TOWARDS AN INTERPLANETARY INTERNET:
A PROPOSED STRATEGY FOR STANDARDIZATION

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ABSTRACT*

A strategy is proposed whereby the current set of internationally standardized space data communications protocols can be incrementally evolved so that "Interplanetary Internet" operations are feasible by the mid-part of the coming decade. The strategy - which is already starting via the deployment of Mars relay links - needs individual missions to each contribute increments of capability so that a standard communications infrastructure can rapidly accrete.

This paper reviews the current set of standard data communications capabilities that exist to support advanced missions, discusses the architectural concepts for the future Interplanetary Internet, and suggests how a standardized set of space communications protocols that can grow to support future scenarios where human intelligence is widely distributed across the Solar System

INTRODUCTION

For exactly twenty years, 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.

CCSDS standardization activities span the five broad operational domains as shown in Figure 1.

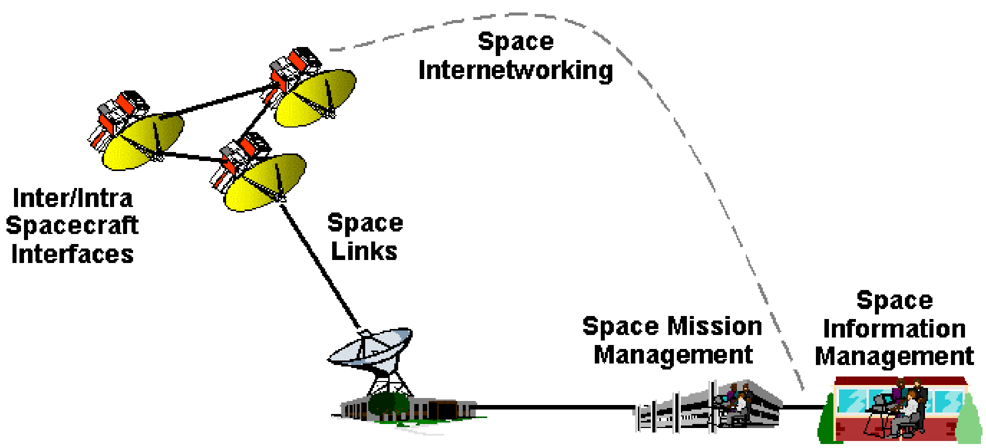

Figure 1: CCSDS Standardization Domains

1. Data handling interfaces within or between spacecraft, including the mechanisms that allow a payload to connect to the onboard data system or a landed vehicle to talk to an orbiter via a space link.

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

This paper focuses on the first three categories of standards, i.e., the data communications capabilities that support the transfer of information to and from space.

CURRENT CCSDS CAPABILITIES

The CCSDS space data communications standards are layered so that they stack together in a modular fashion as shown in Figure 2. The space layers broadly map into the well-known model of Open Systems Interconnection[2].

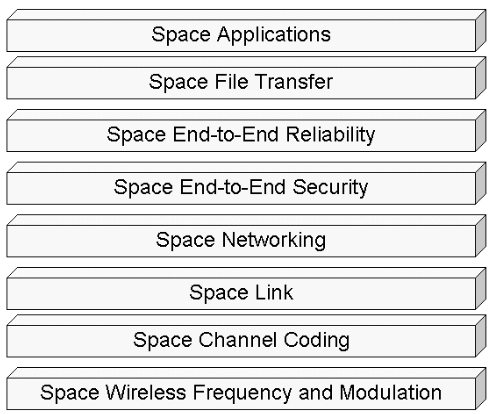

Figure 2: Space Protocol Stack

On top of the stack sit the user applications that run on computers located in space or on the ground. When two applications need to exchange information, they draw on the underlying layers of standard data communications protocol. These layers contain multiple options that can be selected to meet mission needs, and many of the layers can be bypassed if not required.

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.

Coding standards. These capabilities “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.

