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THE INTERPLANETARY INTERNET: A COMMUNICATIONS INFRASTRUCTURE FOR MARS EXPLORATION

S. Burleigh, Jet Propulsion Laboratory, Pasadena, CA, USA
V. Cerf, WorldCom Inc., Loudon, VA, USA
R. Durst, MITRE Corporation, Reston, VA, USA
K. Fall, Intel Corporation, Berkeley, CA, USA
A. Hooke, Jet Propulsion Laboratory, Pasadena, CA, USA
K. Scott, MITRE Corporation, Reston, VA, USA
H. Weiss, Sparta Inc., Columbia, MD, USA

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Scott Burleigh, Jet Propulsion Laboratory, Pasadena, CA, USA
Scott.Burleigh@jpl.nasa.gov
Vinton Cerf, WorldCom Inc., Loudon, VA, USA
vinton.g.cerf@wcom.com
Robert Durst, MITRE Corporation, Reston, VA, USA
durst@mitre.org
Kevin Fall, Intel Corporation, Berkeley, CA, USA
kfall@intel-research.net
Adrian Hooke, Jet Propulsion Laboratory, Pasadena, CA, USA
adrian.hooke@jpl.nasa.gov
Keith Scott, MITRE Corporation, Reston, VA, USA
kscott@mitre.org
Howard Weiss, Sparta Inc., Columbia, MD, USA
hsw@sparta.com

ABSTRACT*

A strategy is being developed whereby the current set of internationally standardized space data communications protocols can be incrementally evolved so that a first version of an operational "Interplanetary Internet" is feasible by the end of the decade. This paper describes its architectural concepts, discusses the current set of standard space data communications capabilities that exist to support Mars exploration and reviews proposed new developments. We also speculate that these current capabilities can grow to support future scenarios where human intelligence is widely distributed across the Solar System and day-to-day communications dialog between planets is routine.

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THE FUTURE: AN INTERPLANETARY INTERNET

In 1998 the US Defense Advanced Research Projects Agency (DARPA), as part of its "Next Generation Internet" initiative, began funding a small group at NASA's Jet Propulsion Laboratory in Pasadena, California to study the technical architecture of an "Interplanetary Internet". The idea was to blend ongoing work in standardized space communications capabilities with state of the art techniques being developed within the terrestrial Internet community, with a goal of achieving end-to-end communication in a multi-network interplanetary environment. The "Interplanetary Internet" name was deliberately coined to suggest a far-future integration of space and terrestrial communications infrastructure to support the migration of human intelligence throughout the Solar System. Joining the JPL team in this work was one of the original designers of the Internet and co-inventor of the "Transmission Control Protocol/Internet Protocol" (TCP/IP) protocol suite. Support for the work has recently transitioned from DARPA to NASA.

The future Interplanetary Internet architectural concept is deceptively simple:

1. Use Internet or Internet-related protocols to form local networks in low delay, relatively low noise environments such as around Earth, within a free flying spacecraft, on and around another planet, etc.

2. A specialized deep space backbone network of long-haul wireless links interconnecting these local internets. This interplanetary backbone is expected to evolve to include multiple space-based data relay satellites.

3. The resulting interplanetary internet thus consists of a "network of internets". Just as the familiar TCP/IP suite unites the Earth's "network of networks" into the Internet, the Interplanetary Internet will employ a new overlay protocol concept called *bundling* to tie together a set of heterogeneous internets.

A routing function will direct *bundles* (messages) through a concatenated series of Internets, just as the Earth's current Internet protocol (IP) routes data through a series of independent networks on Earth. To guarantee reliability of the end-to-end transfer, the bundles will also contain retransmission mechanisms functionally similar to those provided by the terrestrial Internet's Transmission Control Protocol (TCP). However, the similarity of *bundling* with TCP/IP ends there.

Unlike the Earth's backbone environment of continuous connectivity, negligible delay and clean data channels, the hallmarks of the interplanetary backbone are therefore intermittent connectivity, huge propagation delays and noisy data channels.

While the Earth's backbone network is wired – large numbers of fiber or copper circuits interconnecting fixed hubs – the interplanetary backbone is dependent on fragile wireless links.

