# Evolution of the Mars Relay Network End-to-End Information System in the Mars Human Era (2030-2040)

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**The current Mars Relay Network (MRN) is an evolving international network of Mars relay orbiters along with their supporting ground systems that provides communication and navigation relay services (command, telemetry, time and navigation) to Mars bound assets e.g., landers, rovers, probes. Currently, MRN consists of 4 relay orbiters serving 2 landed assets, whose governance is shared between NASA and ESA.**

**The associated MRN End-to-End Information System (EEIS) is the set of distributed functions allocated throughout the flight, ground, launch, and mission operation systems, that interoperate to transport and manage mission information (e.g., science, engineering, radiometric, command, time) throughout this network. These functions are performed cooperatively by flight and ground elements to achieve mission user objectives.**

**In order to help the reader understand this evolution from the current to the future MRN state in the Mars human era, we will provide a description of the current communication infrastructure supporting Mars mission users, and how we envision it to change in order to meet the needs and challenges of supporting both human and robotic communication by 2030-2040. This includes the introduction of new data types like audio and video, and new in-situ relay services for communications and navigation services.**

**We firmly believe that cost will prohibit any sole nation from providing all communication services required by humans in this era. Therefore interoperability and cross-support will be necessary to achieve the connectivity goals of the MRN in the human Mars era. The authors contend that the best way to achieve the necessary network interoperability and cross support will be through the use of international standards predominately but not limited to CCSDS.**

**This paper will discuss: 1) The end-to-end MRN data flows from the key EEIS architectural points of view (physical, functional, communication, enterprise); 2) End-to-End Data Products. How data management (DM), data transport (DT), and data integration (DI) issues must be transparent to the user, so that users/Mission Operations System (MOS) do all their planning in terms of data products and never have to concern themselves with the artifacts of the DT, DM, DI functions with the End-to-End data system; 3) The layered ISO CCSDS protocol stack envisioned to support the MRN including the Delay-Tolerant Networking (DTN) architecture:**

**1) Physical Layer - Optical and RF Communication along with higher order modulation schemes;**
**2) Data Link Layer - Unified Space Link Protocol (USLP) with very high performance coding on both uplink and downlink to be used on all robotic (near Earth and deep space) and manned links;**
**3) Network Layer – End-to-end DTN Bundle Protocol (BP), with reliability ensured by underlying Licklider**
**4) Transmission Protocol (LTP), enabling secure seamless transition between IP (terrestrial) and CCSDS space link based networks.**
**5) Transport Layer - Delay-Tolerant Payload Conditioning (DTPC) providing end-to-end acknowledgment and retransmission as necessary;**
**6) Application Layer - Asynchronous Messaging Service (AMS), CCSDS File Delivery Protocol (CFDP), and Bundle Streaming Service (BSS);**

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## I. Introduction

AN EEIS consists of hardware (e.g., computers and communications links), software, people, and procedures. The "ends" of the EEIS vary from project to project. In the broadest sense at one end are the spaceborne instruments and/or sensors that collect the mission information and at the other end are the end users (e.g., science and technology investigators, mission operators) of the mission information. The EEIS is a system of systems in the abstract that is made concrete through the implementation of flight and ground systems consistent with the overarching EEIS architecture of the program. It is the EEIS layered architecture which defines in greater detail the flight assets, MOS teams, MOS processes, project data system (flight and ground), and multi-mission services the project will use.

In order to visualize the totality of the EEIS architecture, the EEIS engineer develops a set of end-to-end information views: organizational (objectives, roles, policies, activities, lifecycle, contracts), connectivity (physical, configuration, constraints, behaviors), communicational (protocol), functional (interactions, interfaces), informational (structure, semantics, relationships, permanence, rules). These views describe the flow of data and control across the end-to-end information system. This paper will specifically focus upon the physical connectivity and protocol communicational view of the EEIS in the Mars Human Era.