Link standards. These are the “frames” that carry higher layer data across the space link and are defined by the CCSDS Packet Telemetry and Packet Telecommand standards. CCSDS Telecommand provides reliability via a ‘go-back-n’ frame retransmission protocol, the Command Operation Procedure (COP). CCSDS Advanced Orbiting Systems extends 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 provides reliable 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.

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 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 communications overhead associated with carrying large source and destination addresses in every packet).

The set of CCSDS standards described up to this point represent those in use by the large majority of current missions. The details of the stack are shown in Figure 3; each one of the "stalks" represents a service that can be accessed by a user application that wishes to communicate across a space link.

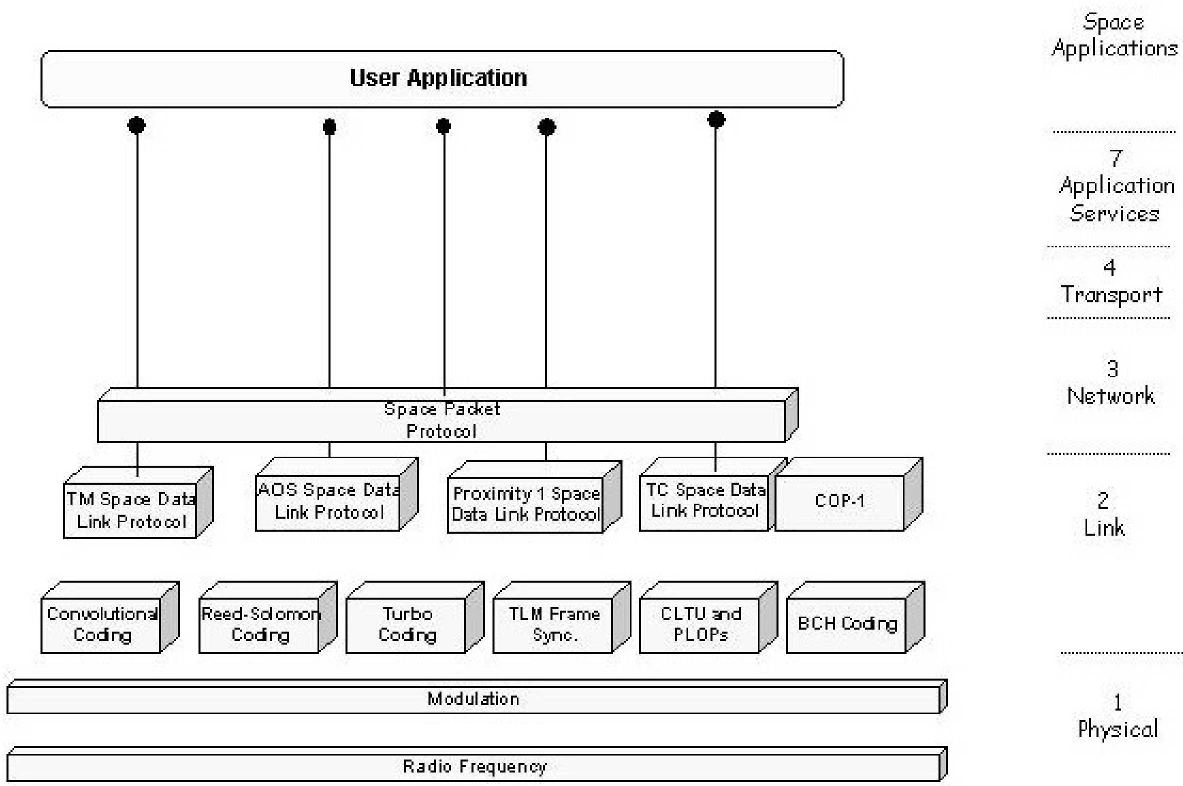

Figure 3: Typical Current CCSDS Stack

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)[3]. Both of these capabilities allow packets to be dynamically routed through different paths in a connectionless manner.