In addition, the hubs on the interplanetary backbone (relay spacecraft or gateways into remote local Internets) are all moving with respect to each other. Planets travel in fixed orbits and sometimes bodies like the Sun cause line of sight occultations that last for days on end. Landed vehicles on remote planetary surfaces will move out of sight of Earth as the body rotates, and may have to communicate through local relay satellites that only provide data transmission contacts for a few minutes at a time.

The *bundling* protocol handles this environment in two ways:

- It operates in a "store and forward" mode, very similar to e-mail, where bundles are held at routers along the way until such time as a forward path is established.
- It avoids the need for a sender to store data until an acknowledgement is received from the other end by operating in a "custodial" mode. In this mode, intermediate nodes in the network can assume responsibility for ensuring that bundles reach their destinations, allowing senders (and previous custodians) to reassign resources to new observations.
- In the presence of high error rate links, the hop-by-hop store-and-forward bundling model with per-hop error control increases the probability of successful end to end transmission.

One key problem in the design of an Interplanetary Internet is identifying the communicating endpoints. If a common, solar system-wide IP address convention were adopted, then every component of the system would need to be upgraded on a common timescale to preserve the commonality of the address space. The current concept is that rather than have a single address space across the entire Solar System end point identifiers comprise a two-part name. One part of the name (the routing part) gets the bundle delivered to a remote destination "region" of the Interplanetary internet. The second part of the name (the administrative part) contains the information required to deliver to one or more local destinations. Thus for Mars operations the routing part of the name will be used to move the bundle across the Deep Space backbone to the entry gateway on the appropriate region on Mars, where the administrative part of the name comes into play and identifies the local recipient(s) on the Martian internet.

THE PRESENT: MARS COMMUNICATIONS IN THE COMING DECADE

A successful program of Mars exploration will need a robust, dependable and high capacity space communications infrastructure. In the terrestrial environment, the g TCP/IP suite provides these features. Programs of Mars exploration will need an analogous set of standard capabilities to support automated communications over the vast distances, heterogeneous and stressed environments that make up the Earth-Mars communications system. Although space exploration is unlikely to experience the sort of commercially driven growth that has been seen in the terrestrial Internet in the last decade, some clear "market forces" are already emerging in the space community:

a. Hard requirements exist for interoperability among the many agencies and organizations that will be cooperatively executing the integrated program of Mars missions.
b. Each of those missions needs to avoid the cost and risk of developing unique systems, so there is the inevitable allure of deploying systems in space that have a pedigree rooted in their robust Earth-based commercial counterparts.
c. In order to feed an intense interest by the general public to participate in the excitement of exploration, large quantities of data must be rapidly acquired from the vicinity of Mars and processed for dissemination via the Web.

Since the early 1980s, the Consultative Committee for Space Data Systems[1] (CCSDS) – an international organization currently supported by thirty-four space agencies - has been incrementally developing a basic set of standardized space communications techniques that are now in ubiquitous use within the world space community. In fact, approximately two hundred and twenty space missions are currently committed to use the CCSDS capabilities.

In a typical space mission configuration, as shown in Figure 1, programmed intelligence is widely distributed across both the space and ground segments and large numbers of computers need to exchange information either locally (within the space system or within the ground system) or end-to-end between space and ground.

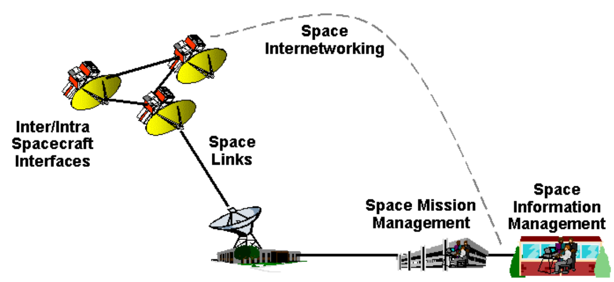

Figure 1: Space Mission Data Interfaces

The CCSDS is organized into technical panels to develop the standards that cluster into five major categories where international interoperability is needed:

1. Data handling interfaces within or between spacecraft, such as the mechanisms whereby a payload may connect to the onboard data system or whereby a landed vehicle may talk to an orbiter via a space link.

