultimately run.

Consequently, ION has been designed for easy portability. POSIX™ API functions are widely used, and differences in operating system support that are not concealed within the POSIX abstractions are mostly encapsulated in two small modules of platform-sensitive ION code. The bulk of the ION software runs, without any source code modification whatsoever, equally well in Linux™ (Red Hat®, Fedora™, and Ubuntu™, so far), FreeBSD®, Solaris® 9, Microsoft Windows (the MinGW environment), OS/X®, VxWorks® 5.4, and RTEMS™, on both 32-bit and 64-bit processors. Developers may compile and test ION modules in whatever environment they find most convenient.

1.4 Organizational Overview

Two broad overviews of the organization of ION may be helpful at this point. First, here is a summary view of the main functional dependencies among ION software elements:



BP, LTP	Bundle Protocol and Licklider Transmission Protocol libraries and daemons
ZCO	Zero-copy objects capability: minimize data copying up and down the stack
SDR	Spacecraft Data Recorder: persistent object database in shared memory, using PSM and SmList
SmList	linked lists in shared memory using PSM
PSM	Personal Space Management: memory management within a pre-allocated memory partition
Platform	common access to O.S.: shared memory, system time, IPC mechanisms
Operating System	POSIX thread spawn/destroy, file system, time

Figure 3 ION software functional dependencies

That is, BP and LTP invoke functions provided by the sdr, zco, psm, and platform elements of the ici package, in addition to functions provided by the operating system itself; the zco functions themselves also invoke sdr, psm, and platform functions; and so on.

Second, here is a summary view of the main line of data flow in ION's DTN protocol implementations:

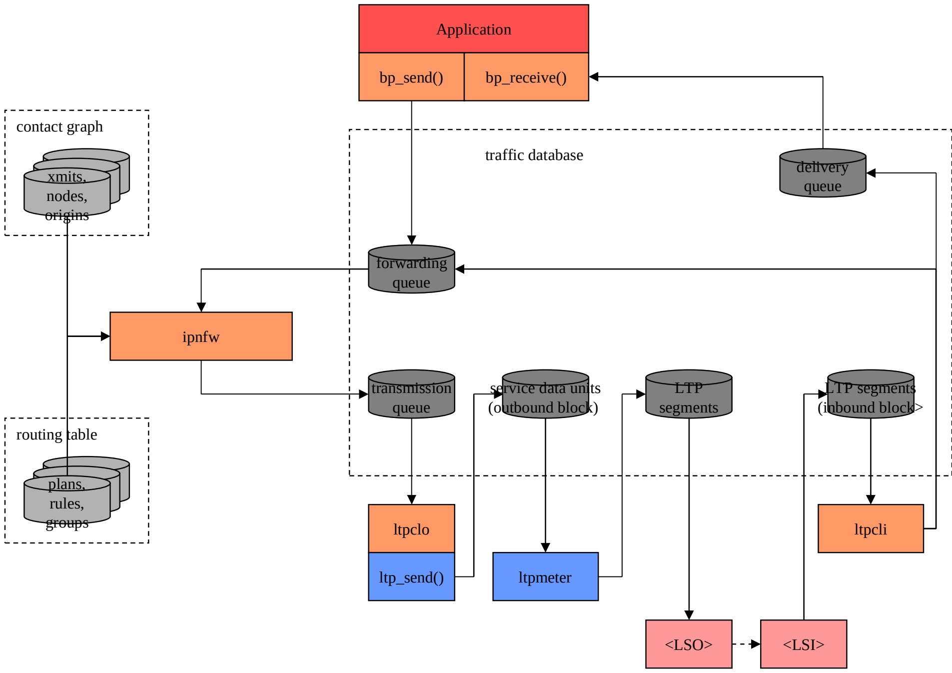


Figure 4 Main line of ION data flow

Note that data objects residing in shared memory, many of them in a nominally non-volatile SDR data store, constitute the central organizing principle of the design. Here as in other diagrams showing data flow in this document:

- Linked lists of data objects are shown as cylinders.
- Darker data entities indicate data that are managed in the SDR data store, while lighter data entities indicate data that are managed in volatile DRAM to improve performance.
- Rectangles indicate processing elements (tasks, processes, threads), sometimes with library references specifically identified.

A few notes on this main line data flow:

- For simplicity, the data flow depicted here is a “loopback” flow in which a single BP “node” is shown sending data to itself (a useful configuration for test purposes). To depict typical operations over a network we would need two instances of this node diagram, such that the <LSO> task of one node is shown sending data to the <LSI> task of the other and vice versa.
- A BP application or application service (such as Remote AMS) that has access to the local BP node – for our purposes, the “sender” – invokes the `bp_send` function to send a unit of application data to a remote counterpart. The destination of the application data unit is expressed as a BP endpoint ID (EID). The application data unit is encapsulated in a bundle and is queued for forwarding.

- The forwarder task identified by the "scheme" portion of the bundle's destination EID removes the bundle from the forwarding queue and computes a route to the destination EID. The first node on the route, to which the local node is able to transmit data directly via some underlying "convergence layer" (CL) protocol, is termed the "proximate node" for the computed route. The forwarder appends the bundle to one of the transmission queues for the CL-protocol-specific interface to the proximate node, termed an *outduct*. Each outduct is serviced by some CL-specific output task that communicates with the proximate node – in this case, the LTP output task **ltpclo**. (Other CL protocols supported by ION include TCP and UDP.)
- The output task for LTP transmission to the selected proximate node removes the bundle from the transmission queue and invokes the `ltp_send` function to append it to a *block* that is being assembled for transmission to the proximate node. (Because LTP acknowledgment traffic is issued on a per-block basis, we can limit the amount of acknowledgment traffic on the network by aggregating multiple bundles into a single block rather than transmitting each bundle in its own block.)
- The **ltpmeter** task for the selected proximate node divides the aggregated block into multiple segments and enqueues them for transmission by underlying link-layer transmission software, such as an implementation of the CCSDS AOS protocol.
- Underlying link-layer software at the sending node transmits the segments to its counterpart at the proximate node (the receiver), where they are used to reassemble the transmission block.
- The receiving node's input task for LTP reception extracts the bundles from the reassembled block and dispatches them: each bundle whose final destination is some other node is queued for forwarding, just like bundles created by local applications, while each bundle whose final destination is the local node is queued for delivery to whatever application "opens" the BP endpoint identified by the bundle's final destination endpoint ID.
- The destination application or application service at the receiving node opens the appropriate BP endpoint and invokes the `bp_receive` function to remove the bundle from the associated delivery queue and extract the original application data unit, which it can then process.

Finally, note that the data flow shown here represents the sustained operational configuration of a node that has been successfully instantiated on a suitable computer. The sequence of operations performed to reach this configuration is not shown. That startup sequence will necessarily vary depending on the nature of the computing platform and the supporting link services. Broadly, the first step normally is to run the **ionadmin** utility program to initialize the data management infrastructure required by all elements of ION. Following this initialization, the next steps normally are (a) any necessary initialization of link service protocols, (b) any necessary initialization of convergence-layer protocols (e.g., LTP – the **ltpadmin** utility program), and finally (c) initialization of the Bundle Protocol by means of the **bpadmin** utility program. BP applications should not try to commence operation until BP has been initialized.

1.5 Resource Management in ION

Successful Delay-Tolerant Networking relies on retention of bundle protocol agent state information – including protocol traffic that is awaiting a transmission opportunity – for potentially lengthy intervals. The nature of that state information will fluctuate rapidly as the protocol agent passes through different phases of operation, so efficient management of the storage resources allocated to state information is a key consideration in the design of ION.

Two general classes of storage resources are managed by ION: volatile "working memory" and non-volatile "heap".

1.5.1 Working Memory

ION's "working memory" is a fixed-size pool of shared memory (dynamic RAM) that is allocated from system RAM at the time the bundle protocol agent commences operation. Working memory is used by ION tasks to store temporary data of all kinds: linked lists, transient buffers, volatile databases, etc. All intermediate data products and temporary data structures that ought not to be retained in the event of a system power cycle are written to working memory.

Data structures residing in working memory may be shared among ION tasks or may be created and managed privately by individual ION tasks. The dynamic allocation of working memory to ION tasks is accomplished by the Personal Space Management (PSM) service, described later. All of the working memory for any single ION bundle protocol agent is managed as a single PSM "partition".

Because the contents of working memory are in most cases highly transient, the working memory partition for any single ION node need not be large, typically on the order of 100KB to 1 MB. The size of the partition is specified in the **wmSize** parameter of the ionconfig file supplied at the time ION is initialized.

1.5.2 Heap

ION's "heap" is a fixed-size pool of notionally non-volatile storage that is likewise allocated at the time the bundle protocol agent commences operation. This notionally non-volatile space **may** occupy a fixed-size pool of shared memory (dynamic RAM, which might or might not be battery-backed), or it **may** occupy only a single fixed-size file in the file system, or it may occupy both. In the latter case, all heap data are written both to memory and to the file but are read only from memory; this configuration offers the reliable non-volatility of file storage coupled with the high performance of retrieval from dynamic RAM.

We characterize ION's heap storage as "notionally" non-volatile because the heap may be configured to reside only in memory. When the heap resides only in memory, its contents are truly non-volatile only if that memory is battery-backed. Otherwise heap storage is in reality as volatile as working memory: heap contents will be lost upon a system power cycle (which may in fact be the preferred behavior for any given deployment of ION). However, the heap should not be thought of as "memory" even when it in fact resides only in DRAM, just as a disk device should not be thought of as "memory" even when it is in fact a ram disk.

The ION heap is used for storage of data that (in at least some deployments) would have to be retained in the event of a system power cycle to ensure the correct continued operation of the node. For example, all queues of bundles awaiting route computation, transmission, or delivery reside in the node's heap. So do the non-volatile databases for all of the protocols implemented within ION, together with all of the node's persistent configuration parameters.

The dynamic allocation of heap space to ION tasks is accomplished by the Simple Data Recorder (SDR) service, described later. The entire heap for any single ION bundle protocol agent is managed as a single SDR "data store".

Space within the ION heap is apportioned as shown below.

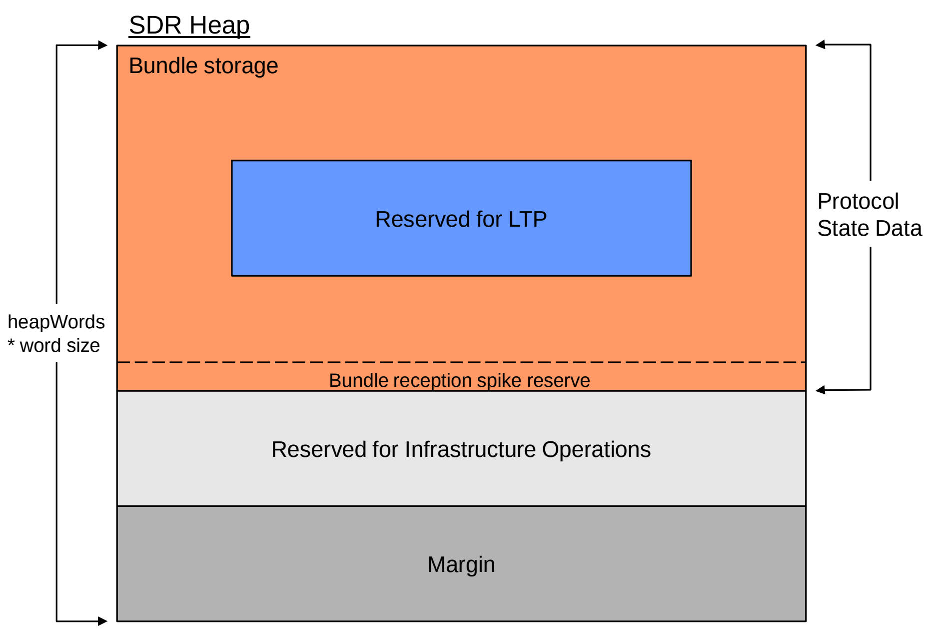


Figure 5 ION heap space use

The total number of bytes of storage space in the heap is computed as the product of the size of a "word" on the deployment platform (i.e., the size of a `long`) multiplied by the value of the **heapWords** parameter of the ionconfig file supplied at the time ION is initialized. Of this total, 20% is normally reserved as margin and another 20% is normally reserved for various infrastructure operations. (Both of these percentages are macros that may be overridden at compile time.) The remainder is available for storage of protocol state data. A fixed share of the protocol state data space is reserved by LTP at the time ION is initialized, as described in the `ltprc(3)` man page (see "initialize"). All remaining heap space is available for bundle storage. Note, though, that about 6% of this bundle storage space may be used only for storage of bundles received from other nodes ("bundle reception spike reserve"), not for bundles that are locally originated for future transmission. This is to ensure that local BP users' transmissions can never cause the node to cease functioning as a bundle forwarder in the network.

Because the heap is used to store queues of bundles awaiting processing, blocks of LTP data awaiting transmission or reassembly, etc., the heap for any single ION node must be large enough to contain the maximum volume of such data that the node will be required to retain during operations. Demand for heap space is substantially mitigated if most of the application data units passed to ION for transmission are file-resident, as the file contents themselves need not be copied into the heap. In general, however, computing the optimum ION heap size for a given deployment remains a research topic.

1.6 Package Overviews

1.6.1 Interplanetary Communication Infrastructure (ICI)

The ICI package in ION provides a number of core services that, from ION's point of view, implement what amounts to an extended POSIX-based operating system. ICI services include the following:

1. Platform

The platform system contains operating-system-sensitive code that enables ICI to present a single, consistent programming interface to those common operating system services that multiple ION modules utilize. For example, the platform system implements a standard semaphore abstraction that may invisibly be mapped to underlying POSIX semaphores, SVR4 IPC semaphores, or VxWorks semaphores, depending on which operating system the package is compiled for. The platform system also implements a standard shared-memory abstraction, enabling software running on operating systems both with and without memory protection to participate readily in ION's shared-memory-based computing environment.

2. Personal Space Management (PSM)

Although sound flight software design may prohibit the uncontrolled dynamic management of system memory, private management of assigned, fixed blocks of system memory is standard practice. Often that private management amounts to merely controlling the reuse of fixed-size rows in static tables, but such techniques can be awkward and may not make the most efficient use of available memory. The ICI package provides an alternative, called PSM, which performs high-speed dynamic allocation and recovery of variable-size memory objects within an assigned memory block of fixed size. A given PSM-managed memory block may be either private or shared memory.

3. Memmgr

The static allocation of privately-managed blocks of system memory for different purposes implies the need for multiple memory management regimes, and in some cases a program that interacts with multiple software elements may need to participate in the private shared-memory management regimes of each. ICI's memmgr system enables multiple memory managers – for multiple privately-managed blocks of system memory – to coexist within ION and be concurrently available to ION software elements.

4. Lyst

The lyst system is a comprehensive, powerful, and efficient system for managing doubly-linked lists in private memory. It is the model for a number of other list management systems supported by ICI; as noted earlier, linked lists are heavily used in ION inter-task communication.

5. Llcv

The llcv (Linked-List Condition Variables) system is an inter-thread communication abstraction that integrates POSIX thread condition variables (vice semaphores) with doubly-linked lists in private memory.

6. Smlist

Smlist is another doubly-linked list management service. It differs from lyst in that the lists it manages reside in shared (rather than private) DRAM, so operations on them must be semaphore-protected to prevent race conditions.

7. Simple Data Recorder (SDR)

SDR is a system for managing non-volatile storage, built on exactly the same model as PSM. Put another way, SDR is a small and simple “persistent object” system or “object database” management system. It enables straightforward management of linked lists (and other data structures of arbitrary complexity) in non-volatile storage, notionally within a single file whose size is pre-defined and fixed.