CCSDS is also currently working on *Intranet* standards that are focused on Internet-like services that are internal to a spacecraft, e.g., onboard local area networking.

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 user data during transit.
- Confidentiality: protection from disclosure of the contents of the user data.

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. 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.

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 infrastructure such as the Deep Space Network becomes 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:

1. 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.
2. 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.

CFDP also 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 resource constrained spacecraft. For missions not wanting to use file transfers, applications can bypass the file process and access most of the underlying layers directly.

The resulting "emerging" stack of standard CCSDS protocols is shown in Figure 4, which reveals how the basic set of CCSDS capabilities that are now in widespread use have been extended into the "upper layers" and can now support three flavors of space networking:

1. Conventional short delay end-to-end internetworking, using space extensions to the familiar "TCP/IP" suite of terrestrial protocols.
2. Custodial, delay tolerant file delivery, using CFDP.
3. Intranetworking within a spacecraft.

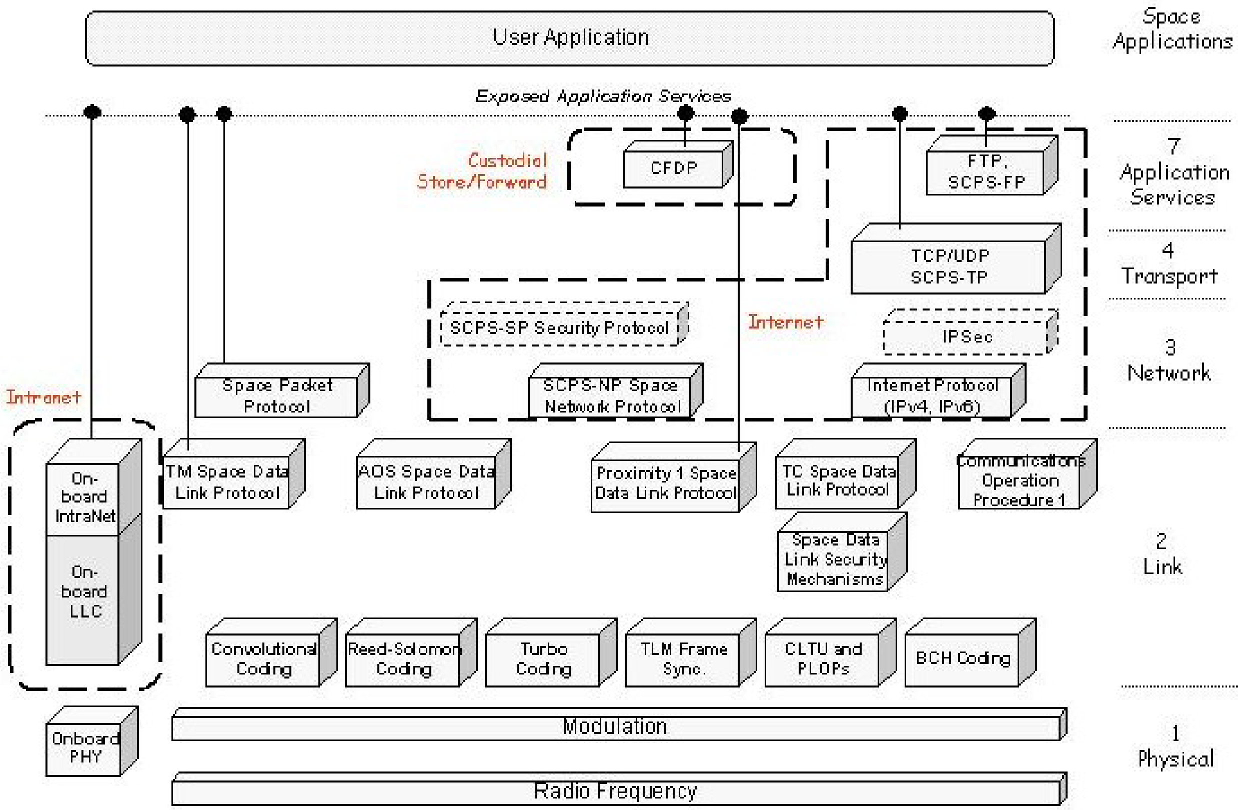

Figure 4: The "Emerging" CCSDS Stack

These new capabilities are available for deployment and may be expected to appear on missions that are launched in the post-2004 timeframe.