2. Long-haul data links that connect a spacecraft with its ground system.
3. End-to-end data paths that utilize those space links to support networked data flow between ground and space.

These first three categories form the "space/ground communications system" that provide bi-directional data exchange in support of users, who access:

4. Mission management services (such as navigation, flight operations and facility control) that are exposed by one organization to another.
5. Mechanisms for describing, sharing and archiving the scientific information products derived from the mission.

CURRENT SPACE/GROUND COMMUNICATIONS STANDARDS

CCSDS protocol standards are "layered" so that they stack together in a modular fashion.

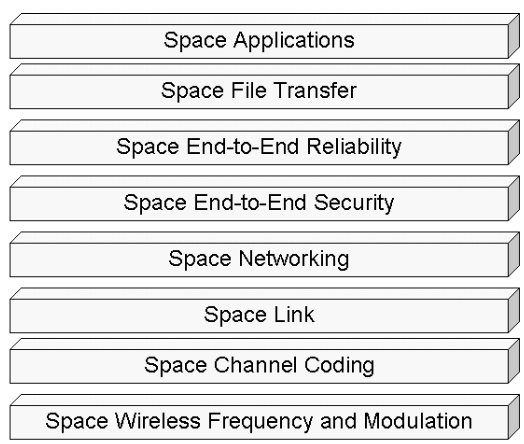

Figure 2: Space Protocol Stack

The main logical components of the protocol stack are shown in Figure 2. At the top of the stack are the user "applications" (typically sensor and control systems) that run on computers located in space or on the ground. When two applications need to exchange information, several underlying layers of standard data communications protocol support them. Most of these standard layers contain multiple options that can be selected to meet mission needs, and most of the layers can be bypassed if not required. Working from the bottom the stack upwards, the layers are as follows.

1. *Wireless standards*. These standards specify the frequencies and efficient modulation types to be used to create the channel connecting the spacecraft to its ground stations or other spacecraft.

2. *Coding standards*. These "clean up" errors on those wireless channels and make them more suitable for automated data transfer. The CCSDS coding standards include a variety of high performance technologies including Convolutional, Reed-Solomon and Turbo Codes.

3. *Link standards.* The "frames" that carry higher layer data across the space link are specified here. The CCSDS "Packet Telemetry" and "Packet Telecommand" standards handle virtually all the long-haul links. Packet Telecommand supports Link-layer reliability by providing a 'go-back-n' frame retransmission protocol, known as the "Command Operation Procedure" (COP), that works best in a short-delay environment. A more general retransmission protocol for long delay communications is planned but not yet available. CCSDS "Advanced Orbiting Systems" is an adaptation of Packet Telemetry to handle high rate data transfer, and is used by the International Space Station and many Earth-observing missions. A new CCSDS "Proximity-1" protocol handles short-range communications, such as between landed vehicles and planetary orbiters, or between multiple spacecraft flying in a constellation. It is derived from CCSDS Telecommand and provides bi-directional Link layer reliability via a

derivative of the COP retransmission scheme.

4. *Networking Standards*. The Space link is just one component of the end-to-end data path between a spacecraft instrument and a user. In order to traverse the whole path, "routing' information needs to be associated with each chunk of user data.

   The CCSDS Packet (the "packet" part of Packet Telemetry and Telecommand) has been in use as a "CCSDS Path" (connection oriented) networking protocol for well over a decade. It exploits the fact that for most current missions there is a highly predictable data routing path between an instrument and a user, so there is little need for adaptive packet routing (and the concomitant extra communications overhead associated with carrying large source and destination addresses in every packet).

   More recently, CCSDS has added the capability to allow onboard systems to have their own Internet Protocol (IP) addresses. This is accomplished by either direct use of IP, or an abbreviated form of IP that is the Network Protocol (NP) component of a four-part stack of protocols known as the Space Communication Protocol Standards (SCPS)[2]. Both of these capabilities allow packets to be dynamically routed through different paths in a connectionless manner.