SDR includes a transaction mechanism that protects database integrity by ensuring that the failure of any database operation will cause all other operations undertaken within the same transaction to be backed out. The intent of the system is to assure retention of coherent protocol engine state even in the event of an unplanned flight computer reboot in the midst of communication activity.

8. Sptrace

The sptrace system is an embedded diagnostic facility that monitors the performance of the PSM and SDR space management systems. It can be used, for example, to detect memory “leaks” and other memory management errors.

9. Zco

ION’s zco (zero-copy objects) system leverages the SDR system’s storage flexibility to enable user application data to be encapsulated in any number of layers of protocol without copying the successively augmented protocol data unit from one layer to the next. It also implements a reference counting system that enables protocol data to be processed safely by multiple software elements concurrently – e.g., a bundle may be both delivered to a local endpoint and, at the same time, queued for forwarding to another node – without requiring that distinct copies of the data be provided to each element.

10. Rfx

The ION rfx (R/F Contacts) system manages lists of scheduled communication opportunities in support of a number of LTP and BP functions.

11. Ionsec

The IONSEC (ION security) system manages information that supports the implementation of security mechanisms in the other packages: security policy rules and computation keys.

1.6.2 Licklider Transmission Protocol (LTP)

The ION implementation of LTP conforms fully to RFC 5326, but it also provides two additional features that enhance functionality without affecting interoperability with other implementations:

- The service data units – nominally bundles – passed to LTP for transmission may be aggregated into larger blocks before segmentation. By controlling block size we can control the volume of acknowledgment traffic generated as blocks are received, for improved accommodation of highly asynchronous data rates.
- The maximum number of transmission sessions that may be concurrently managed by LTP (a protocol control parameter) constitutes a transmission "window" – the basis for a delay-tolerant, non-conversational flow control service over interplanetary links.

In the ION stack, LTP serves effectively the same role that is performed by TCP in the Internet architecture, providing flow control and retransmission-based reliability.

All LTP session state is safely retained in the ION heap for rapid recovery from a spacecraft or software fault.

1.6.3 Bundle Protocol (BP)

The ION implementation of BP conforms fully to RFC 5050, including support for the following standard capabilities:

- Prioritization of data flows
- Bundle reassembly from fragments
- Flexible status reporting
- Custody transfer, including re-forwarding of custodial bundles upon failure of nominally reliable convergence-layer transmission

The system also provides two additional features that enhance functionality without affecting interoperability with other implementations:

- Rate control provides support for congestion forecasting and avoidance.
- Bundle headers are encoded into compressed form (CBHE, as noted earlier) before issuance, to reduce protocol overhead and improve link utilization.

In addition, ION BP includes a system for computing dynamic routes through time-varying network topology assembled from scheduled, bounded communication opportunities. This system, called "Contact Graph Routing," is described later in this Guide.

In short, BP serves effectively the same role that is performed by IP in the Internet architecture, providing route computation, forwarding, congestion avoidance, and control over quality of service.

Together, the BP/LTP combination offers capabilities comparable to TCP/IP in the Internet.

All bundle transmission state is safely retained in the ION heap for rapid recovery from a spacecraft or software fault.

1.6.4 Asynchronous Message Service (AMS)

The ION implementation of the CCSDS AMS standard conforms fully to CCSDS 735.0-B-1. AMS is a data system communications architecture under which the modules of mission systems may be designed as if they were to operate in isolation, each one producing and consuming mission information without explicit awareness of which other modules are currently operating. Communication relationships among such modules are self-configuring; this tends to minimize complexity in the development and operations of modular data systems.

A system built on this model is a "society" of generally autonomous inter-operating modules that may fluctuate freely over time in response to changing mission objectives, modules' functional upgrades, and recovery from individual module failure. The purpose of AMS, then, is to reduce mission cost and risk by providing standard, reusable infrastructure for the exchange of information among data system modules in a manner that is simple to use, highly automated, flexible, robust, scalable, and efficient.

A detailed discussion of AMS is beyond the scope of this Design Guide. For more information, please see the AMS Programmer's Guide.

1.6.5 Datagram Retransmission (DGR)

The DGR package in ION is an alternative implementation of LTP that is designed to operate responsibly – i.e., with built-in congestion control – in the Internet or other IP-based networks. It is provided as a candidate "primary transfer service" in support of AMS operations in an Internet-like (non-delay-tolerant) environment. The DGR design combines LTP's concept of concurrent transmission transactions with congestion control and timeout interval computation algorithms adapted from TCP.

1.6.6 CCSDS File Delivery Protocol (CFDP)

The ION implementation of CFDP conforms fully to Service Class 1 (Unreliable Transfer) of CCSDS 727.0-B-4, including support for the following standard capabilities:

- Segmentation of files on user-specified record boundaries.
- Transmission of file segments in protocol data units that are conveyed by an underlying Unitdata Transfer service, in this case the DTN protocol stack. File data segments may optionally be protected by CRCs. When the DTN protocol stack is configured for reliable data delivery (i.e., with BP custody transfer running over a reliable convergence-layer protocol such as LTP), file delivery is reliable; CFDP need not perform retransmission of lost data itself.

- Reassembly of files from received segments, possibly arriving over a variety of routes through the delay-tolerant network. The integrity of the delivered files is protected by checksums.
- User-specified fault handling procedures.
- Operations (e.g., directory creation, file renaming) on remote file systems.

All CFDP transaction state is safely retained in the ION heap for rapid recovery from a spacecraft or software fault.

1.7 Acronyms

BP	Bundle Protocol
CCSDS	Consultative Committee for Space Data Systems
CFDP	CCSDS File Delivery Protocol
CGR	Contact Graph Routing
CL	convergence layer
CLI	convergence layer input
CLO	convergence layer output
DTN	Delay-Tolerant Networking
ICI	Interplanetary Communication Infrastructure
ION	Interplanetary Overlay Network
LSI	link service input
LSO	link service output
LTP	Licklider Transmission Protocol
OWLT	one-way light time
RFC	request for comments
RFX	Radio (R/F) Contacts
RTT	round-trip time
TTL	time to live

1.8 Network Operation Concepts

A small number of network operation design elements – fragmentation and reassembly, bandwidth management, and delivery assurance (retransmission) – can potentially be addressed at multiple layers of the protocol stack, possibly in different ways for different reasons. In stack design it's important to allocate this functionality carefully so that the effects at lower layers complement, rather than subvert, the effects imposed at higher layers of the stack. This allocation of functionality is discussed below, together with a discussion of several related key concepts in the ION design.

1.8.1 Fragmentation and Reassembly

To minimize transmission overhead and accommodate asymmetric links (i.e., limited "uplink" data rate from a ground data system to a spacecraft) in an interplanetary network, we ideally want to send "downlink" data in the largest possible aggregations – coarse-grained transmission.

But to minimize head-of-line blocking (i.e., delay in transmission of a newly presented high-priority item) and minimize data delivery latency by using parallel paths (i.e., to provide fine-grained partial data delivery, and to minimize the impact of unexpected link termination), we want to send "downlink" data in the smallest possible aggregations – fine-grained transmission.

We reconcile these impulses by doing both, but at different layers of the ION protocol stack.

First, at the application service layer (AMS and CFDP) we present relatively small application data units (ADUs) – on the order of 64 KB – to BP for encapsulation in bundles. This establishes an upper bound on head-of-line blocking when bundles are de-queued for transmission, and it provides perforations in the data stream at which forwarding can readily be switched from one link (route) to another, enabling partial data delivery at relatively fine, application-appropriate granularity. In so doing, it makes "proactive fragmentation" within the Bundle Protocol itself unnecessary.

But then, at the BP/LTP convergence layer adapter lower in the stack, we aggregate these small bundles into *blocks* for presentation to LTP:

> Any continuous sequence of bundles that are to be shipped to the same LTP engine and all require assured delivery may be aggregated into a single block, to reduce overhead and minimize report traffic.
>
> However, this aggregation is constrained by a block size limit rule: each block must contain an integral number N – where N is greater than zero – complete bundles, but N can only exceed 1 when the sum of the sizes of all N bundles does not exceed the *nominal block size* declared for the applicable *span* (the relationship between the local node and the receiving LTP engine) during LTP protocol configuration via **ltpadmin**.

Given a preferred block acknowledgment period – e.g., an acknowledgment traffic limit of one report per second – nominal block size is notionally computed as the amount of data that can be sent over the link to the receiving LTP engine in a single block acknowledgment period at the planned outbound data rate to that engine.

Taken together, application-level fragmentation and LTP aggregation place an upper limit on the amount of data that would need to be re-transmitted over a given link at next contact in the event of an unexpected link termination that caused delivery of an entire block to fail. For example, if the data rate is 1 Mbps and the nominal block size is 128 KB (equivalent to 1 second of transmission time), we would prefer to avoid the risk of having wasted five minutes of downlink in sending a 37.5 MB file that fails on transmission of the last kilobyte, forcing retransmission of the entire 37.5 MB. We therefore divide the file into, say, 1200 bundles of 32 KB each which are aggregated into blocks of 128 KB each: only a single block failed, so only that block (containing just 4 bundles) needs to be retransmitted. The cost of this retransmission is only 1 second of link time rather than 5 minutes. By controlling the cost of convergence-layer protocol failure in this way, we avoid the overhead and complexity of "reactive fragmentation" in the BP implementation.

Finally, within LTP itself we fragment the block as necessary to accommodate the Maximum Transfer Unit (MTU) size of the underlying link service, typically the transfer frame size of the applicable CCSDS link protocol.

1.8.2 Bandwidth Management

The allocation of bandwidth (transmission opportunity) to application data is requested by the application task that's passing data to DTN, but it is necessarily accomplished only at the lowest layer of the stack at which bandwidth allocation decisions can be made – and then always in the context of node policy decisions that have global effect.

The "outduct" interface to a given neighbor in the network is actually three queues of outbound bundles rather than one: one queue for each of the defined levels of priority ("class of service") supported by BP. When an application presents an ADU to BP for encapsulation in a bundle, it indicates its own assessment of the ADU's priority. Upon selection of a proximate forwarding destination node for that bundle, the bundle is appended to whichever of the neighbor interface queues corresponds to the ADU's priority.

Normally the convergence-layer output (CLO) task servicing a given outduct – e.g., the LTP output task **ltpclo** – extracts bundles in strict priority order from the heads of the outduct's three queues. That is, the bundle at the head of the highest-priority non-empty queue is always extracted.

However, if the ION_BANDWIDTH_RESERVED compiler option is selected at the time ION is built, the convergence-layer output (CLO) task servicing a given outduct extracts bundles in interleaved fashion from the heads of the outduct's three queues:

- Whenever the priority-2 ("express") queue is non-empty, the bundle at the head of that queue is the next one extracted.
- At all other times, bundles from both the priority-1 queue and the priority-0 queue are extracted, but over a given period of time twice as many bytes of priority-1 bundles will be extracted as bytes of priority-0 bundles.

CLO tasks other than **ltpclo** simply segment the extracted bundles as necessary and transmit them using the underlying convergence-layer protocol. In the case of **ltpclo**, the output task aggregates the extracted bundles into blocks as described earlier and a second daemon task named **ltpmeter** waits for aggregated blocks to be completed; **ltpmeter**, rather than the CLO task itself, segments each completed block as necessary and passes the segments to the link service protocol that underlies LTP. Either way, the transmission ordering requested by application tasks is preserved.

1.8.3 Contact Plans

In the Internet, protocol operations can be largely driven by currently effective information that is discovered opportunistically and immediately, at the time it is needed, because the latency in communicating this information over the network is negligible: distances between communicating entities are small and connectivity is continuous. In a DTN-based network, however, ad-hoc information discovery would in many cases take so much time that it could not be completed before the information lost currency and effectiveness. Instead, protocol operations must be largely driven by information that is pre-placed at the network nodes and tagged with the dates and times at which it becomes effective. This information takes the form of *contact plans* that are managed by the R/F Contacts (rfx) services of ION's ici package.

The structure of ION's RFX (contact plan) database, the rfx system elements that populate and use that data, and affected portions of the BP and LTP protocol state databases are shown in the following diagram. The <u>node</u>, <u>xmit</u>, and <u>origin</u> data objects contain the information that functions as ION's "contact graph".

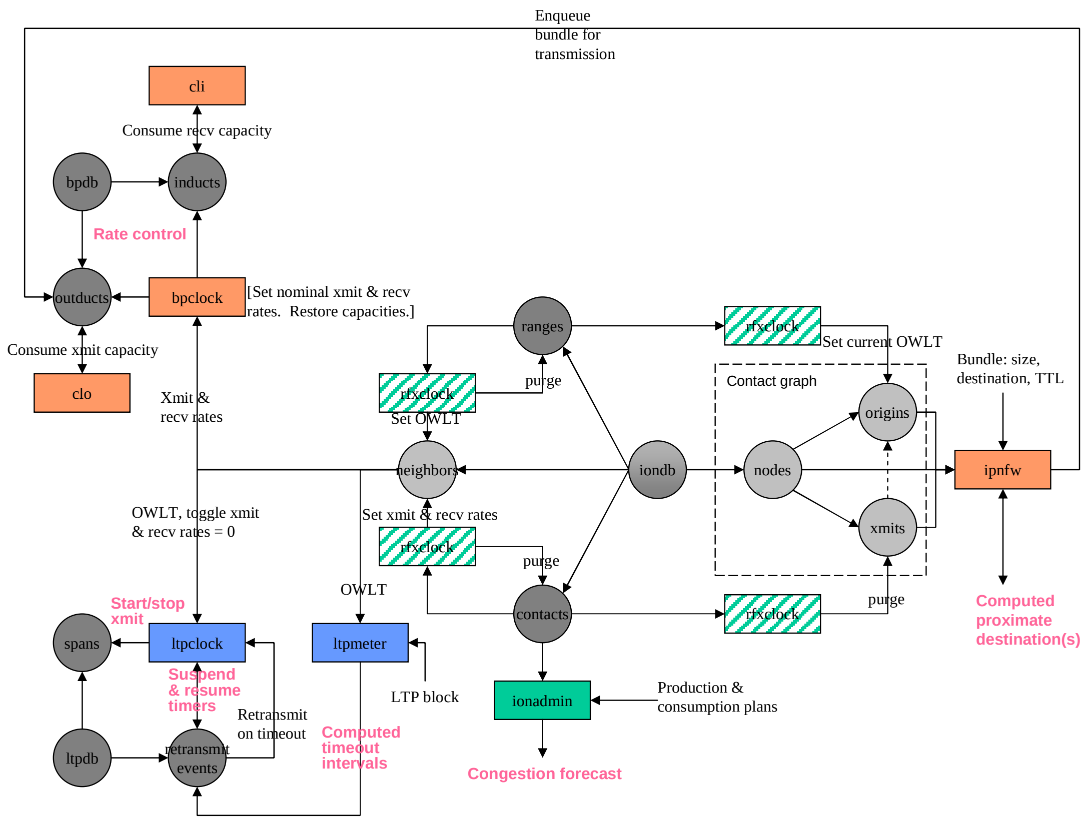


Figure 6 RFX services in ION

(For additional details of BP and LTP database management, see the BP/LTP discussion later in this document.)

To clarify the notation of this diagram, which is also used in other database structure diagrams in this document:

- Data objects of defined structure are shown as circles.
- Solid arrows connecting circles indicate one-to-many cardinality.
- A dashed arrow between circles indicates a potentially many-to-one reference mapping.
- Arrows from processing elements (rectangles) to data entities indicate data production, while arrows from data entities to processing element indicate data retrieval.

A *contact* is here defined as an interval during which it is expected that data will be transmitted by DTN node A (the contact's transmitting node) and most or all of the transmitted data will be received by node B (the contact's receiving node). Implicitly, the transmitting mode will utilize some "convergence-layer" protocol underneath the Bundle Protocol to effect this direct transmission of data to the receiving node. Each contact is characterized by its start time, its end time, the identities of the transmitting and receiving nodes, and the rate at which data are expected to be transmitted by the transmitting node throughout the indicated time period.