AN INTERPLANETARY INTERNET

The US Defense Advanced Research Projects Agency (DARPA), as part of its "Next Generation Internet" initiative, has recently been supporting a small group at the Jet Propulsion Laboratory in Pasadena, California to study the technical architecture of an "Interplanetary Internet". The idea was to blend ongoing CCSDS work in standardized space communications capabilities with state of the art techniques being developed within the terrestrial Internet community, with a goal of facilitating a transition as the Earth's Internet moves off-planet. 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 basic architectural concept[4] is that local in-situ short delay Internets, distributed across the Solar System on free flying spacecraft and on and around other planets, are interconnected via a long delay deep space backbone network. In the same way that the TCP/IP suite unites the Earth's Internet as a "network of networks", a new protocol suite called *bundling* unites the Interplanetary Internet as a "network of Internets" by supporting interplanetary dialog. This architecture is sketched in Figure 5.

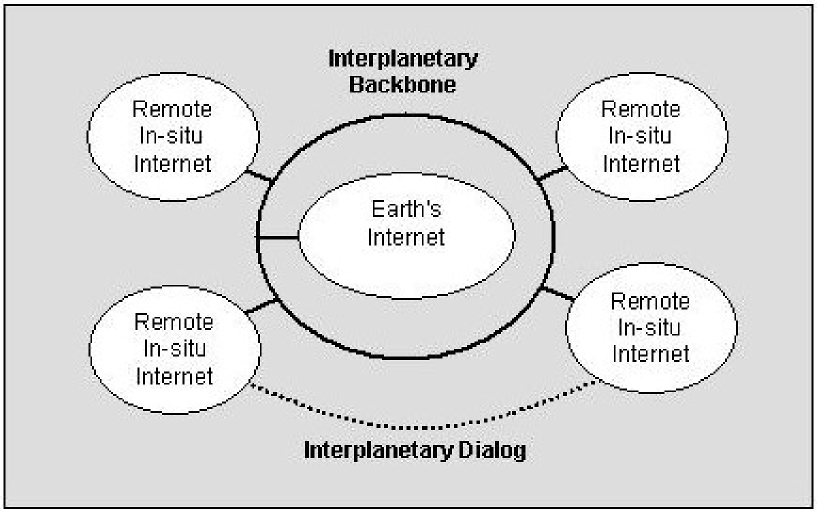

Figure 5: "Interplanetary Internet" Architecture

The architecture recognizes that in the space environment a real time end-to-end path between two users may never exist as a connected entity. Instead, communications must occur by stitching together a series of time-disjoint individual hops. The *bundling* protocol suite is the mechanism by which the stitching occurs. A routing function will direct "bundles" through a concatenated series of Internets, conceptually just as the Earth's 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 analogous to those provided by the terrestrial Internet's Transmission Control Protocol (TCP).

The *bundling* protocol handles the space 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.

While deep space communications (with their enormous propagation delays) are obvious examples of "delay tolerant networks", it is expected that the disconnected mode of operation will become increasingly important to terrestrial communications as the edges of the Internet become untethered. Other applications that may use these techniques include stressed tactical military communications and remotely located sensor webs. The costs of the *bundling* protocol development are therefore likely to be shared across a fairly wide community, and bundling will therefore become correspondingly robust.

The CCSDS File Delivery Protocol (Figure 6) is - by design - a prototypical form of the *bundling* protocol. The current CFDP consists of three parts:

1. File handling mechanisms, plus;
2. Point to point reliability mechanisms, which draw upon underlying;
3. Space link data transfer services.