5. *Security Standards.* As missions become more Internet-accessible, they become more vulnerable to attack. Basic authentication and encryption can be accomplished within the CCSDS Link standards but more powerful end-to-end techniques can protect the entire flow of user data. Two standard protocol choices exist: Internet Protocol Security (IPSec) and a SCPS Security Protocol (SP). Both provide multiple levels of data protection:
   - Access Control – prevention of unauthorized users from sending data.
   - Authentication – guarantee of the identity of the sender.
   - Integrity – protection against the intentional or accidental modification of the user data during transit.
   - Confidentiality – protection from disclosure of the contents of the user data.

6. *End-to-End Reliability Standards.* All of the standards up to this layer have been primarily associated with getting a single packet of data delivered between two end systems. By concatenating powerful channel coding with Link layer retransmission over the space link, and assuming no loss on Earth or in the spacecraft or local Mars networks, there is a high probability that the packet will be delivered.

   However, if the packet gets lost due to buffer overflows somewhere in the end-to-end path, or damaged by bit errors during transit, there will be a gap in the user data. Absent any other hop-by-hop remedies, the only way to fill such gaps is via end-to-end retransmission. This retransmission can be performed three ways: manually by humans; by custom code running in each of the applications that are sending and receiving data; or by invoking a general-purpose communications protocol that is dedicated to that job.

   For short delay communications, the CCSDS recommends a protocol solution and has adopted the Internet "Transmission Control Protocol" (TCP) and SCPS extensions to TCP know as "TCP Tranquility". For those applications not needing TCP's services, the Internet User

Datagram Protocol (UDP) can be used to segment and encapsulate user data.

7. *Space File Transfer Standards.* This layer of protocol – the first of several so-called "Application Services" that will probably be developed in the near future – directly supports the user applications that are running end-to-end. In recent years there has been a rapid shift towards organizing space data transfer into standalone and autonomous files that may be assigned different priorities and individually accounted-for. This is particularly important as ground networks such as the DSN become heavily subscribed, so that a large amount of two way traffic between the spacecraft and the ground can be conducted and verified in a short interval and the tracking assets can then be released to service another spacecraft.

   The CCSDS currently supports two file-based standard capabilities:
   - The Internet File Transfer Protocol (FTP), and SCPS space-adapted extensions to FTP. These are primarily for use in short-delay Internet-like environments, and assume an underlying layer of TCP.
   - The CCSDS File Delivery Protocol (CFDP). This is a delay tolerant protocol whose model of operations is fundamentally store-and-forward, much like e-mail that conveys files as attachments. The protocol as currently designed contains its own reliability mechanisms and does not assume an underlying retransmission capability. It presently operates point-to-point across a single link and contains three parts: file manipulation commands that allow files to be created and exchanged; filestore commands used to manage remote file systems; and a reliability protocol that ensures that all of the pieces of the file are properly delivered across the link, with any missing pieces being automatically retransmitted.

The long-term CFDP concept has its own notion of "custodial transfer" where a sender can transmit a file to a receiver over a single link and, upon receipt of the entire file, the receiver can notify the sender that it will take care of any successive forward transmission hops. This allows the sender to release local processing and storage resources and to deploy them on new data acquisition – a very important feature for transmission of data to and from the surface of Mars. For missions not wanting to use file transfers, applications can bypass the file process and access most of the underlying layers directly.

COMMUNICATIONS SCENARIO FOR MARS OPERATIONS

Data communications in support of Mars exploration has already moved into the "networked" era as we have started to deploy communications relay orbiters around the planet.

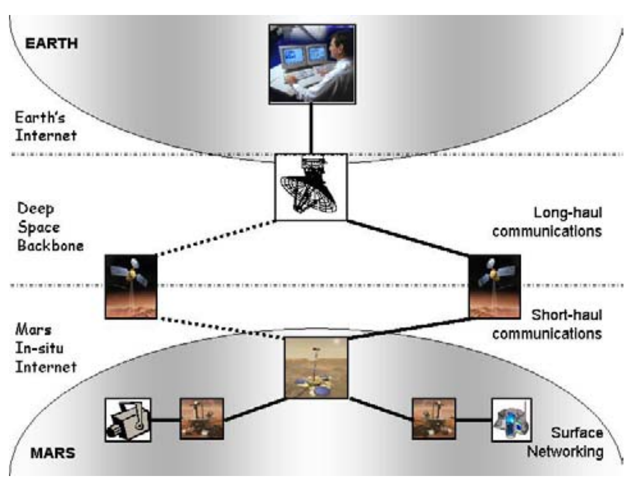

Figure 3: Mars Networking Scenario

A typical scenario (Figure 3) reveals that space-based data communications cluster into three main groups:

a. Local networking among surface vehicles that are stationary, roving and in the atmosphere.
b. Short-haul relay communications between landed vehicles and Mars-orbiting spacecraft.
c. Long haul data transfer directly between the surface and the Earth, or from the relay spacecraft to Earth.