A *range interval* is a period of time during which the displacement between two nodes A and B is expected to vary by less than 1 light second from a stated anticipated distance. (We expect this information to be readily computable from the known orbital elements of all nodes.) Each range interval is characterized by its start time, its end time, the identities of the two nodes to which it pertains, and the anticipated approximate distance between those nodes throughout the indicated time period.

The *topology timeline* at each node in the network is a time-ordered list of scheduled or anticipated changes in the topology of the network. Entries in this list are of two types:

- Contact entries characterize scheduled contacts.
- Range entries characterize anticipated range intervals.

Each node to which, according to the RFX database, the local node transmits data directly via some convergence-layer protocol at some time is termed a *neighbor* of the local node. Each neighbor is associated with an outduct – a set of outbound transmission queues – for the applicable BP convergence-layer (CL) protocol adapter, so bundles that are to be transmitted directly to this neighbor can simply be queued for transmission via that CL protocol (as discussed in the Bandwidth Management notes above).

At startup, and at any time while the system is running, **ionadmin** inserts and removes Contact and Range entries in topology timeline of the RFX database. Inserting a Contact that affects at least one node other than the local node causes corresponding Xmit objects to be inserted for the affected Node object(s), for use in route computation. Inserting an Xmit for a Node may entail creation of the Node and/or creation of an Origin for the affected Node. Removing a Contact that affects at least one node other than the local node causes the corresponding Xmits to be removed from the affected Node(s).

Once per second, the **rfxclock** task (which appears in multiple locations on the diagram to simplify the geometry) purges all Contacts and Ranges with end time in the past, resets to zero the data rates and one-way light time (OWLT – that is, range) between the local node and each of its neighbors (represented by Neighbor objects in the volatile database), resets to zero the OWLT between each Node and each of its Origins, and then applies all Contacts and Ranges with start time in the past. Purging a Contact for transmission to some node other than the local node additionally removes the corresponding Xmit object. Applying a Contact sets the transmission or reception data rate between the local node and one of its Neighbors. Applying a Range sets the OWLT for the Origin of one of the affected nodes and either (a) if the other node is the local node, sets the OWLT for the corresponding Neighbor or (b) otherwise sets the OWLT for that other node's Origin. Setting data rate or OWLT for a node with which the local node will at some time be in direct communication may entail creation of a Neighbor object.

1.8.4 Route Computation

ION's computation of a route for a given bundle with a given destination endpoint is accomplished by one of two methods, depending on the destination. In every case, the result of successful routing is the insertion of the bundle into an outbound transmission queue (selected according to the bundle's priority) for one or more neighboring nodes.

But before discussing these methods it will be helpful to establish some terminology:

> Egress plans
>
> ION can only forward bundles to a neighboring node by queuing them on some explicitly specified outduct. Specifications that associate neighboring nodes with outducts – possibly varying depending on the node numbers and/or service numbers of bundles' source entity IDs – are termed *egress plans*.
>
> Static routes
>
> ION can be configured to forward to some specified node all bundles that are destined for a given node to which no *dynamic route* can be discovered from an examination of the contact graph, as described later. Static routing is implemented by means of the "group" mechanism described below.
>
> Groups
>
> When routes must be computed to nodes for which no contact plan information is known (.g., the size of the network makes it impractical to distribute all Contact and Range information for all nodes to every node, or the destination nodes don't participate in Contact Graph Routing at all), the job of computing routes to all nodes may be partitioned among multiple *gateway* nodes. Each gateway is responsible for managing routing information (for example, a comprehensive contact graph) for some subset of the total network population – a *group*, comprising all nodes whose node numbers fall within the range of node numbers assigned to the gateway. A bundle destined for a node for which no dynamic route can be computed from the local node's contact graph may be routed to the gateway node for the group within whose range the destination's node number falls. (Note that the group mechanism implements *static routes* in CGR in addition to improving scalability.)

We begin route computation by attempting to compute a dynamic route to the bundle's final destination node. The details of this algorithm are described in the section on ***Contact Graph Routing***, below.

If no dynamic route can be computed, but the final destination node is a "neighboring" node that is directly reachable, then we assume that taking this direct route is the best strategy unless the outduct to that neighbor is flagged as "blocked" due to a lapse in convergence-layer functionality .

Otherwise we must look for a static route. If the bundle's destination node number is in the range of node numbers assigned to the gateways for one or more groups, then we forward the bundle to that gateway node for the smallest such group. (If the gateway node is a neighbor and the outduct to that neighbor is not blocked, we simply queue the bundle on that outduct; otherwise we similarly look up the static route for the gateway until eventually we resolve to some egress plan.)

If we can determine neither a dynamic route nor a static route for this bundle, but the reason for this failure was outduct blockage that might be resolved in the future, then the bundle is placed in a "limbo" list for future re-forwarding when some outduct is "unblocked."

Otherwise, the bundle cannot be forwarded. If custody transfer is requested for the bundle, we send a custody refusal to the bundle's current custodian; in any case, we discard the bundle.

1.8.5 Delivery Assurance

End-to-end delivery of data can fail in many ways, at different layers of the stack. When delivery fails, we can either accept the communication failure or retransmit the data structure that was transmitted at the stack layer at which the failure was detected. ION is designed to enable retransmission at multiple layers of the stack, depending on the preference of the end user application.

At the lowest stack layer that is visible to ION, the convergence-layer protocol, failure to deliver one or more segments due to segment loss or corruption will trigger segment retransmission if a "reliable" convergence-layer protocol is in use: LTP "red-part" transmission or TCP (including Bundle Relay Service, which is based on TCP)[1].

Segment loss may be detected and signaled via NAK by the receiving entity, or it may only be detected at the sending entity by expiration of a timer prior to reception of an ACK. Timer interval computation is well understood in a TCP environment, but it can be a difficult problem in an environment of scheduled contacts as served by LTP. The round-trip time for an acknowledgment dialogue may be simply twice the one-way light time (OWLT) between sender and receiver at one moment, but it may be hours or days longer at the next moment due to cessation of scheduled contact until a future contact opportunity. To account for this timer interval variability in retransmission, the **ltpclock** task infers the initiation and cessation of LTP transmission, to and from the local node, from changes in the current xmit and recv data rates in the corresponding Neighbor objects. This controls the dequeuing of LTP segments for transmission by underlying link service adapter(s) and it also controls suspension and resumption of timers, removing

[1] In ION, reliable convergence-layer protocols (where available) are by default used for every bundle. The application can instead mandate selection of "best-effort" service at the convergence layer by setting the BP_BEST_EFFORT flag in the "extended class of service flags" parameter, but this feature is an ION extension that is not supported by other BP implementations at the time of this writing.

the effects of contact interruption from the retransmission regime. For a further discussion of this mechanism, see the section below on ***LTP Timeout Intervals***.

Note that the current OWLT in Neighbor objects is also used in the computation of the nominal expiration times of timers and that **ltpclock** is additionally the agent for LTP segment retransmission based on timer expiration.

It is, of course, possible for the nominally reliable convergence-layer protocol to fail altogether: a TCP connection might be abruptly terminated, or an LTP transmission might be canceled due to excessive retransmission activity (again possibly due to an unexpected loss of connectivity). In this event, BP itself detects the CL protocol failure and re-forwards all bundles whose acquisition by the receiving entity is presumed to have been aborted by the failure. This re-forwarding is initiated in different ways for different CL protocols, as implemented in the CL input and output adapter tasks.

In addition to the implicit forwarding failure detected when a CL protocol fails, the forwarding of a bundle may be explicitly refused by the receiving entity, provided the bundle is flagged for custody transfer service. A receiving node's refusal to take custody of a bundle may have any of a variety of causes: typically the receiving node either (a) has insufficient resources to store and forward the bundle, (b) has no route to the destination, or (c) will have no contact with the next hop on the route before the bundle's TTL has expired. In any case, a "custody refusal signal" (packaged in a bundle) is sent back to the sending node, which must re-forward the bundle in hopes of finding a more suitable route.

In the worst case, the combined efforts of all the retransmission mechanisms in ION are not enough to assure delivery of a given bundle, even when custody transfer is requested. In that event, the bundle's "time to live" will eventually expire while the bundle is still in custody at some node: the **bpclock** task will send a bundle status report to the bundle's report-to endpoint, noting the TTL expiration, and destroy the bundle. The report-to endpoint, upon receiving this report, may be able to initiate application-layer retransmission of the original application data unit in some way. This final retransmission mechanism is wholly application-specific, however.

1.8.6 Rate Control

In the Internet, the rate of transmission at a node can be dynamically negotiated in response to changes in level of activity on the link, to minimize congestion. On deep space links, signal propagation delays (distances) may be too great to enable effective dynamic negotiation of transmission rates. Fortunately, deep space links are operationally reserved for use by designated pairs of communicating entities over pre-planned periods of time at pre-planned rates. Provided there is no congestion inherent in the contact plan, congestion in the network can be avoided merely by adhering to the planned contact periods and data rates. *Rate control* in ION serves this purpose.

While the system is running, transmission and reception of bundles is constrained by the *current capacity* in the *throttle* of each outduct and induct. Completed bundle transmission or reception activity reduces the current capacity of the applicable duct by the capacity consumption computed for that bundle. This reduction may cause the duct's current capacity to become negative. Once the current capacity of the applicable duct's throttle goes negative, activity is blocked until non-negative capacity has been restored by **bpclock**.

Once per second, the **bpclock** task increases the current capacity of each induct and outduct throttle by one second's worth of traffic at the nominal data rate for that duct, thus enabling some possibly blocked bundle transmission and reception to proceed.

The nominal data rate for any duct of any CL protocol other than LTP (e.g., TCP) is a constant, established at the time the protocol was declared during ION initialization. For LTP, however, **bpclock** revises all ducts' nominal data rates once per second in accord with the current data rates in the corresponding Neighbor objects, as adjusted by **rfxclock** per the contact plan. This contact-plan-based adjustment is currently not possible for CL protocols other than LTP because at present there is no straightforward mechanism for mapping from Neighbor node number to protocol duct ID for any CL protocol other than LTP. So data flow over LTP links may be episodic, but data flow over non-LTP links is always continuous.

Note that this means that:

- ION's rate control system will enable data flow over non-LTP links even if there are no contacts in the contact plan that announce it. In this context the contact plan serves only to support route computation, and no contact plan is needed at all if static routes are provided for all destinations.
- ION's rate control system will enable data flow over LTP links ***only*** if there are contacts in the contact plan that announce it. In this context, announced contacts are mandatory for at least all neighboring nodes that are reachable by LTP.

1.8.7 Flow Control

A further constraint on rates of data transmission in an ION-based network is LTP flow control. LTP is designed to enable multiple block transmission sessions to be in various stages of completion concurrently, to maximize link utilization: there is no requirement to wait for one session to complete before starting the next one. However, if unchecked this design principle could in theory result in the allocation of all memory in the system to incomplete LTP transmission sessions. To prevent complete storage resource exhaustion, we set a firm upper limit on the total number of outbound blocks that can be concurrently in transit at any given time. These limits are established by **ltpadmin** at node initialization time.

The maximum number of transmission sessions that may be concurrently managed by LTP therefore constitutes a transmission "window" – the basis for a delay-tolerant, non-conversational flow control service over interplanetary links. Once the maximum number of sessions are in flight, no new block transmission session can be initiated – regardless of how much outduct transmission capacity is provided by rate control – until some existing session completes or is canceled.

Note that this consideration emphasizes the importance of configuring the aggregation size limits and session count limits of spans during LTP initialization to be consistent with the maximum data rates scheduled for contacts over those spans.

1.8.8 Storage Management

Congestion in a dtnet is the imbalance between data enqueuing and dequeuing rates that results in exhaustion of queuing (storage) resources at a node, preventing continued operation of the protocols at that node.

In ION, the affected queuing resources are allocated from notionally non-volatile storage space in the SDR data store. The design of ION is required to prevent resource exhaustion by simply refusing to enqueue additional data that would cause it.

However, a BP router's refusal to enqueue received data for forwarding could result in costly retransmission, data loss, and/or the "upstream" propagation of resource exhaustion to other nodes. Therefore the ION design additionally attempts to prevent <u>potential</u> resource exhaustion by forecasting levels of queuing resource occupancy and reporting on any congestion that is predicted. Network operators, upon reviewing these forecasts, may revise contact plans to avert the anticipated resource exhaustion.

The SDR data store used by ION serves several purposes: it contains queues of bundles awaiting forwarding, transmission, and delivery; it contains LTP transmission and reception sessions, including the blocks of data that are being transmitted and received; it contains queues of LTP segments awaiting radiation; and it contains protocol operational state information, such as configuration parameters, static routes, the contact graph, etc.

Effective utilization of SDR space is a complex problem. Static pre-allocation of storage resources is in general less efficient (and also more labor-intensive to configure) than storage resource pooling and automatic, adaptive allocation: trying to predict a reasonable maximum size for every data storage structure and then rigidly enforcing that limit typically results in underutilization of storage resources and underperformance of the system as a whole. However, static pre-allocation is mandatory for safety-critical resources, where certainty of resource availability is more important than efficient resource utilization.

The tension between the two approaches is closely analogous to the tension between circuit switching and packet switching in a network: circuit switching results in underutilization of link resources and underperformance of the network as a whole (some peaks of activity can never be accommodated, even while some resources lie idle much of the time), but dedicated circuits are still required for some kinds of safety-critical communication.

So the ION data management design combines these two approaches (see 1.5 above for additional discussion of this topic):

- A fixed percentage of the total SDR data store heap size (by default, 20%) is statically allocated to the storage of protocol operational state information, which is critical to the operation of ION.
- Another fixed percentage of the total SDR data store heap size (by default, 20%) is statically allocated to "margin", a reserve that helps to insulate node management from errors in resource allocation estimates.

- A fixed allocation, whose size is computed at LTP initialization time, is reserved for LTP transmission accounting. This assures that LTP traffic management is not affected by variations in bundle flow and vice versa.
- The remainder of the heap is allocated to bundle traffic[3]. Of this total:
    - A small fraction (one-sixteenth of the total, but at least 100 KB) is reserved for spikes in the reception of inbound bundles.
    - The *occupied fraction* of the total traffic allocation is either the *current occupancy* of the heap (the sum of the lengths of all bundles currently stored) or the *maximum projected occupancy* (as defined below), whichever is greater.
    - The *unoccupied fraction* of the total traffic allocation is the total traffic allocation less the occupied fraction.

The maximum projected occupancy of the node is the result of computing a *congestion forecast* for the node, by adding to the current occupancy all anticipated net increases and decreases from now until some future time, termed the *horizon* for the forecast.

The forecast horizon is indefinite – that is, "forever" – unless explicitly declared by network management via the `ionadmin` utility program. The difference between the horizon and the current time is termed the *interval* of the forecast.

Net occupancy increases and decreases are of four types:

1. Bundles that are originated locally by some application on the node, which are enqueued for forwarding to some other node.
2. Bundles that are received from some other node, which are enqueued either for forwarding to some other node or for local delivery to an application.
3. Bundles that are transmitted to some other node, which are dequeued from some forwarding queue.
4. Bundles that are delivered locally to an application, which are dequeued from some delivery queue.

The **ionadmin** utility program computes a congestion forecast each time it runs, immediately before it exits. The type-1 anticipated net increase (total data origination) is computed by multiplying the node's production rate, as declared via an **ionadmin** command, by the interval of the forecast. Similarly, the type-4 anticipated net decrease (total data delivery) is computed by multiplying the node's consumption rate, as declared via an **ionadmin** command, by the interval of the forecast. Net changes of types 2 and 3 are computed by multiplying inbound and outbound data rates, respectively, by the durations of all periods of planned communication contact that begin and/or end within the interval of the forecast.