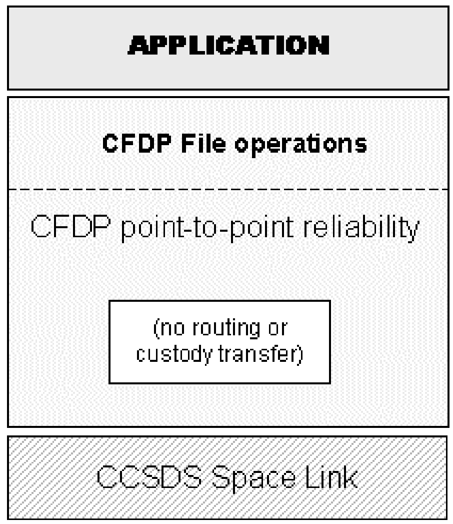

Figure 6: Current CFDP Architecture

Extensions to CFDP (Figure 7) are presently under development that will allow it to support multi-hop file data transfers of the sort envisioned by the "Mars Network" concept, where multiple Mars orbiters provide data relay services in the vicinity of the planet.

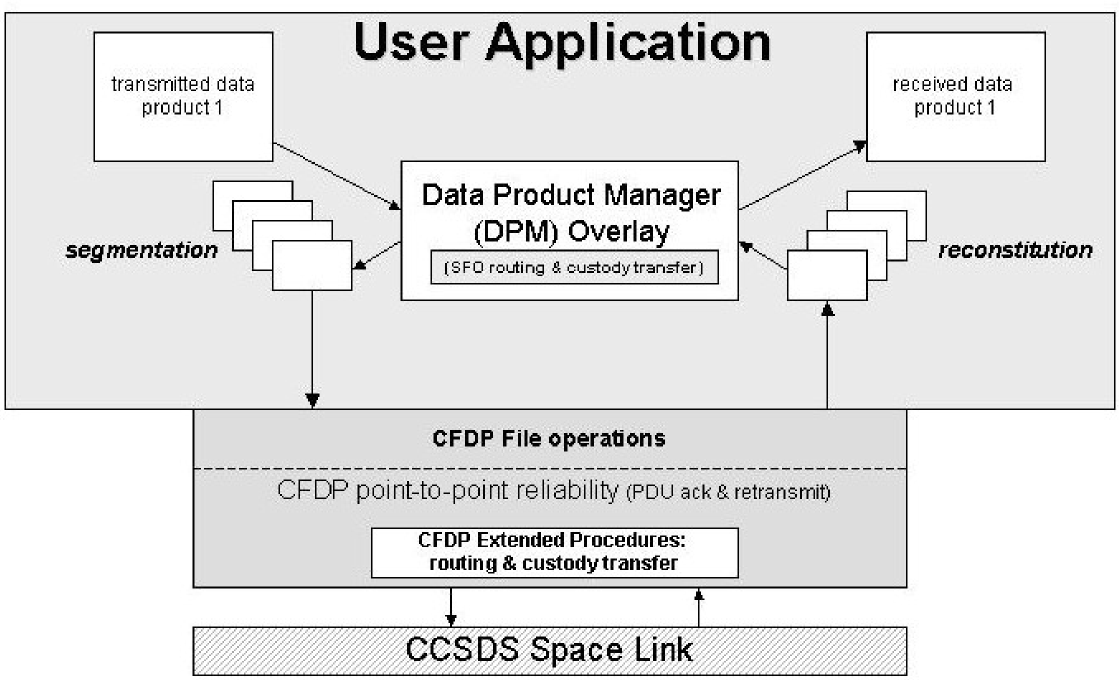

Figure 7: Extensions to CFDP

The new set of CFDP capabilities includes:

a. Extended Procedures, added to the CFDP protocol, that support routing and custody transfer. They enable incremental, immediate forwarding protocol data units at waypoints without requiring retention of complete files.
b. A Store and Forward overlay (added to the user application) that augments those procedures by providing route tracing and diagnostic facilities and enabling continuation from a known failure point. This overlay does not entail modification of the implementation of CFDP itself.

c. An additional user application capability – a "Data Product Manager" – that enables operation for missions using multiple parallel relays, such as Mars Network operations.

