THE INTERPLANETARY INTERNET:

A COMMUNICATIONS INFRASTRUCTURE FOR MARS EXPLORATION

Presented by

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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. It is also speculated 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.

INTRODUCTION

The vision of future space exploration includes missions to deep space that require communication among planets, moons, satellites, asteroids, robotic spacecrafts, and crewed vehicles. These missions produce significant amount of scientific data to be delivered to the Earth. In addition, these missions require autonomous space data delivery at high data rates, interactivity among the in-space instruments, security of operations, and seamless inter-operability between in-space entities. The next step in the design and development of deep space networks is expected to be the Internet of the deep space planetary networks and defined as the InterPlaNetary (IPN) Internet. The Interplanetary Internet is envisioned to provide communication services for scientific data delivery and navigation services for the explorer spacecrafts and orbiters of the future deep space missions. All of these future space missions have a common objective of scientific data acquisition and delivery, which are also the main possible applications of the Interplanetary Internet.

THE FUTURE---INTERPLANETARY INTERNET

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.

2. A specialized deep space backbone network of long-haul wireless links interconnecting these local internets.This interplanetary backbones 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 suites the earth "networks of networks" into the internet, 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*** through a concatenated series of Internets. 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).

While the Earth's backbone network is wired the interplanetary backbone is dependent on fragile wireless links.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, 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 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. 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 gets the bundle delivered to a remote destination "region" of the Inter planetary internet. The second part of the name 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 TCP/IP suite provides these features. Programs of Mars exploration will need an analogous set of standard capabilities.

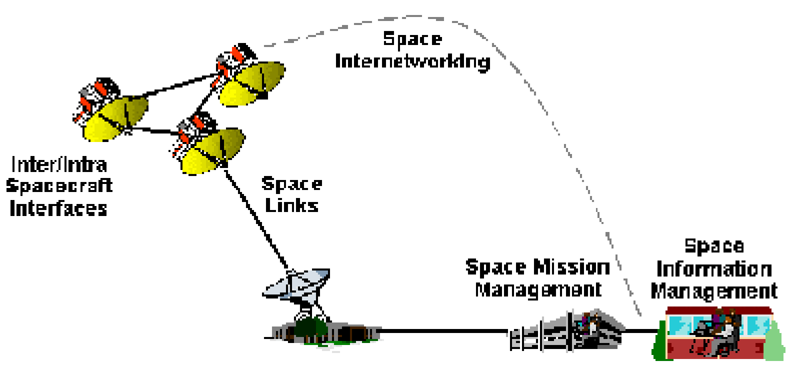

FIG:1 SPACE MISSION DATA INTERFACES

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 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. At the top of the stack are the user "applications" that run on computers located in space or on ground.

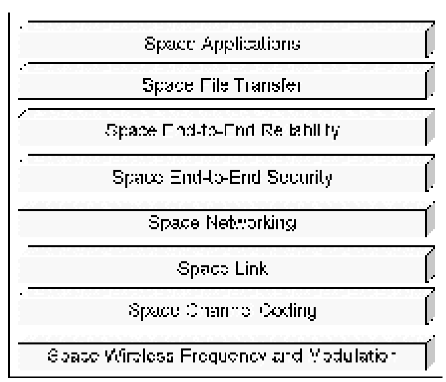

FIG:2 SPACE PROTOCOL STACK

When two applications need to exchange information, several underlying layers of standard data communications protocol support them. 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.

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 Linklayer 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. 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 bidirectional Link layer reliability via a available 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 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

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) 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

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– 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 filebased 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 under lying 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.

COMMUNICATIONS SCENARIO FOR MARS OPERATIONS

Data communications in support of Mars exploration has already moved into the "networked" era .The spacebased 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.