If the final result of the forecast computation – the maximum projected occupancy of the node over the forecast interval – is less than the total protocol traffic allocation, then no

[3] Note that, in all occupancy figures, ION data management accounts not only for the sizes of the payloads of all queued bundles but also for the sizes of their headers.

congestion is forecast. Otherwise, a congestion forecast status message is logged noting the time at which maximum projected occupancy is expected to equal the total protocol traffic allocation.

Congestion control in ION, then, has two components:

> First, ION's congestion detection is anticipatory (via congestion forecasting) rather than reactive as in the Internet.
>
> Anticipatory congestion detection is important because the second component – congestion mitigation – must also be anticipatory: it is the adjustment of communication contact plans by network management, via the propagation of revised schedules for future contacts.

(Congestion mitigation in an ION-based network is likely to remain mostly manual for many years to come, because communication contact planning involves much more than mathematics: science operations plans, thermal and power constraints, etc. It will, however, rely on the automated rate control features of ION, discussed above, which assure that actual network operations conform to established contact plans.)

The computed maximum projected occupancy of the node is additionally retained in the RFX database for the purpose of *admission control*. ION will not permit new bundles to be locally originated when queuing them for forwarding would reduce the unoccupied fraction of the total traffic allocation (as defined above) to less than the level reserved for spikes in inbound bundle reception.

That is, ION's admission control mechanism implicitly recognizes that the node's first responsibility is to conform to contact plans (thus minimizing congestion elsewhere in the network) by receiving expected inbound data whenever possible; this is the reason for maintaining an explicit reserve for inbound bundle reception spikes. Note that there is no such explicit reserve for the node's total net bundle reception rate. This is because an implicit reserve for reception traffic is already built into the congestion forecast computation. Every received bundle is either:

- Immediately delivered to a local application, with no net effect on traffic allocation occupancy.
- Immediately forwarded and transmitted to another node, with no net effect on traffic allocation occupancy.
- Or queued for future forwarding or delivery, in which case its size is already reflected in the computed maximum projected occupancy (limiting the unoccupied fraction of the total traffic allocation) – so it has no additional net effect on traffic allocation occupancy.

1.8.9 Optimizing an ION-based network

ION is designed to deliver critical data to its final destination with as much certainty as possible (and optionally as soon as possible), but otherwise to try to maximize link utilization. The delivery of critical data is expedited by contact graph routing and bundle prioritization as described elsewhere. Optimizing link utilization, however, is a more complex problem.

If the volume of data traffic offered to the network for transmission is less than the capacity of the network, then all offered data should be successfully delivered[4]. But in that case the users of the network are paying the opportunity cost of whatever portion of the network capacity was not used.

Offering a data traffic volume that is exactly equal to the capacity of the network is in practice infeasible. TCP in the Internet can usually achieve this balance because it exercises end-to-end flow control: essentially, the original source of data is *blocked* from offering a message until notified by the final destination that transmission of this message can be accommodated given the current negotiated data rate over the end-to-end path (as determined by TCP's congestion control mechanisms). In a delay-tolerant network no such end-to-end negotiated data rate may exist, much less be knowable, so such precise control of data flow is impossible.[5]

The only alternative: the volume of traffic offered by the data source must be greater than the capacity of the network and the network must automatically discard excess traffic, shedding lower-priority data in preference to high-priority messages on the same path.

ION discards excess traffic proactively when possible and reactively when necessary.

<u>Proactive data triage</u> occurs when ION determines that it cannot compute a route that will deliver a given bundle to its final destination prior to expiration of the bundle's Time To Live (TTL). That is, a bundle may be discarded simply because its TTL is too short, but more commonly it will be discarded because the planned contacts to whichever neighboring node is first on the path to the destination are already fully subscribed: the queue of bundles awaiting transmission to that neighbor is already so long as to consume the entire capacity of all announced opportunities to transmit to it. Proactive data triage causes the bundle to be immediately destroyed as one for which there is "No known route to destination from here."

The determination of the degree to which a contact is subscribed is based not only on the aggregate size of the queued bundles but also on the estimated aggregate size of the overhead imposed by all the convergence-layer (CL) protocol data units – at all layers of the underlying stack – that encapsulate those bundles: packet headers, frame headers, etc. This means that the accuracy of this overhead estimate will affect the aggressiveness of ION's proactive data triage:

- If CL overhead is overestimated, the size of the bundle transmission backlog for planned contacts will be overstated, unnecessarily preventing the enqueuing of additional bundles – a potential under-utilization of available transmission capacity in the network.
- If CL overhead is underestimated, the size of the bundle transmission backlog for planned contacts will be understated, enabling the enqueuing of bundles whose

[4] Barring data loss or corruption for which the various retransmission mechanisms in ION cannot compensate.

[5] Note that ION may indeed block the offering of a message to the network, but this is local admission control – assuring that the node's local buffer space for queuing outbound bundles is not oversubscribed – rather than end-to-end flow control. It is always possible for there to be ample local buffer space yet insufficient network capacity to convey the offered data to their final destination, and vice versa.

transmission cannot in fact be accomplished by the network within the constraints of the current contact plan. This will eventually result in reactive data triage.

Essentially, all reactive data triage – the destruction of bundles due to TTL expiration prior to successful delivery to the final destination – occurs when the network conveys bundles at lower net rates than were projected during route computation. These performance shortfalls can have a variety of causes:

- As noted above, underestimating CL overhead causes CL overhead to consume a larger fraction of contact capacity than was anticipated, leaving less capacity for bundle transmission.
- Conversely, the total volume of traffic offered may have been accurately estimated but the amount of contact capacity may be less than was promised: a contact might be started late, stopped early, or omitted altogether, or the actual data rate on the link might be less than was advertised.
- Contacts may be more subtly shortened by the configuration of ION itself. If the clocks on nodes are known not to be closely synchronized then a "maximum clock error" of N seconds may be declared, causing reception episodes to be started locally N seconds earlier and stopped N seconds later than scheduled, to avoid missing some transmitted data because it arrived earlier than anticipated. But this mechanism also causes transmission episodes to be started N seconds later and stopped N seconds earlier than scheduled, to avoid transmitting to a neighbor before it is ready to receive data, and this contact truncation ensures transmission of fewer bundles than planned.
- Flow control within the convergence layer underlying the bundle protocol may constrain the effective rate of data flow over a link to a rate that's lower than the link's configured maximum data rate. In particular, mis-configuration of the LTP flow control window can leave transmission capacity unused while LTP engines are awaiting acknowledgments.
- Even if all nodes are correctly configured, a high rate of data loss or corruption due to unexpectedly high R/F interference or underestimated acknowledgment round-trip times may cause an unexpectedly high volume of retransmission traffic. This will displace original bundle transmission, reducing the effective "goodput" data rate on the link.
- Finally, custody transfer may propagate operational problems from one part of the network to other nodes. One result of reduced effective transmission rates is the accumulation of bundles for which nodes have taken custody: the custodial nodes can't destroy those bundles and reclaim the storage space they occupy until custody has been accepted by "downstream" nodes, so abbreviated contacts that prevent the flow of custody acceptances can increase local congestion. This reduces nodes' own ability to take custody of bundles transmitted by "upstream" custodians, increasing queue sizes on those nodes, and so on. In short, custody transfer may itself ultimately impose reactive data triage simply by propagating congestion.

Some level of data triage is essential to cost-effective network utilization, and proactive triage is preferable because its effects can be communicated immediately to users, improving user control over the use of the network. Optimizing an ION-based network therefore amounts to managing for a modicum of proactive data triage and as little reactive data triage as possible. It entails the following:

1. Estimating convergence-layer protocol overhead as accurately as possible, erring (if necessary) on the side of optimism – that is, underestimating a little.

    > As an example, suppose the local node uses LTP over CCSDS Telemetry to send bundles. The immediate convergence-layer protocol is LTP, but the total overhead per CL "frame" (in this case, per LTP segment) will include not only the size of the LTP header (nominally 5 bytes) but also the size of the encapsulating space packet header (nominally 6 bytes) and the overhead imposed by the outer encapsulating TM frame.
    >
    > Suppose each LTP segment is to be wrapped in a single space packet, which is in turn wrapped in a single TM frame, and Reed-Solomon encoding is applied. An efficient TM frame size is 1115 bytes, with an additional 160 bytes of trailing Reed-Solomon encoding and another 4 bytes of leading pseudo-noise code. The frame would contain a 6-byte TM frame header, a 6-byte space packet header, a 5-byte LTP segment header, and 1098 bytes of some LTP transmission block.
    >
    > So the number of "payload bytes per frame" in this case would be 1098 and the number of "overhead bytes per frame" would be 4 + 6 + 6 + 5 + 160 = 181. Nominal total transmission overhead on the link would be 181 / 1279 = about 14%.

2. Synchronizing nodes' clocks as accurately as possible, so that timing margins configured to accommodate clock error can be kept as close to zero as possible.
3. Setting the LTP session limit and block size limit as generously as possible (whenever LTP is at the convergence layer), to assure that LTP flow control does not constrain data flow to rates below those supported by BP rate control.
4. Setting ranges (one-way light times) and queuing delays as accurately as possible, to prevent unnecessary retransmission. Err on the side of pessimism – that is, overestimate a little.
5. Communicating changes in configuration – especially contact plans – to all nodes as far in advance of the time they take effect as possible.
6. Providing all nodes with as much storage capacity as possible for queues of bundles awaiting transmission.

1.9 BP/LTP detail – how it works

Although the operation of BP/LTP in ION is complex in some ways, virtually the entire system can be represented in a single diagram. The interactions among all of the concurrent tasks that make up the node – plus a Remote AMS task or CFDP UT-layer task, acting as the application at the top of the stack – are shown below. (The notation is as used earlier but with semaphores added. Semaphores are shown as small circles, with arrows pointing into them signifying that the semaphores are being given and arrows pointing out of them signifying that the semaphores are being taken.)

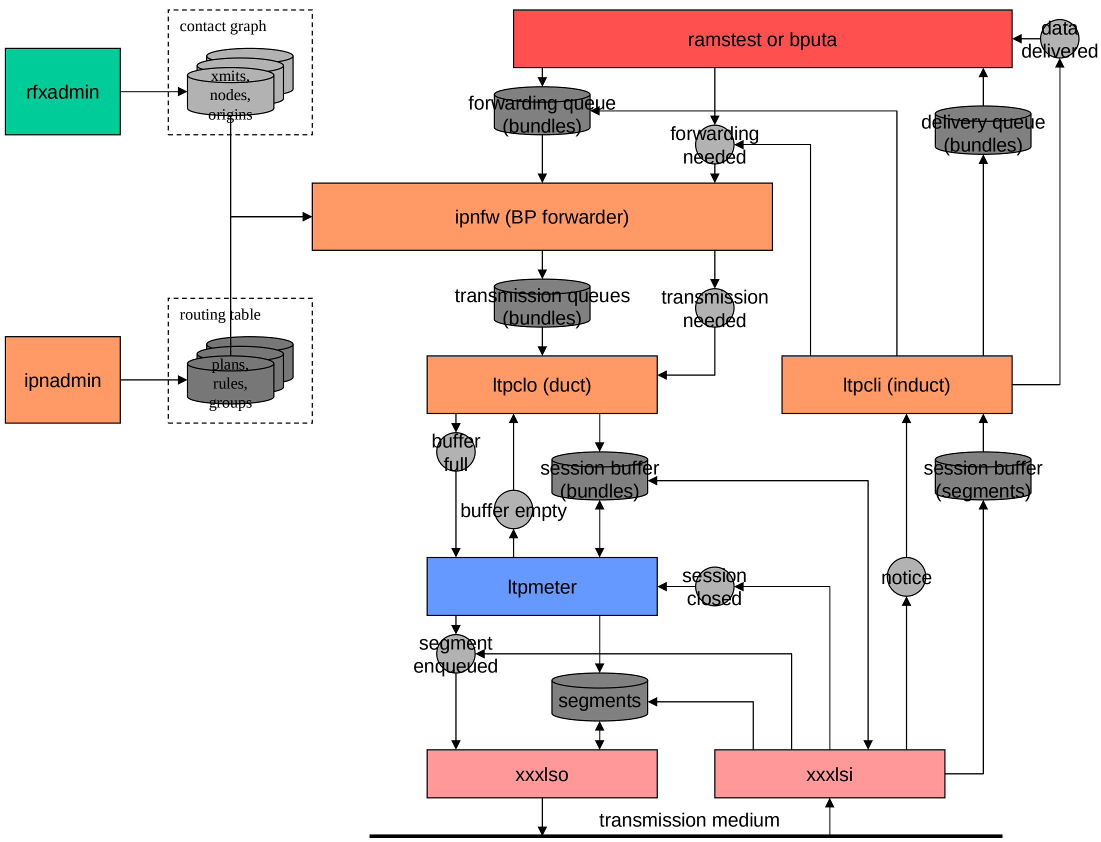


Figure 7 ION node functional overview

Further details of the BP/LTP data structures and flow of control and data appear on the following pages. (For specific details of the operation of the BP and LTP protocols as implemented by the ION tasks, such as the nature of report-initiated retransmission in LTP, please see the protocol specifications. The BP specification is documented in Internet RFC 5050, while the LTP specification is documented in Internet RFC 5326.)

1.9.1 Databases

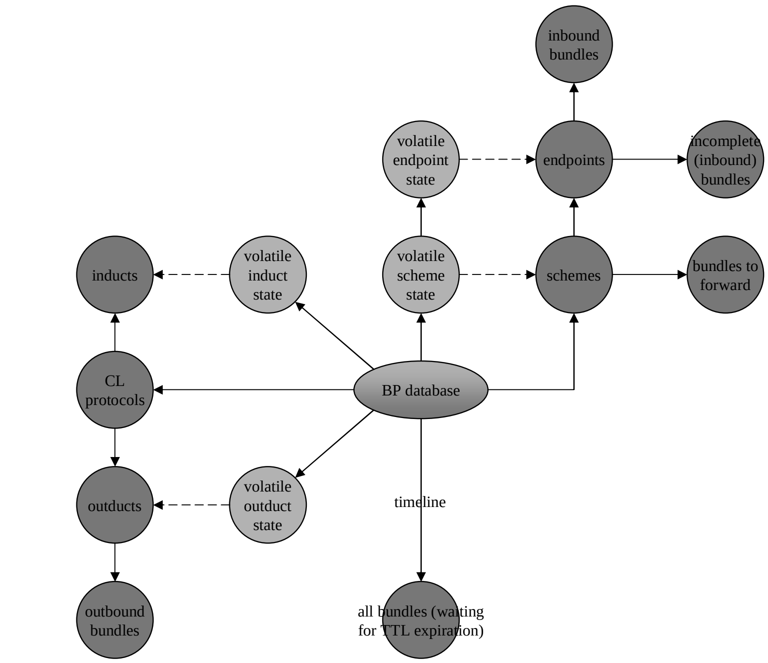


Figure 8 Bundle protocol database

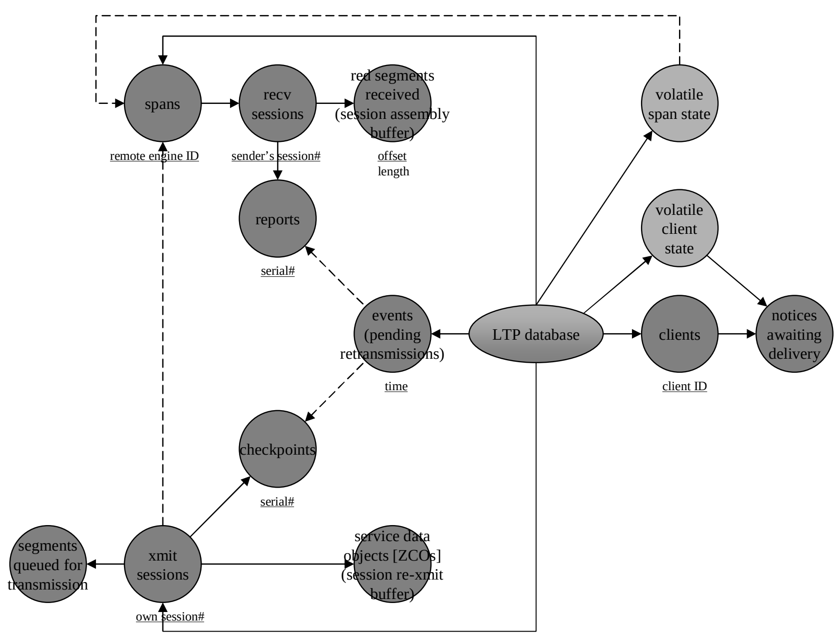
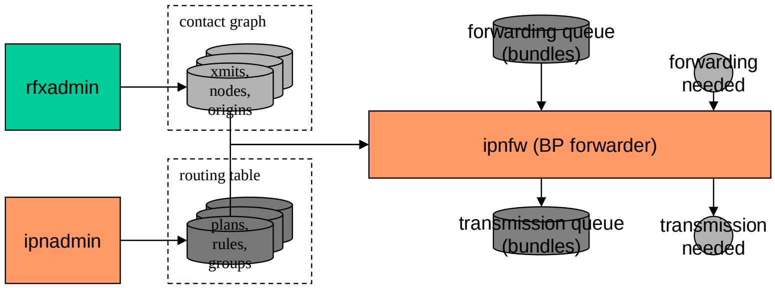