With these added capabilities, CFDP should be sufficient to satisfy immediate space mission needs through the 2007 timeframe. However, an intriguing opportunity exists to possibly avoid additional CFDP complexity by making a fairly rapid transition to the *bundling* protocol (Figure 8).

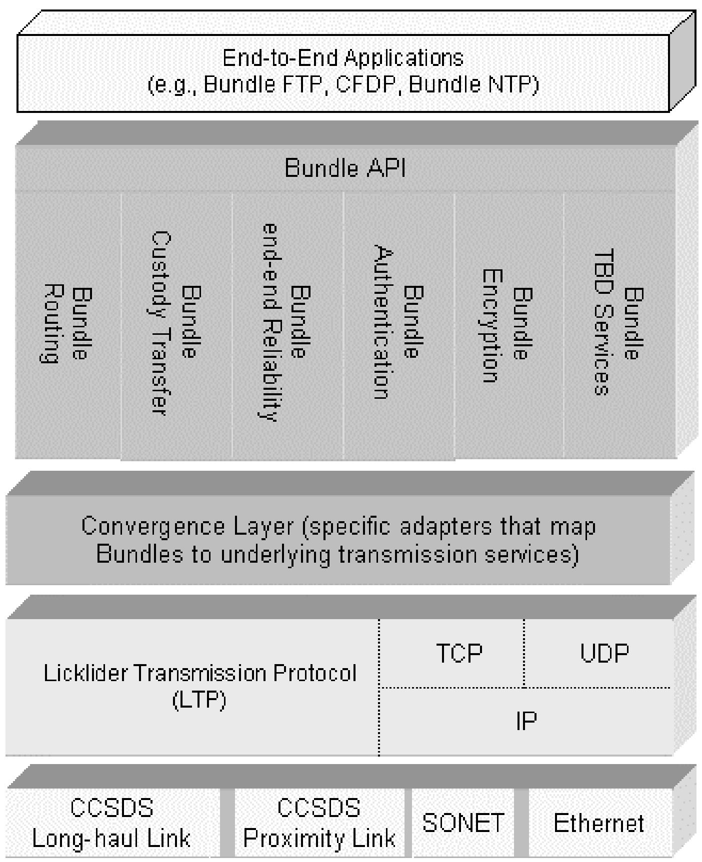

Figure 8: Current *bundling* Architecture

The current *bundling* protocol architecture differs from CFDP in several key respects:

- 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.
- Its internal functions are more clearly layered than CFDP, so that it should be easier to evolve over time.
- It will provide a rich and comprehensive set of application services, including a more mature custodial transfer capability than is achievable with CFDP.

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

CONCLUSION

Twenty years into the age of space standardization, CCSDS has achieved remarkable success in developing the basic set of data communications techniques that have allowed space agencies to build an interoperable space mission support infrastructure. That success is intended to continue, slowly building on and evolving those techniques throughout the coming decade during a period that – particularly in the area of Mars exploration – promises to be full of exciting new discoveries. Disruptive events are likely to occur, so we should prepare our space data communications systems to be able to handle them.

As a result of the Interplanetary Internet studies, we now have charted a pragmatic forward strategy that will allow us to quite rapidly integrate our space missions with technologies that are likely to be used in several emerging parts of the terrestrial Internet. By rapidly adding upper layer capabilities such as CFDP to our space missions, we will start a shift towards fully automated network operations. By developing and inserting *bundling* on a timescale that is compatible with the evolution of CFDP, we will begin a strategic shift towards laying the foundations for a true Interplanetary Internet that can scale to handle new mission challenges.

REFERENCES

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