For the most part, the international standards that are now coming into widespread use can satisfy these communications problems. A typical mapping of these existing standard capabilities across these various environments is shown in Figure 4.

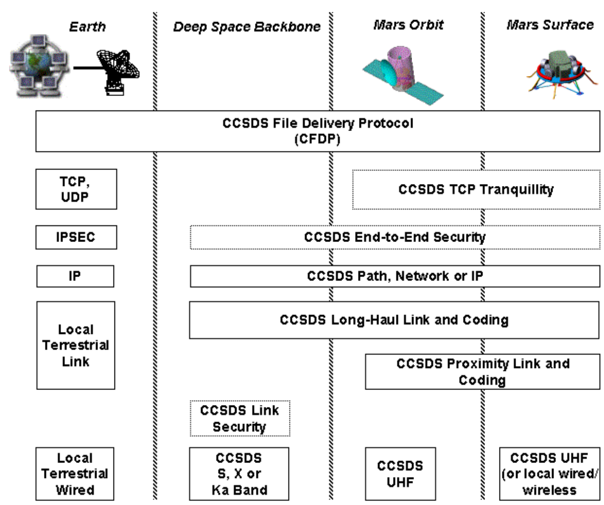

Figure 4: Mars Communications Protocol Stack

1. The CCSDS File Delivery Protocol (CFDP) is emerging as the leading candidate for the ubiquitous "end-to-end" protocol for most near-term Mars operations. It operates bi-directionally and allows users to exchange files between assets on and around Mars and facilities on the ground.
2. Within the Earth's Internet, CFDP will be transported using standard Internet protocols. On the Deep Space backbone, CFDP is transferred using the CCSDS Networking protocols, running over the CCSDS Long-Haul space link and coding protocols, which run over the S, X or Ka-band wireless channels.
3. For those missions with direct links between the Martian surface and Earth, the Deep Space backbone long-haul protocols will run all the way down to the surface and near-surface vehicles.
4. For those missions using communications relay spacecraft, the long haul link protocols will be terminated at the orbiter and the CCSDS Proximity Link and Coding protocols will be used to communicate between the orbiters and the landed assets. The orbiters will bridge the CCSDS Networking protocol from the long-haul link protocol to the proximate protocol.

STANDARDS EVOLUTION IN THE COMING DECADE

The current CCSDS File Delivery Protocol, CFDP, is by design a prototypical form of the *bundling* protocol that will be required for the future Interplanetary Internet.

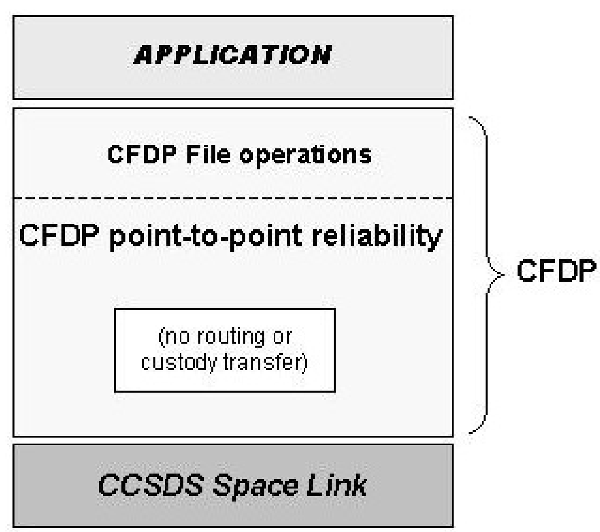

Figure 5: Current CFDP Architecture

The current CFDP architecture (Figure 5) consists of three parts:

a. file handling mechanisms, plus;
b. point to point reliability mechanisms, which;
c. draw upon underlying space link data transfer services.