Figure 9 Licklider transmission protocol database

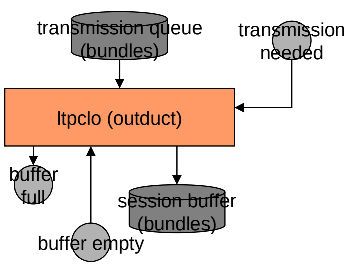
1.9.2 Control and data flow

Bundle Protocol



1. Waits for *forwarding needed* semaphore.
2. Gets bundle from queue.
3. Consults routing table and contact graph to determine all plausible proximate destinations – routing.
   - A plausible proximate destination is the destination node of the first entry in a contact sequence (a list of concatenated, connected contact periods) ending in a contact period whose destination node is the bundle's destination node and whose start time is less than the bundle's expiration time.
4. Appends bundle to transmission queue (based on priority) for best plausible proximate destination.
5. Gives *transmission needed* semaphore for that transmission queue.

Figure 10 BP forwarder



1. Waits for *buffer empty* semaphore (indicating that the link's session buffer has room for the bundle).
2. Waits for *transmission needed* semaphore.
3. Gets bundle from queue, subject to priority.
4. Appends bundle to link's session buffer – aggregation. Buffer size is notionally limited by aggregation size limit, a persistent attribute of the Duct object: implicitly, the rate at which we want reports to be transmitted by the destination engine.
5. Gives *buffer full* semaphore when buffer occupancy reaches the aggregation size limit.

Figure 11 BP convergence layer output

1. Waits for *notice* semaphore (indicating that reception buffer is complete – "red part" of block has been reconstituted).
2. Extracts and dispatches all bundles in reception buffer:
   - If no room for bundle in local storage, destroys bundle.
   - If bundle's destination endpoint is at the local node:
     - If destination endpoint is unknown, destroys bundle.
     - Otherwise appends bundle to delivery queue for that endpoint and gives *data delivered* semaphore.
   - Otherwise:
     - If scheme identified by the destination endpoint is unknown, destroys bundle.
     - Otherwise appends bundle to forwarding queue for that scheme and gives *forwarding needed* semaphore.
3. For each destroyed bundle for which custody transfer was requested, posts custody refusal bundle. (Creates bundle, appends to forwarding queue, gives *forwarding needed* semaphore.)

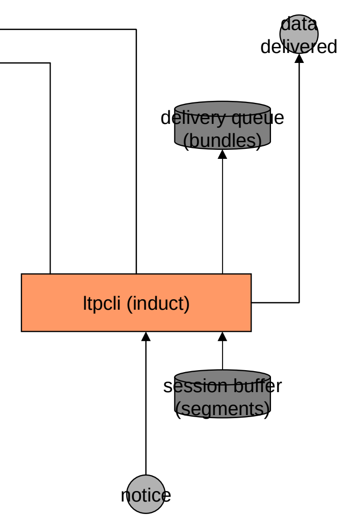


Figure 12 BP convergence layer input

LTP

1. Waits for *session closed* semaphore (indicating that a new session can be started) – flow control.
2. Initializes session buffer, gives *buffer empty* semaphore.
3. Waits for *buffer full* semaphore (indicating that the session buffer is ready for transmission).
4. Segments the entire buffer into segments of managed MTU size – fragmentation.
5. Appends all segments to segments queue for immediate transmission.
6. Gives *segment enqueued* semaphore.

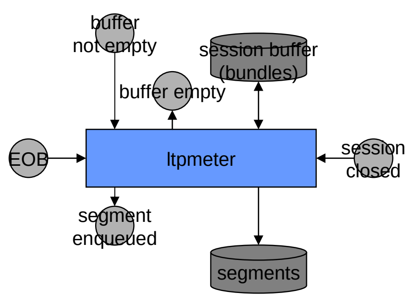


Figure 13 LTP transmission metering

1. Waits for *segment enqueued* semaphore (indicating that there is now something to transmit).
2. Gets segment from queue.
3. Sets retransmission timer if necessary.
4. Transmits the segment using link service protocol.

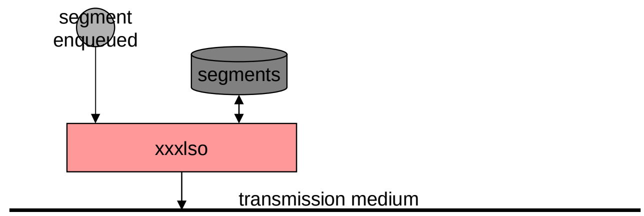


Figure 14 LTP link service output

1. Receives a segment using link service protocol.
2. If data, generates report segment and appends it to queue – reliability. Also inserts data into reception session buffer "red part" and, if that buffer is complete, gives *notice* semaphore to trigger bundle extraction and dispatching by ltpcli.
3. If a report, appends acknowledgement to segments queue.
4. If a report of missing data, recreates lost segments and appends them to queue.
5. If a report of complete reception, clears transmission session buffer and gives *session closed* semaphore.
6. Gives *segment enqueued* semaphore.

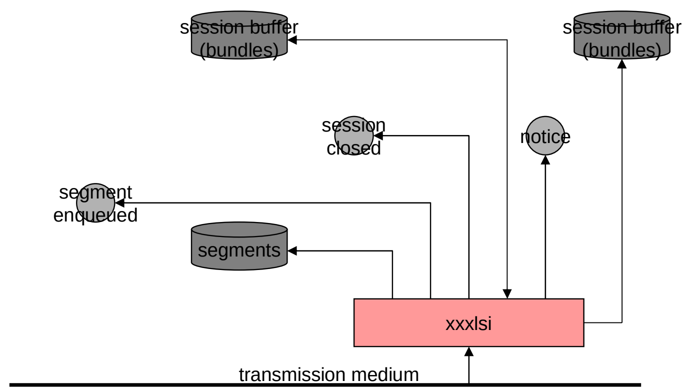


Figure 15 LTP link service input

1.10 Contact Graph Routing (CGR)

CGR is a dynamic routing system that computes routes through a time-varying topology of scheduled communication contacts in a DTN network. It is designed to support operations in a space network based on DTN, but it also could be used in terrestrial applications where operation according to a predefined schedule is preferable to opportunistic communication, as in a low-power sensor network.

The basic strategy of CGR is to take advantage of the fact that, since communication operations are planned in detail, the communication routes between any pair of "bundle agents" in a population of nodes that have all been informed of one another's plans can be inferred from those plans rather than discovered via dialogue (which is impractical over long-one-way-light-time space links).

1.10.1 Contact Plan Messages

CGR relies on accurate contact plan information provided in the form of contact plan messages that currently are only read from **ionrc** files and processed by **ionadmin**, which retains them in the topology timeline of the RFX database, in ION's SDR data store.

Contact plan messages are of two types: *contact messages* and *range messages*.

Each contact message has the following content:

- The starting UTC time of the interval to which the message pertains.
- The stop time of this interval, again in UTC.
- The Transmitting node number.
- The Receiving node number.
- The planned rate of transmission from node A to node B over this interval, in bytes per second.

Each range message has the following content:

- The starting UTC time of the interval to which the message pertains.
- The stop time of this interval, again in UTC.
- Node number A.
- Node number B.
- The anticipated distance between A and B over this interval, in light seconds.

1.10.2 Contact Graphs

Each node uses Range and Contact timeline entries to build a "contact graph" data structure. The contact graph constructed locally by each node in the network contains, <u>for every other node D in the network</u>:

- A list of *xmit* objects encapsulating Contact start time, stop time, transmitting node number, and data transmission rate, derived from all Contact messages whose receiving node is node D; ordered by stop time.
- A list of *origin* objects encapsulating transmitting node number S and that node's presumed current distance from node D, based on the information in Range messages.

This information is periodically updated by the **rfxclock** task, which applies stored Contact and Range messages to the contact graph as their start times are reached, purging Contact and Range messages and corresponding xmit objects whose stop times have passed.

1.10.3 Key Concepts

Well-formed routes

A well-formed route for given bundle is defined as a sequence of contacts such that the first contact is from the bundle's source to some other node, every subsequent contact in the sequence is from the receiving node of the prior contact to some other node, the last contact in the sequence is from some node to the bundle's final destination, and the route contains no loops – i.e., no two contacts in the sequence involve transmission from the same node and no two contacts in the sequence involve transmission to the same node.

Expiration time

Every bundle transmitted via DTN has a time-to-live (TTL), the length of time after which the bundle is subject to destruction if it has not yet been delivered to its destination. The *expiration time* of a bundle is computed as its creation time plus its TTL. When computing the next-hop destination for a bundle that the local bundle agent is required to forward, there is no point in selecting a route that can't get the bundle to its final destination prior to the bundle's expiration time.

OWLT margin

One-way light time (OWLT) – that is, distance – is obviously a factor in delivering a bundle to a node prior to a given time. OWLT can actually change during the time a bundle is en route, but route computation becomes intractably complex if we can't assume an OWLT "safety margin" – a maximum delta by which OWLT between any pair of nodes can change during the time a bundle is in transit between them.

We assume that the maximum rate of change in distance between any two nodes in the network is about 150,000 miles per hour, which is about 40 miles per second. (This was the speed of the Helios spacecraft, the fastest man-made object launched to date.)

At this speed, the distance between any two nodes that are initially separated by a distance of N light seconds will increase by a maximum of 40 miles per second of transit. This will result in data arrival no later than roughly (N + Q) seconds after transmission – where the "OWLT margin" value Q is (40 * N) divided by 186,000 – rather than just N seconds after transmission as would be the case if the two nodes were stationary relative to each other. When computing the expected time of arrival of a transmitted bundle we simply use N + Q, the most pessimistic case, as the anticipated total in-transit time.

Last moment

The *last moment* for sending a bundle during a given contact such that it will arrive at the receiving node prior to some deadline is computed as the deadline minus the sum of (a) the current one-way light time N between the contact's transmitting and receiving nodes (which can be obtained from the origin object for the transmitting node, in the receiving node's list of origins) and (b) the applicable OWLT margin for N, as above. If the contact's start time is after the last moment for the deadline, then clearly no transmission whatsoever that is initiated during that contact can be assured of getting the bundle to the contact's receiving node prior to the deadline.

Capacity

The *capacity* of a contact is the product of its data transmission rate (in bytes per second) and its duration (stop time minus start time, in seconds).

Estimated capacity consumption

The size of a bundle is the sum of its payload size and its header size[6], but bundle size is not the only lien on the capacity of a contact. The total estimated capacity consumption (or "ECC") for a bundle that is queued for transmission via some outduct is a more lengthy computation.

For each recognized convergence-layer protocol, we can estimate the number of bytes of "overhead" (that is, data that serves the purposes of the protocol itself rather than the user application that is using it) for each frame of convergence-layer protocol transmission. If the convergence layer protocol were UDP/IP over the Internet, for example, we might estimate the convergence layer overhead per frame to be 100 bytes – allowing for the nominal sizes of the UDP, IP, and Ethernet or SONET overhead for each IP packet.

We can estimate the number of bundle bytes per CL protocol frame as the total size of each frame less the per-frame convergence layer overhead. Continuing the example begun above, we might estimate the number of bundle bytes per frame to be 1400, which is the standard MTU size on the Internet (1500 bytes) less the estimated convergence layer overhead per frame

We can then estimate the total number of frames required for transmission of a bundle of a given size: this number is the bundle size divided by the estimated number of bundle bytes per CL protocol frame, rounded up.

The estimated total convergence layer overhead for a given bundle is, then, the per-frame convergence layer overhead multiplied by the total number of frames required for transmission of a bundle of that size

Finally the ECC for that bundle can be computed as the sum of the bundle's size and its estimated total convergence layer overhead.

[6] The minimum size of an ION bundle header is 26 bytes. Adding extension blocks (such as those that effect the Bundle Security Protocol) will increase this figure.

Residual capacity

The *residual capacity* of a given contact between the local node and one of its neighbors, as computed for a given bundle, is the sum of the capacities of that contact and all prior scheduled contacts between the local node and that neighbor, less the sum of the ECCs of all bundles with priority equal to or higher than the priority of the subject bundle that are currently queued on the outduct for transmission to that neighbor.

Plausible opportunity

A *plausible opportunity* for transmitting a given bundle to some neighboring node is defined as a contact whose residual capacity is at least equal to the bundle's ECC. That is, if the capacity of a given contact is already fully subscribed, when computing routes for the next bundle there is no purpose served by assuming transmission during that contact.

Plausible routes

A *plausible route* for a given bundle is a well-formed route whose constituent contacts are all plausible transmission opportunities such that transmission of the bundle during each contact can occur before the last moment for that contact's applicable deadline. The applicable deadline for the last contact in the route is the bundle's expiration time; the applicable deadline for each preceding contact is the end of that contact.

Forfeit time

The *forfeit time* for a plausible route is the time by which the subject bundle must be transmitted from the local node to a neighboring node in order to have any chance of taking that route. Typically it is the stop time of the first contact in the route (the contact between the local node and its neighbor). However, it is possible for the first contact in a route to be a continuous contact, in which case the actual forfeit time may be the stop time of a downstream contact that starts after the start of the first contact but ends before the first contact stops. So, more generally, the forfeit time for a route is the earliest stop time among all contacts in the route.

Network distance

The *network distance* for a plausible route is the number of intermediate forwarding nodes that will be utilized in conveying the bundle to the destination node from the node at which route computation is being performed.

Excluded neighbors

A neighboring node C that refuses custody of a bundle destined for some remote node D is termed an *excluded neighbor* for (that is, with respect to computing routes to) D. So long as C remains an excluded neighbor for D, no bundles destined for D will be forwarded to C – except that occasionally (once per lapse of the RTT between the local node and C) a custodial bundle destined for D will be forwarded to C as a "probe bundle". C ceases to be an excluded neighbor for D as soon as it accepts custody of a bundle destined for D.

Critical bundles

A Critical bundle is one that absolutely has got to reach its destination and, moreover, has got to reach that destination as soon as is physically possible[7].

For ordinary non-Critical bundles, the CGR dynamic route computation algorithm uses the contact graph to calculate which of the plausible routes to the bundle's final destination is determined to be "best" (as defined below). It then inserts the bundle into the outbound transmission queue for transmission to the neighboring node that is the first step along that route. It is possible, though, that due to some unforeseen delay the selected route will turn out to be less successful than another route that was not selected: the bundle might arrive later than it would have if another route had been selected, or it might not even arrive at all.