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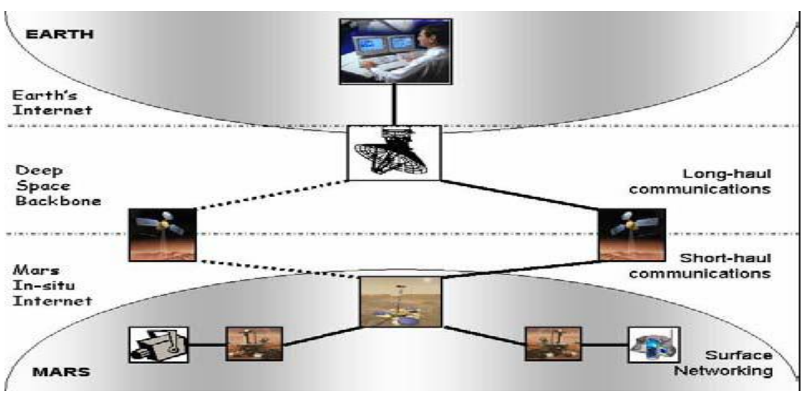

FIG: MARS NETWORKIN SCENARIO

For the most part, the international standards that are now coming into widespread use can satisfy these communications problems.

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 bidirectionally.

2. 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 space craft, the long haul link protocols

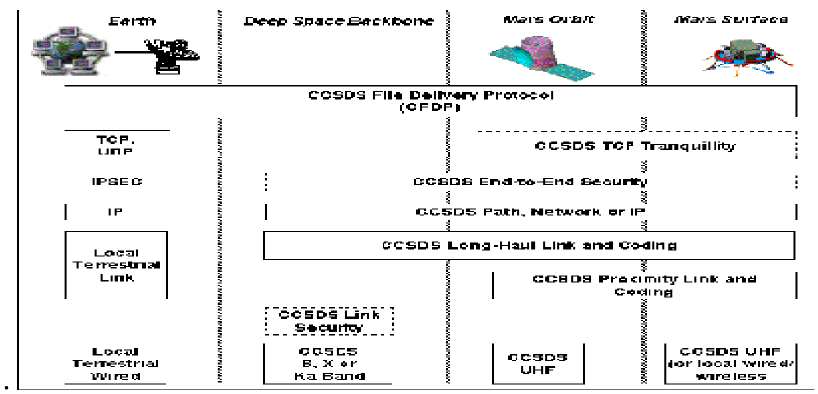

FIG:4 MARS COMMUNICATIONS PROTOCOL STACK

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. The current CFDP architecture 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.

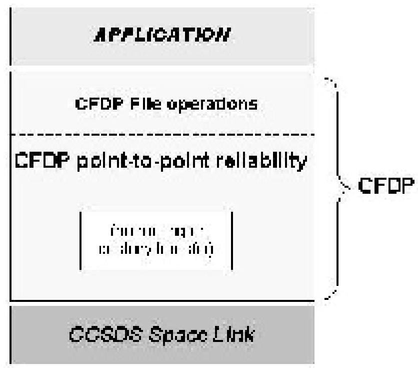

FIG:5 CURRENT CFDP ARCHITECTURE

Extensions to CFDP are currently under development that will allow it to support multihop custodial file data transfers.The current *bundling* protocol architecture improves on CFDP in several key respects:

a. It is not confined to supporting just file transfer, but it can handle virtually any end-to-end space application.

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.

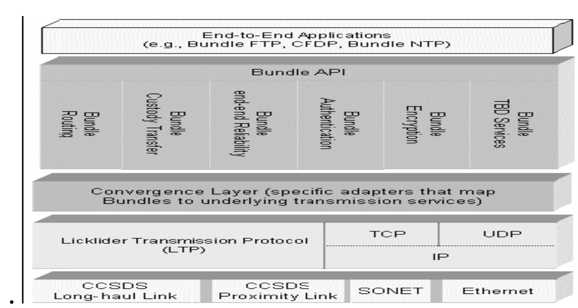

FIG:6 CURRENT BUNDLING ARCHITECTURE

INTERPLANETARY INTERNET: DEPLOYMENT STRATEGY

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. Coordinated mass exploration provides a rare sense of community. In particular, Mars exploration offers a unique communications opportunity because of the presence of multiple orbiting spacecraft .Anything landed on the surface of Mars faces stringent communications challenges, of which power availability is currently the most constraining. Surface vehicles can now exploit approximate 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. It is believed 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

A rich and proven set of international standards are already existing to support our needs for communicating between Mars and Earth. Those standards will continue to evolve and grow in capability. Many researchers and several international research organizations are currently engaged in developing the required technologies to realize the Interplanetary Internet. Despite the considerable amount of ongoing research in this direction, there still remains significantly challenging tasks for the research community to address before the realization of the interplanetary Internet.

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