Extensions to CFDP are currently under development that will allow it to support multi-hop custodial file data transfers of the sort envisioned by the "Mars Network" concept[3]. This set of capabilities should therefore be sufficient to satisfy immediate Mars mission needs.

The current *bundling* protocol architecture (Figure 6) improves on CFDP in several key respects:

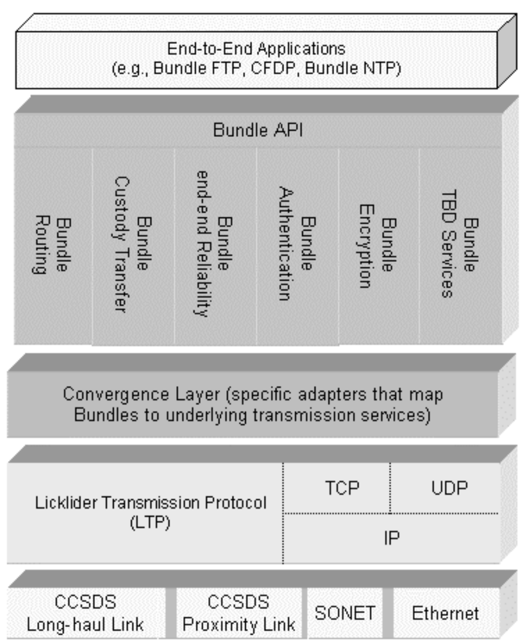

Figure 6: Current *bundling* Architecture

a. It is not confined to supporting just file transfer, but it can handle virtually any end-to-end space application. Eventually, CFDP will simply "move up the stack" to become one of those applications.
b. Its internal functions are more clearly modular than CFDP, so that it should be easier to evolve over time.
c. It will provide a more flexible custodial transfer capability than is achievable with CFDP.

The detailed specification and prototyping of *bundling* is already underway and it is hoped by the middle of this decade to be in a position for CFDP to make a smooth transition from running directly over the space link to running over *bundling*. At that point, we will be ready to begin Interplanetary Internet operations.

INTERPLANETARY INTERNET: DEPLOYMENT STRATEGY

The terrestrial Internet did not just "happen overnight"; it has evolved over a period of thirty years. Similarly, standardized space communications have been evolving for the last twenty years. In the coming decades, intense interest in Mars exploration and the correspondingly large number of missions that will be flown provides a good opportunity to accelerate that evolution.

Individual mission organizations are rarely altruistic. They typically focus their scarce resources on solving immediate problems, and let subsequent missions solve their own. Coordinated Mars exploration, however, provides a rare sense of community because many space vehicles from many different organizations are all focused on a common goal. In particular, Mars exploration offers a unique communications opportunity because of the presence of multiple orbiting spacecraft that can act as communications relays.

Anything landed on the surface of Mars, or deployed in its atmosphere, faces stringent communications challenges, of which power availability is currently the most constraining. Instead of having to transmit and receive over the vast interplanetary distances to and from Earth, surface vehicles can now exploit proximate relay spacecraft to reduce their communications burdens. In order to expedite these relays, payloads such as the Electra Mars Network Transceiver[4] are already being developed that may be shared by multiple missions. Even if large numbers of dedicated communications relay satellites are not affordable, communications payloads can be added to scientific orbiters that increase their utility and inherently make them part of a larger community.

We believe that the Interplanetary Internet will follow a similar path, where "primary" scientific missions will be given "secondary" relay capabilities that will facilitate the slow accretion of communications network infrastructure throughout the Solar System. Missions will help each other out by supporting each other, because they themselves may be the beneficiaries of such cooperation.

CONCLUSION

As we enter this exciting period of Mars exploration, we already have a rich and proven set of international standards to support our needs for communicating between Mars and Earth. Those standards will continue to evolve and grow in capability, and by the 2005-2007 timeframe we should have sufficient capabilities on hand to make Mars one of the first true extensions of the Internet: the Interplanetary Internet is about to be launched. To track its progress, refer to the Interplanetary Internet Special Interest Group[5] within the Internet Society.

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