For Critical bundles, the CGR dynamic route computation algorithm causes the bundle to be inserted into the outbound transmission queues for transmission to <u>all</u> neighboring nodes that are on plausible routes to the bundle's final destination. The bundle is therefore guaranteed to travel over the most successful route, as well as over all other plausible routes. Note that this may result in multiple copies of a Critical bundle arriving at the final destination.

1.10.4 Dynamic Route Computation Algorithm

We start this algorithm by setting destination variable *D* to the bundle's final destination node number, setting "deadline" variable **X** to the bundle's expiration time, creating an empty list of Proximate Nodes to send to, initializing the forfeit time to infinity, initializing network distance to zero, and creating a list of Excluded Nodes, i.e., nodes through which we will <u>not</u> compute a route for this bundle. The list of Excluded Nodes is initially populated with:

- the node from which the bundle was directly received (so that we avoid cycling the bundle between that node and the local node) – <u>unless</u> the Dynamic Route Computation Algorithm is being re-applied due to custody refusal as discussed later;
- all excluded neighbors for the bundle's final destination node.

Then we invoke the **Contact Review Procedure** as described below.

Contact Review Procedure:

> First append node *D* to the list of Excluded Nodes, to prevent routing loops. (We don't want to re-compute routes through *D* in the course of computing routes for the intermediate nodes on any path to *D*.)
>
> Then, for each xmit *m* in node *D*'s list of xmits (in descending order of transmission stop time):
>
> > If either the current time or *m*'s start time is after the last moment **T** (a function of *m*) for deadline **X**, then skip this xmit.

[7] In ION, all bundles are by default non-critical. The application can indicate that data should be sent in a Critical bundle by setting the BP_MINIMUM_LATENCY flag in the "extended class of service" parameter, but this feature is an ION extension that is not supported by other BP implementations at the time of this writing.

Otherwise:

If *D* is the final destination node:

Set projected delivery time on this path to *m*'s stop time.

If *m*'s transmitting node *S* is the local node (that is, *D* is a neighbor of the local node):

Compute the ECC of the bundle, assuming transmission via the local node's outduct to *D*.

If *m*'s residual capacity is less than the computed ECC, then skip this xmit.

Otherwise, if *D* is already in the list of Proximate Nodes to send this bundle to:

If the path's projected delivery time is less than the projected delivery time currently noted for *D*, change to the new projected delivery time.

If the path's projected delivery time is the same as the one that's currently noted for *D* but its network distance is less than the network distance currently noted for *D*, change to the new network distance.

Otherwise:

Add *D* to the list of Proximate Nodes.

Note the path's projected delivery time and network distance in the event that the bundle is queued for transmission to *D*.

Otherwise:

If *S* is already in the list of Excluded Nodes, then skip this xmit.

Otherwise:

If *m*'s stop time is less than the forfeit time computed so far for this path:

Set the forfeit time to *m*'s stop time.

Compute *estimated forwarding latency* **L** as twice the size of the bundle, divided by the data transmission rate for xmit *m*. (This value is used to allow for the time needed by node *S* simply to receive the bundle from its origin, queue it for transmission, and re-radiate it.)

Invoke the **Contact Review Procedure** again, recursively, but with destination variable *D* now set to *S*, with network distance increased by 1, and with deadline variable **X** set to either **T** or the time that is **L** seconds before the stop time of xmit *m*, whichever is earlier.

Finally, remove *D* from the list of Excluded Nodes and let the forfeit time and network distance revert to their previous values (unraveling the recursion stack).

At this point, each member of the Proximate Nodes list is a neighboring node to which we can forward the bundle in the expectation that one of that node's planned contacts will enable conveyance of the bundle on a plausible route toward its final destination.

If the list of Proximate Nodes is non-empty:

If the bundle is Critical, then we now insert the bundle into the appropriate outbound transmission queue (depending on priority) for every Proximate Node in the list.

Otherwise (the bundle is non-critical, so we must select only a single Proximate Node for transmission):

We insert the bundle into the appropriate outbound transmission queue (depending on priority) of the Proximate Node that has the earliest associated projected delivery time.

If the earliest projected delivery time is associated with multiple Proximate Nodes, we choose the one that has the smallest associated network distance.

If both the earliest projected delivery time and the smallest network distance are associated with multiple Proximate Nodes, we arbitrarily choose the one with the smallest node number.

1.10.5 Exception Handling

Conveyance of a bundle from source to destination through a DTN can fail in a number of ways, many of which are best addressed by means of the Delivery Assurance mechanisms described earlier. Failures in Contact Graph Routing, specifically, occur when the expectations on which routing decisions are based prove to be false. These failures of information fall into two general categories: contact failure and custody refusal.

1) <u>Contact failure</u>

A scheduled contact between some node and its neighbor on the end-to-end route may be initiated later than the originally scheduled start time, or be terminated earlier than the originally scheduled stop time, or be canceled altogether. Alternatively, the available capacity for a contact might be overestimated due to, for example, diminished link quality resulting in unexpectedly heavy retransmission at the convergence layer. In each of these cases, the anticipated transmission of a given bundle during the affected contact may not occur as planned: the bundle might expire before the contact's start time, or the contact's stop time might be reached before the bundle has been transmitted.

For a non-Critical bundle, we handle this sort of failure by means of a timeout: if the bundle is not transmitted prior to the forfeit time for the selected Proximate Node, then the bundle is removed from its outbound transmission queue and the Dynamic Route Computation Algorithm is re-applied to the bundle so that an alternate route can be computed.

2) Custody refusal

A node that receives a bundle may find it impossible to forward it, for any of several reasons: it may not have enough storage capacity to hold the bundle, it may be unable to compute a forward route (static, dynamic, or default) for the bundle, etc. Such bundles are simply discarded, but discarding any such bundle that is marked for custody transfer will cause a custody refusal signal to be returned to the bundle's current custodian.

When the affected bundle is non-Critical, the node that receives the custody refusal re-applies the Dynamic Route Computation Algorithm to the bundle so that an alternate route can be computed – except that in this event the node from which the bundle was originally directly received is omitted from the initial list of Excluded Nodes. This enables a bundle that has reached a dead end in the routing tree to be sent back to a point at which an altogether different branch may be selected.

For a Critical bundle no mitigation of either sort of failure is required or indeed possible: the bundle has already been queued for transmission on all plausible routes, so no mechanism that entails re-application of CGR's Dynamic Route Computation Algorithm could improve its prospects for successful delivery to the final destination. However, in some environments it may be advisable to re-apply the Dynamic Route Computation Algorithm to all Critical bundles that are still in local custody whenever a new Contact is added to the contact graph: the new contact may open an additional forwarding opportunity for one or more of those bundles.

1.10.6 Remarks

The CGR routing procedures respond dynamically to the changes in network topology that the nodes are able know about, i.e., those changes that are subject to mission operations control and are known in advance rather than discovered in real time. This dynamic responsiveness in route computation should be significantly more effective and less expensive than static routing, increasing total data return while at the same time reducing mission operations cost and risk.

Note that the non-Critical forwarding load across multiple parallel paths should be balanced automatically:

- Initially all traffic will be forwarded to the node(s) on what is computed to be the best path from source to destination.
- At some point, however, a node on that preferred path may have so much outbound traffic queued up that no contacts scheduled within bundles' lifetimes have any residual capacity. This can cause forwarding to fail, resulting in custody refusal.

- Custody refusal causes the refusing node to be temporarily added to the current custodian’s excluded neighbors list for the affected final destination node. If the refusing node is the only one on the path to the destination, then the custodian may end up sending the bundle back to its upstream neighbor. Moreover, that custodian node too may begin refusing custody of bundles subsequently sent to it, since it can no longer compute a forwarding path.
- The upstream propagation of custody refusals directs bundles over alternate paths that would otherwise be considered suboptimal, balancing the queuing load across the parallel paths.
- Eventually, transmission and/or bundle expiration at the oversubscribed node relieves queue pressure at that node and enables acceptance of custody of a “probe” bundle from the upstream node. This eventually returns the routing fabric to its original configuration.

Although the route computation procedures are relatively complex they are not computationally difficult. The impact on computation resources at the vehicles should be modest.

1.11 LTP Timeout Intervals

Suppose we've got Earth ground station ES that is currently in view of Mars but will be rotating out of view ("Mars-set") at some time T1 and rotating back into view ("Mars-rise") at time T3. Suppose we've also got Mars orbiter MS that is currently out of the shadow of Mars but will move behind Mars at time T2, emerging at time T4. Let's also suppose that ES and MS are 4 light-minutes apart (Mars is at its closest approach to Earth). Finally, for simplicity, let's suppose that both ES and MS want to be communicating at every possible moment (maximum link utilization) but never want to waste any electricity.

Neither ES nor MS wants to be wasting power on either transmitting or receiving at a time when either Earth or Mars will block the signal.

ES will therefore stop transmitting at either T1 or (T2 - 4 minutes), whichever is earlier; call this time T_{et0}. It will stop receiving – that is, power off the receiver – at either T1 or (T2 + 4 minutes), whichever is earlier; call this time T_{er0}. It will resume transmitting at either T3 or (T4 - 4 minutes), whichever is <u>later</u>, and it will resume reception at either T3 or (T4 + 4 minutes), whichever is later; call these times T_{et1} and T_{er1}.

Similarly, MS will stop transmitting at either T2 or (T1 - 4 minutes), whichever is earlier; call this time T_{mt0}. It will stop receiving – that is, power off the receiver – at either T2 or (T1 + 4 minutes), whichever is earlier; call this time T_{mr0}. It will resume transmitting at either T4 or (T3 - 4 minutes), whichever is later, and it will resume reception at either T4 or (T3 + 4 minutes), whichever is later; call these times T_{mt1} and T_{mr1}.

By making sure that we don't transmit when the signal would be blocked, we guarantee that anything that is transmitted will arrive at a time when it can be received. Any reception failure is due to data corruption en route.

So the moment of transmission of an acknowledgment to any message is always equal to the moment the original message was sent plus some imputed outbound queuing delay QO1 at the sending node, plus 4 minutes, plus some imputed inbound and outbound queuing delay QI1 + QO2 at the receiving node. The nominally expected moment of reception of this acknowledgment is that moment of transmission plus 4 minutes, plus some imputed inbound queuing delay QI2 at the original sending node. That is, the timeout interval is 8 minutes + QO1 + QI1 + QO2 + QO2 – *unless* this moment of acknowledgment transmission is during an interval when the receiving node is not transmitting, for whatever reason. In this latter case, we want to suspend the acknowledgment timer during any interval in which we know the remote node will not be transmitting. More precisely, we want to add to the timeout interval the time difference between the moment of message arrival and the earliest moment at which the acknowledgment could be sent, i.e., the moment at which transmission is resumed[8].

[8] If we wanted to be extremely accurate we could also <u>subtract</u> from the timeout interval the imputed inbound queuing delay QI, since inbound queuing would presumably be completed during the interval in which transmission was suspended. But since we're guessing at the queuing delays anyway, this adjustment doesn't make a lot of sense.

So the timeout interval Z computed at ES for a message sent to MS at time T_X is given by:

$$Z = QO1 + 8 + QI1 + ((T_A = T_X + 4) > T_{mt0} \; \&\& \; T_A < T_{mt1}) \; ? \; T_{mt1} - T_A : 0) + QI2 + QO2;$$

This can actually be computed in advance (at time T_X) if T1, T2, T3, and T4 are known and are exposed to the protocol engine.

If they are not exposed, then Z must initially be estimated to be (2 * the one-way light time) + QI + QO. The timer for Z must be dynamically suspended at time T_{mt0} in response to a state change as noted by **ltpclock**. Finally, the timer must be resumed at time T_{mt1} (in response to another state change as noted by **ltpclock**), at which moment the correct value for Z can be computed.

1.12 CFDP

The ION implementation of CFDP is very simple, because only Class-1 (Unacknowledged) functionality is implemented: the store-and-forward routing performed by Bundle Protocol makes the CFDP Extended Procedures unnecessary and the inter-node reliability provided by the CL protocol underneath BP – in particular, by LTP – makes the CFDP Acknowledged Procedures unnecessary. All that CFDP is required to do is segment and reassemble files, interact with the underlying Unitdata Transfer layer – BP/LTP – to effect the transmission and reception of file data segments, and handle CFDP metadata including filestore requests. CFDP-ION does all this, including support for cancellation of a file transfer transaction by cancellation of the transmission of the bundles encapsulating the transaction's protocol data units.

Note that all CFDP data transmission is "by reference", via the ZCO system, rather than "by value": the retransmission buffer for a bundle containing CFDP file data is an extent of the original file itself, not a copy retained in the ION database, and data received in bundles containing CFDP PDU is written immediately to the appropriate location in the reconstituted file rather than stored in the ION database. This minimizes the space needed for the database. In general, file transmission via CFDP is the most memory-efficient way to use ION in flight operations.

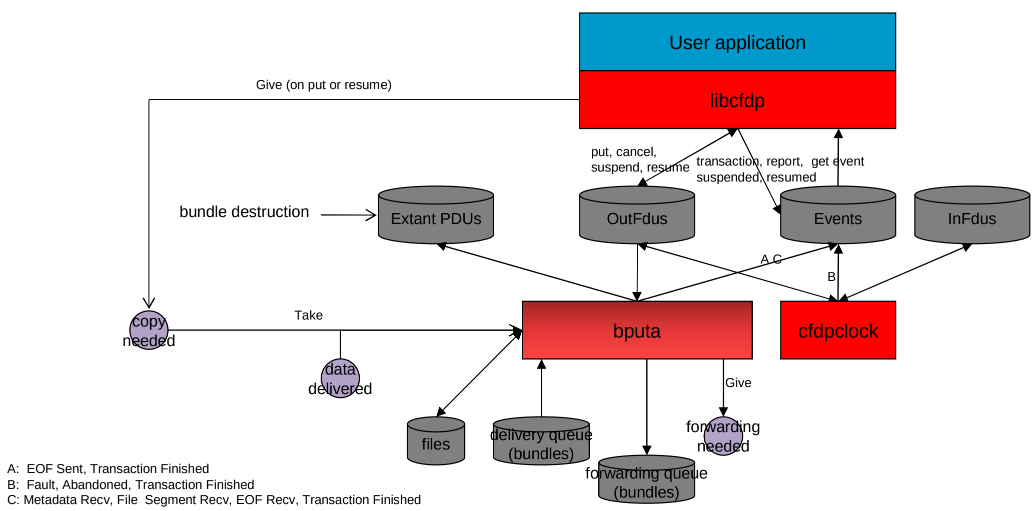


Figure 16 A CFDP-ION entity

1.13 Additional Figures for Manual Pages

1.13.1 list data structures (lyst, sdrlist, smlist)

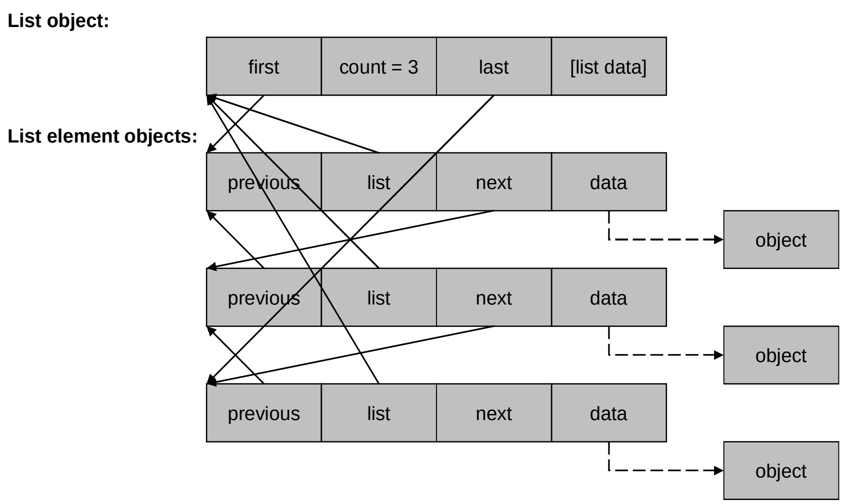


Figure 17 ION list data structures

1.13.2 psm partition structure

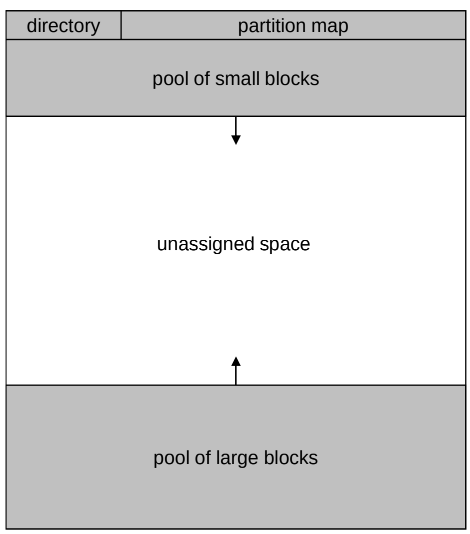


Figure 18 psm partition structure

1.13.3 psm and sdr block structures

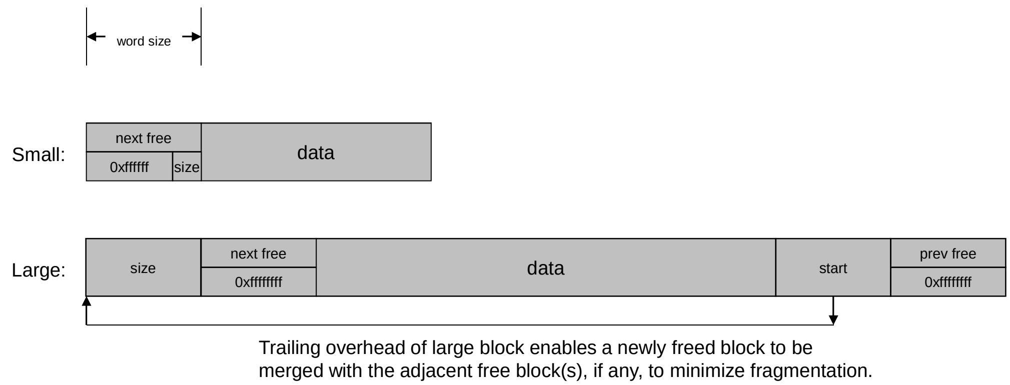


Figure 19 psm and sdr block structures

1.13.4 sdr heap structure

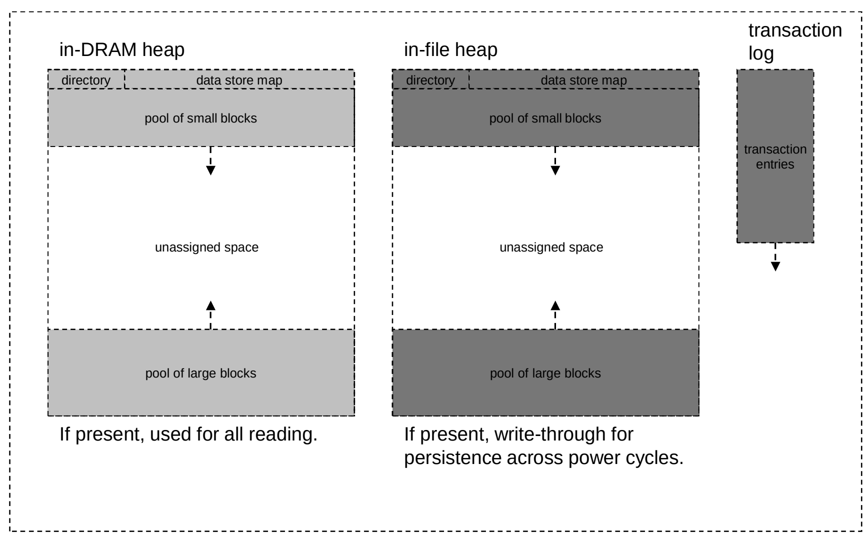


Figure 20 sdr heap structure

2 Operation

One compile-time option is applicable to all ION packages: the platform selection parameters –DVXWORKS and –DRTEMS affect the manner in which most task instantiation functions are compiled. For VXWORKS and RTEMS, these functions are compiled as library functions that must be identified by name in the platform's symbol table, while for Unix-like platforms they are compiled as `main()`functions.

2.1 Interplanetary Communication Infrastructure (ICI)

2.1.1 Compile-time options

Declaring values for the following variables, by setting parameters that are provided to the C compiler (for example, `–DFSWSOURCE` or `–DSM_SEMBASEKEY=0xff13`), will alter the functionality of ION as noted below.

PRIVATE_SYMTAB

This option causes ION to be built for VxWorks 5.4 or RTEMS with reliance on a small private local symbol table that is accessed by means of a function named `sm_FindFunction`. Both the table and the function definition are, by default, provided by the `symtab.c` source file, which is automatically included within the `platform_sm.c` source when this option is set. The table provides the address of the top-level function to be executed when a task for the indicated symbol (name) is to be spawned, together with the priority at which that task is to execute and the amount of stack space to be allocated to that task.

PRIVATE_SYMTAB is defined by default for RTEMS but not for VxWorks 5.4.

Absent this option, ION on VxWorks 5.4 must successfully execute the VxWorks `symFindByName` function in order to spawn a new task. For this purpose the entire VxWorks symbol table for the compiled image must be included in the image, and task priority and stack space allocation must be explicitly specified when tasks are spawned.

FSWLOGGER

This option causes the standard ION logging function, which simply writes all ION status messages to a file named `ion.log` in the current working directory, to be replaced (by `#include`) with code in the source file `fswlogger.c`. A file of this name must be in the inclusion path for the compiler, as defined by `–Ixxxx` compiler option parameters.

FSWCLOCK

This option causes the invocation of the standard `time` function within `getUTCTime` (in `ion.c`) to be replaced (by `#include`) with code in the source file `fswutc.c`, which might for example invoke a mission-specific function to read a value from the spacecraft clock. A file of this name must be in the inclusion path for the compiler.

FSWWDNAME

This option causes the invocation of the standard `getcwd` function within `cfdpInit` (in `libcfdpP.c`) to be replaced (by `#include`) with code in the source file `wdname.c`, which must in some way cause the mission-specific value of current working directory name to be copied into `cfdpdbBuf.workingDirectoryName`. A file of this name must be in the inclusion path for the compiler.

FSWSYMTAB

If the PRIVATE_SYMTAB option is also set, then the FSWSYMTAB option causes the code in source file `mysymtab.c` to be included in `platform_sm.c` in place of the default symbol table access implementation in `symtab.c`. A file named `mysymtab.c` must be in the inclusion path for the compiler.

FSWSOURCE

This option simply causes FSWLOGGER, FSWCLOCK, FSWWDNAME, and FSWSYMTAB all to be set.

GDSLOGGER

This option causes the standard ION logging function, which simply writes all ION status messages to a file named `ion.log` in the current working directory, to be replaced (by `#include`) with code in the source file `gdslogger.c`. A file of this name must be in the inclusion path for the compiler, as defined by `–Ixxxx` compiler option parameters.

GDSSOURCE

This option simply causes GDSLOGGER to be set.

ION_OPS_ALLOC=*xx*

This option specifies the percentage of the total non-volatile storage space allocated to ION that is reserved for protocol operational state information, i.e., is not available for the storage of bundles or LTP segments. The default value is 20.

ION_SDR_MARGIN=*xx*

This option specifies the percentage of the total non-volatile storage space allocated to ION that is reserved simply as margin, for contingency use. The default value is 20.

The sum of ION_OPS_ALLOC and ION_SDR_MARGIN defines the amount of non-volatile storage space that is sequestered at the time ION operations are initiated: for purposes of congestion forecasting and prevention of resource oversubscription, this sum is subtracted from the total size of the SDR “heap” to determine the maximum volume of space available for bundles and LTP segments. Data reception and origination activities fail whenever they would cause the total amount of data store space occupied by bundles and segments to exceed this limit.

USING_SDR_POINTERS

This is an optimization option for the SDR non-volatile data management system: when set, it enables the value of any variable in the SDR data store to be accessed directly by means of a pointer into the dynamic memory that is used as the data store storage medium, rather than by reading the variable into a location in local stack memory. Note that this option must **not** be enabled if the data store is configured for file storage only, i.e., if the SDR_IN_DRAM flag was set to zero at the time the data store was created by calling `sdr_load_profile`. See the ionconfig(5) man page in Appendix A for more information.

NO_SDR_TRACE

This option causes non-volatile storage utilization tracing functions to be omitted from ION when the SDR system is built. It disables a useful debugging option but reduces the size of the executable software.

NO_PSM_TRACE

This option causes memory utilization tracing functions to be omitted from ION when the PSM system is built. It disables a useful debugging option but reduces the size of the executable software.

IN_FLIGHT

This option controls the behavior of ION when an unrecoverable error is encountered.

If it is set, then the status message "Unrecoverable SDR error" is logged and the SDR non-volatile storage management system is globally disabled: the current database access transaction is ended and (provided transaction reversibility is enabled) rolled back, and all ION tasks terminate.

Otherwise, the ION task that encountered the error is simply aborted, causing a core dump to be produced to support debugging.

SM_SEMKEY=0x*XXXX*

This option overrides the default value (0xee01) of the identifying "key" used in creating and locating the global ION shared-memory system mutex.

SVR4_SHM

This option causes ION to be built using svr4 shared memory as the pervasive shared-memory management mechanism. svr4 shared memory is selected by default when ION is built for any platform other than MinGW, VxWorks 5.4, or RTEMS. (For these latter operating systems all memory is shared anyway, due to the absence of a protected-memory mode.)

POSIX1B_SEMAPHORES

This option causes ION to be built using POSIX semaphores as the pervasive semaphore mechanism. POSIX semaphores are selected by default when ION is built for RTEMS but are otherwise not used or supported; this option enables the default to be overridden.

SVR4_SEMAPHORES

This option causes ION to be built using svr4 semaphores as the pervasive semaphore mechanism. svr4 semaphores are selected by default when ION is built for any platform other than MinGW (for which Windows event objects are used), VxWorks 5.4 (for which VxWorks native semaphores are the default choice), or RTEMS (for which POSIX semaphores are the default choice).

SM_SEMBASEKEY=0x*XXXX*

This option overrides the default value (0xee02) of the identifying “key” used in creating and locating the global ION shared-memory semaphore database, in the event that svr4 semaphores are used.

SEMMNI=*xxx*

This option declares to ION the total number of svr4 semaphore sets provided by the operating system, in the event that svr4 semaphores are used. It overrides the default value, which is 10 for Cygwin and 128 otherwise. (Changing this value typically entails rebuilding the O/S kernel.)

SEMMSL=*xxx*

This option declares to ION the maximum number of semaphores in each svr4 semaphore set, in the event that svr4 semaphores are used. It overrides the default value, which is 6 for Cygwin and 250 otherwise. (Changing this value typically entails rebuilding the O/S kernel.)

SEMMNS=*xxx*

This option declares to ION the total number of svr4 semaphores that the operating system can support; the maximum possible value is SEMMNI x SEMMSL. It overrides the default value, which is 60 for Cygwin and 32000 otherwise. (Changing this value typically entails rebuilding the O/S kernel.)

ION_NO_DNS

This option causes the implementation of a number of Internet socket I/O operations to be omitted for ION. This prevents ION software from being able to operate over Internet connections, but it prevents link errors when ION is loaded on a spacecraft where the operating system does not include support for these functions.

ERRMSGS_BUFSIZE=*xxxx*

This option set the size of the buffer in which ION status messages are constructed prior to logging. The default value is 4 KB.

SPACE_ORDER=*x*

This option declares the word size of the computer on which the compiled ION software will be running: it is the base-2 log of the number of bytes in an address. The default value is 2, i.e., the size of an address is 2^2 = 4 bytes. For a 64-bit machine, SPACE_ORDER must be declared to be 3, i.e., the size of an address is 2^3 = 8 bytes.

NO_SDRMGT

This option enables the SDR system to be used as a data access transaction system only, without doing any dynamic management of non-volatile data. With the NO_SDRMGT option set, the SDR system library can (and in fact must) be built from the `sdrxn.c` source file alone.

DOS_PATH_DELIMITER

This option causes ION_PATH_DELIMITER to be set to '\' (backslash), for use in construction path names. The default value of ION_PATH_DELIMITER is '/' (forward slash, as is used in Unix-like operating systems).

2.1.2 Build

To build ICI for a given deployment platform:

1. Decide where you want ION's executables, libraries, header files, etc. to be installed. The ION makefiles all install their build products to subdirectories (named **bin**, **lib**, **include**, **man**, **man/man1**, **man/man3**, **man/man5**) of an ION root directory, which by default is the directory named **/opt**. If you wish to use the default build configuration, be sure that the default directories (**/opt/bin**, etc.) exist; if not, select another ION root directory name – this document will refer to it as **$OPT** – and create the subdirectories as needed. In any case, make sure that you have read, write, and execute permission for all of the ION installation directories and that:
    - The directory **/$OPT/bin** is in your execution path.
    - The directory **/$OPT/lib** is in your $LD_LOADLIB_PATH.
2. Edit the Makefile in **ion/trunk/ici**:
    - Make sure PLATFORMS is set to the appropriate platform name, e.g., x86-redhat, sparc-sol9, etc.
    - Set OPT to your ION root directory name, if other than "/opt".
3. Then:

```
cd ion/trunk/ici
make
make install
```

2.1.3 Configure

Three types of files are used to provide the information needed to perform global configuration of the ION protocol stack: the ION system configuration (or **ionconfig**) file, the ION administration command (**ionrc**) file, and the ION security configuration (**ionsecrc**) file. For details, see the man pages for ionconfig(5), ionrc(5), and ionsecrc(5) in Appendix A.

Normally the instantiation of ION on a given computer establishes a single ION node on that computer, for which hard-coded values of wmKey and sdrName (see ionconfig(5)) are used in common by all executables to assure that all elements of the system operate within the same state space. For some purposes, however, it may be desirable to establish multiple ION nodes on a single workstation. (For example, constructing an entire self-contained DTN network on a single machine may simplify some kinds of regression testing.) ION supports this configuration option as follows:

- Multi-node operation on a given computer is enabled if and only if the environment variable ION_NODE_LIST_DIR is defined in the environment of every participating ION process. Moreover, the value assigned to this variable must be the same text string in the environments of all participating ION processes. That value must be the name (preferably, fully qualified) of the directory in which the ION multi-node database file “ion_nodes” will reside.

- The definition of ION_NODE_LIST_DIR makes it possible to establish up to one ION nodes per directory rather than just one ION node on the computer. When **ionadmin** is used to establish a node, the `ionInitialize()` function will get that node's wmKey and sdrName from the .ionconfig file, use them to allocate working memory and create the SDR database, and then write a line to the ion_nodes file noting the nodeNbr, wmKey, sdrName, and wdName for the node it just initialized. wdName is the current working directory in which **ionadmin** was running at the time it called `ionInitialize()`; it is the directory within which the node resides.
- This makes it easy to connect all the node's daemon processes – running within the same current working directory – to the correct working memory partition and SDR database: the `ionAttach()` function simply searches the ion_nodes file for a line whose wdName matches the current working directory of the process that is trying to attach, then uses that line's wmKey and sdrName to link up.
- It is also possible to initiate a process from within a directory other than the one in which the node resides. To do so, define the additional environment variable ION_NODE_WDNAME in the shell from which the new process is to be initiated. When `ionAttach()` is called it will first try to get "current working directory" (for ION attachment purposes **only**) from that environment variable; only if ION_NODE_WDNAME is undefined will it use the actual cwd that it gets from calling igetcwd().

2.1.4 Run

The executable programs used in operation of the ici component of ION include:

- The **ionadmin** system configuration utility and **ionsecadmin** security configuration utility, invoked at node startup time and as needed thereafter.
- The **rfxclock** background daemon, which effects scheduled network configuration events.
- The **sdrmend** system repair utility, invoked as needed.
- The **sdrwatch** and **psmwatch** utilities for resource utilization monitoring, invoked as needed.

Each time it is executed, **ionadmin** computes a new congestion forecast and, if a congestion collapse is predicted, invokes the node's congestion alarm script (if any). **ionadmin** also establishes the node number for the local node and starts/stops the **rfxclock** task, among other functions. For further details, see the man pages for ionadmin(1), ionsecadmin(1), rfxclock(1), sdrmend(1), sdrwatch(1), and psmwatch(1) in Appendix A.

2.1.5 Test

Six test executables are provided to support testing and debugging of the ICI component of ION:

- The **file2sdr** and **sdr2file** programs exercise the SDR system.
- The **psmshell** program exercises the PSM system.
- The **file2sm**, **sm2file**, and **smlistsh** programs exercise the shared-memory linked list system.

For details, see the man pages for file2sdr(1), sdr2file(1), psmshell(1), file2sm(1), sm2file(1), and smlistsh(1) in Appendix A.

2.2 Licklider Transmission Protocol (LTP)

2.2.1 Build

To build LTP:

1. Make sure that the “ici” component of ION has been built for the platform on which you plan to run LTP.
2. Edit the Makefile in **ion/trunk/ltp**:
   - As for ici, make sure PLATFORMS is set to the name of platform on which you plan to run LTP.
   - Set OPT to the directory containing the bin, lib, include, etc. directories used for building ici.
3. Then:

```
cd ion/trunk/ltp
make
make install
```

2.2.2 Configure

The LTP administration command (**ltprc**) file provides the information needed to configure LTP on a given ION node. For details, see the man page for ltprc(5) in Appendix A.

2.2.3 Run

The executable programs used in operation of the ltp component of ION include:

- The **ltpadmin** protocol configuration utility, invoked at node startup time and as needed thereafter.
- The **ltpclock** background daemon, which effects scheduled LTP events such as segment retransmissions.
- The **ltpmeter** block management daemon, which segments blocks and effects LTP flow control.
- The **udplsi** and **udplso** link service input and output tasks, which handle transmission of LTP segments encapsulated in UDP datagrams (mainly for testing purposes).

ltpadmin starts/stops the **ltpclock** task and, as mandated by configuration, the **udplsi** and **udplso** tasks.

For details, see the man pages for ltpadmin(1), ltpclock(1), ltpmeter(1), udplsi(1), and udplso(1) in Appendix A.

2.2.4 Test

Two test executables are provided to support testing and debugging of the LTP component of ION:

- **ltpdriver** is a continuous source of LTP segments.
- **ltpcounter** is an LTP block receiver that counts blocks as they arrive.

For details, see the man pages for ltpdriver(1) and ltpcounter(1) in Appendix A.

2.3 *Bundle Protocol (BP)*

2.3.1 Compile-time options

Declaring values for the following variables, by setting parameters that are provided to the C compiler (for example, `–DION_NOSTATS` or `–DBRSTERM=60`), will alter the functionality of BP as noted below.

<u>TargetFFS</u>

Setting this option adapts BP for use with the TargetFFS flash file system on the VxWorks operating system. TargetFFS apparently locks one or more system semaphores so long as a file is kept open. When a BP task keeps a file open for a sustained interval, subsequent file system access may cause a high-priority non-BP task to attempt to lock the affected semaphore and therefore block; in this event, the priority of the BP task may automatically be elevated by the inversion safety mechanisms of VxWorks. This "priority inheritance" can result in preferential scheduling for the BP task – which does not need it – at the expense of normally higher-priority tasks, and can thereby introduce runtime anomalies. BP tasks should therefore close files immediately after each access when running on a VxWorks platform that uses the TargetFFS flash file system. The TargetFFS compile-time option ensures that they do so.

<u>BRSTERM=*xx*</u>

This option sets the maximum number of seconds by which the current time at the BRS server may exceed the time tag in a BRS authentication message from a client; if this interval is exceeded, the authentication message is presumed to be a replay attack and is rejected. Small values of BRSTERM are safer than large ones, but they require that clocks be more closely synchronized. The default value is 5.

<u>ION_NOSTATS</u>

Setting this option prevents the logging of bundle processing statistics in status messages.

<u>KEEPALIVE_PERIOD=*xx*</u>

This option sets the number of seconds between transmission of keep-alive messages over any TCP or BRS convergence-layer protocol connection. The default value is 15.

<u>ION_BANDWIDTH_RESERVED</u>

Setting this option overrides strict priority order in bundle transmission, which is the default. Instead, bandwidth is shared between the priority-1 and priority-0 queues on a 2:1 ratio whenever there is no priority-2 traffic.

2.3.2 Build

To build BP:

1. Make sure that the "ici" and "dg" (see below) components of ION have been built for the platform on which you plan to run BP.
2. Edit the Makefile in **ion/trunk/bp**:

- As for ici, make sure PLATFORMS is set to the name of platform on which you plan to run BP.
- Set OPT to the directory containing the bin, lib, include, etc. directories used for building ici.

3. Then:

```
cd ion/trunk/bp
make
make install
```

2.3.3 Configure

The BP administration command (**bprc**) file provides the information needed to configure generic BP on a given ION node. The IPN scheme administration command (**ipnrc**) file provides information that configures static and default routes for endpoints whose IDs conform to the “ipn” scheme. The DTN scheme administration command (**dtn2rc**) file provides information that configures static and default routes for endpoints whose IDs conform to the “dtn” scheme, as supported by the DTN2 reference implementation. For details, see the man pages for bprc(5), ipnrc(5), and dtn2rc(5) in Appendix A.

2.3.4 Run

The executable programs used in operation of the bp component of ION include:

- The **bpadmin, ipnadmin,** and **dtn2admin** protocol configuration utilities, invoked at node startup time and as needed thereafter.
- The **bpclock** background daemon, which effects scheduled BP events such as TTL expirations and which also implements rate control.
- The **ipnfw** and **dtn2fw** forwarding daemons, which compute routes for bundles addressed to “ipn”-scheme and “dtn”-scheme endpoints, respectively.
- The **ipnadminep** and **dtn2adminep** administrative endpoint daemons, which handle custody acceptances, custody refusals, and status messages.
- The **brsscla** (server) and **brsccla** (client) Bundle Relay Service convergence-layer adapters.
- The **tcpcli** (input) and **tcpclo** (output) TCP convergence-layer adapters.
- The **udpcli** (input) and **udpclo** (output) UDP convergence-layer adapters.
- The **ltpcli** (input) and **ltpclo** (output) LTP convergence-layer adapters.
- The **dgrcla** Datagram Retransmission convergence-layer adapter.
- The **bpsendfile** utility, which sends a file of arbitrary size, encapsulated in a single bundle, to a specified BP endpoint.
- The **bpstats** utility, which prints a snapshot of currently accumulated BP processing statistics on the local node.

- The **bptrace** utility, which sends a bundle through the network to enable a forwarding trace based on bundle status reports.
- The **lgsend** and **lgagent** utilities, which are used for remote administration of ION nodes.
- The **hmackeys** utility, which can be used to create hash keys suitable for use in bundle authentication blocks and BRS convergence-layer protocol connections.

bpadmin starts/stops the **bpclock** task and, as mandated by configuration, the **ipnfw**, **dtn2fw**, **ipnadminep**, **dtn2adminep**, **brsscla**, **brsccla**, , **tcpcli**, **tcpclo**, **udpcli**, **udpclo**, **ltpcli**, **ltpclo**, and **dgrcla** tasks.

For details, see the man pages for bpadmin(1),ipnadmin(1), dtn2admin(1), bpclock(1), ipnfw(1), dtn2fw(1), ipnadminep(1), dtn2adminep(1), brsscla(1), brsccla(1), tcpcli(1), tcpclo(1), udpcli(1), udpclo(1), ltpcli(1), ltpclo(1), dgrcla(1), bpsendfile(1), bpstats(1), bptrace(1), lgsend(1), lgagent(1), and hmackeys(1) in Appendix A.

2.3.5 Test

Five test executables are provided to support testing and debugging of the BP component of ION:

- **bpdriver** is a continuous source of bundles.
- **bpcounter** is a bundle receiver that counts bundles as they arrive.
- **bpecho** is a bundle receiver that sends an "echo" acknowledgment bundle back to bpdriver upon reception of each bundle.
- **bpsource** is a simple console-like application for interactively sending text strings in bundles to a specified DTN endpoint, nominally a **bpsink** task.
- **bpsink** is a simple console-like application for receiving bundles and printing their contents.

For details, see the man pages for bpdriver(1), bpcounter(1), bpecho(1), bpsource(1), and bpsink(1) in Appendix A.

2.4 Datagram Retransmission (DGR)

2.4.1 Build

To build DGR:

1. Make sure that the “ici” component of ION has been built for the platform on which you plan to run DGR.
2. Edit the Makefile in **ion/trunk/dgr**:
   - As for ici, make sure PLATFORMS is set to the name of platform on which you plan to run DGR.
   - Set OPT to the directory containing the bin, lib, include, etc. directories used for building ici.
3. Then:

```
cd ion/trunk/dgr
make
make install
```

2.4.2 Configure

No additional configuration files are required for the operation of the DGR component of ION.

2.4.3 Run

No runtime executables are required for the operation of the DGR component of ION.

2.4.4 Test

Two test executables are provided to support testing and debugging of the DGR component of ION:

- **file2dgr** repeatedly reads a file of text lines and sends copies of those text lines via DGR to **dgr2file**, which writes them to a copy of the original file.

For details, see the man pages for file2dgr(1) and dgr2file(1) in Appendix A.

2.5 Asynchronous Message Service (AMS)

2.5.1 Compile-time options

Defining the following macros, by setting parameters that are provided to the C compiler (for example, -DNOEXPAT or –DAMS_INDUSTRIAL), will alter the functionality of AMS as noted below.

<u>NOEXPAT</u>

Setting this option adapts AMS to expect MIB information to be presented to it in "amsrc" syntax (see the amsrc(5) man page in Appendix A) rather than in XML syntax, normally because the expat XML interpretation system is not installed. The default syntax for AMS MIB information is XML, as described in the amsxml(5) man page in Appendix A.

AMS_INDUSTRIAL

Setting this option adapts AMS to an "industrial" rather than safety-critical model for memory management. By default, the memory acquired for message transmission and reception buffers in AMS is allocated from limited ION working memory, which is fixed at ION start-up time; this limits the rate at which AMS messages may be originated and acquired. When –DAMS_INDUSTRIAL is set at compile time, the memory acquired for message transmission and reception buffers in AMS is allocated from system memory, using the familiar malloc() and free() functions; this enables much higher message traffic rates on machines with abundant system memory.

2.5.2 Build

To build AMS:

1. Make sure that the "bp" component of ION has been built for the platform on which you plan to run AMS.
2. Edit the Makefile in **ion/trunk/cfdp**:
   - Just as for bp, make sure PLATFORMS is set to the name of platform on which you plan to run AMS.
   - Set OPT to the directory containing the bin, lib, include, etc. directories used for building bp.
3. Then:

```
cd ion/trunk/ams
make
make install
```

2.5.3 Configure

There is no central configuration of AMS; each AMS entity (configuration server, registrar, or application module) is individually configured at the time its initial MIB is loaded at startup. For details of MIB file syntax, see the man pages for amsrc(5) and amsxml(5) in Appendix A.

2.5.4 Run

The executable programs used in operation of the AMS component of ION include:

- The **amsd** background daemon, which serves as configuration server and/or as the registrar for a single application cell.
- The **ramsgate** application module, which serves as the Remote AMS gateway for a single message space.
- The **amsstop** utility, which terminates all AMS operation throughout a single message space.
- The **amsmib** utility, which announces supplementary MIB information to selected subsets of AMS entities without interrupting the operation of the message space.

For details, see the man pages for amsd(1), ramsgate(1), amsstop(1), and amsmib(1) in Appendix A.

2.5.5 Test

Seven test executables are provided to support testing and debugging of the AMS component of ION:

- **amsbenchs** is a continuous source of messages.
- **amsbenchr** is a message receiver that calculates bundle transmission performance statistics.
- **amshello** is an extremely simple AMS “hello, world” demo program – a self-contained distributed application in a single source file of about seventy lines.
- **amsshell** is a simple console-like application for interactively publishing, sending, and announcing text strings in messages.
- **amslog** is a simple console-like application for receiving messages and piping their contents to stdout.
- **amslogprt** is a pipeline program that simply prints AMS message contents piped to it from amslog.
- **amspubsub** is a pair of functions for rudimentary testing of AMS functionality in a VxWorks environment.

For details, see the man pages for amsbenchs(1), amsbenchr(1), amshello(1), amsshell(1), amslog(1), amslogprt(1), amspub(1), and amssub(1) in Appendix A.

For further operational details of the AMS system, please see sections 4 and 5 of the AMS Programmer’s Guide.

2.6 CCSDS File Delivery Protocol (CFDP)

2.6.1 Compile-time options

Defining the following macro, by setting a parameter that is provided to the C compiler (i.e., `–DTargetFFS`), will alter the functionality of CFDP as noted below.

TargetFFS

Setting this option adapts CFDP for use with the TargetFFS flash file system on the VxWorks operating system. TargetFFS apparently locks one or more system semaphores so long as a file is kept open. When a CFDP task keeps a file open for a sustained interval, subsequent file system access may cause a high-priority non-CFDP task to attempt to lock the affected semaphore and therefore block; in this event, the priority of the CFDP task may automatically be elevated by the inversion safety mechanisms of VxWorks. This “priority inheritance” can result in preferential scheduling for the CFDP task – which does not need it – at the expense of normally higher-priority tasks, and can thereby introduce runtime anomalies. CFDP tasks should therefore close files immediately after each access when running on a VxWorks platform that uses the TargetFFS flash file system. The TargetFFS compile-time option assures that they do so.

2.6.2 Build

To build CFDP:

4. Make sure that the “bp” component of ION has been built for the platform on which you plan to run CFDP.
5. Edit the Makefile in **ion/trunk/cfdp**:
   - Just as for bp, make sure PLATFORMS is set to the name of platform on which you plan to run CFDP.
   - Set OPT to the directory containing the bin, lib, include, etc. directories used for building bp.
6. Then:

```
cd ion/trunk/cfdp
make
make install
```

2.6.3 Configure

The CFDP administration command (**cfdprc**) file provides the information needed to configure CFDP on a given ION node. For details, see the man page for cfdprc(5) in Appendix A.

2.6.4 Run

The executable programs used in operation of the CFDP component of ION include:

- The **cfdpadmin** protocol configuration utility, invoked at node startup time and as needed thereafter.
- The **cfdpclock** background daemon, which effects scheduled CFDP events such as check timer expirations. The **cfdpclock** task also effects CFDP transaction cancellations, by canceling the bundles encapsulating the transaction's protocol data units.
- The **bputa** UT-layer input/output task, which handles transmission of CFDP PDUs encapsulated in bundles.

cfdpadmin starts/stops the **cfdpclock** task and, as mandated by configuration, the **bputa** task.

For details, see the man pages for cfdpadmin(1), cfdpclock(1), and bputa(1) in Appendix A.

2.6.5 Test

A single executable, **cfdptest**, is provided to support testing and debugging of the DGR component of ION. For details, see the man page for cfdptest(1) in Appendix A.