But no architecture no matter how intrinsically beautiful on paper is truly worth its salt unless it is implementable. Therefore we explore the EEIS engineering aspects of operability in the context of the Mars Human Era EEIS. EEIS engineering is to a large extent Operability Engineering. Its main focus is to:

1) Reduce life cycle costs and mission risk by influencing the instrument, spacecraft, and MOS designs to make it easier to "operate the mission".
2) Enhance the visibility and controllability of the flight/ground system.
3) Provide improved EEIS performance and accountability by integrating leading CCSDS information system recommendations into the ground infrastructure services and program/project spacecraft capabilities.
4) Provide the means to account for the execution, production and delivery of observational data products.

The evolution of on-board data handling (OBDH) systems towards both managing and transferring data products is largely driven by the scalability of future high rate systems. Data products represent a much smaller set of objects to manage than their component transmission artifacts, i.e., frames and packets. Mars missions today still use CCSDS space packets for some engineering housekeeping and accountability (EHA) data but even these packets are stored and transmitted as data products to manage them more efficiently and effectively. A transitional step towards a data products based architecture is the use of file transfer and the CFDP[1].

In order to be more forward looking than the current Mars mission architecture, we advocate pushing aggressively toward the use of "data products" on-board and in the ground segment, along with its associated meta-data (a more comprehensive approach than just conveying product types by using file naming conventions as in the current Mars Relay Network[2]. It's a natural fit for CFDP now and for DTN[3] in the future.

## II. Current vs. Future Mars Human Era EEIS Architecture

We compare and contrast below the current (2016) vs the future (2030-40) Mars EEIS architectures by evaluating two EEIS architecture views: the connectivity view and the protocol view. The connectivity view shows how space data systems are made up of physical elements that must operate in space, and the connections between elements, the physics of motion, and external environmental forces that must be considered[4]. The protocol view defines the layered sets of communications protocols that are required to support communications primarily among the software engineering elements in a space data system[4].

## A. Current Mars EEIS Architecture and Constraints

The current connectivity view of the MRN in 2016 is depicted in Figure 1 below:

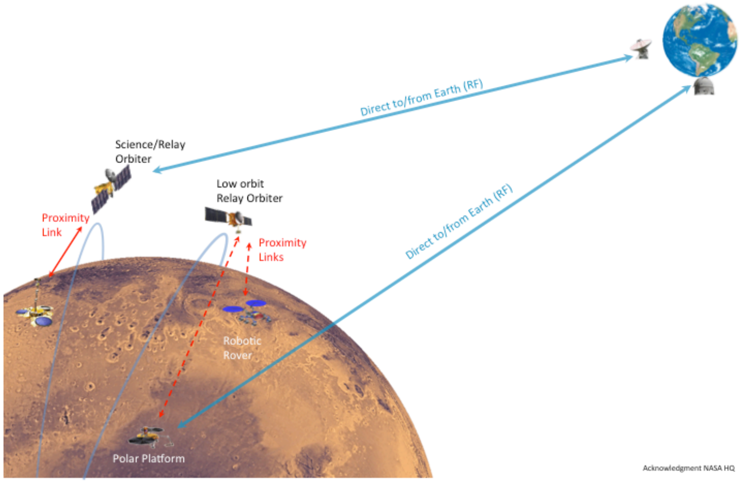

**Figure 1. MRN Connectivity View 2016**

The current era is characterized by robotic remote sensing only. One is immediately struck by the lack of connectivity options. Connectivity at Mars is simple and reliable but quite constrained in many dimensions. There are two main types of connection paths between Earth and Mars. The initial and traditional pathway consists of the long haul links in blue: Direct From Earth (DFE) containing command data and Direct to Earth (DTE) containing telemetry. The more recently used pathway, enabling greather throughput, is provided by the MRN relay orbiters. They provide connectivity between the Mars landed assets via the proximity forward (command) and return (telemetry) links and connectivity with Earth via their DFE/DTE links. There is a strong notion in mission operations in this era of link directionality i.e., forward or uplink (command) and return or downlink (telemetry). Link directionality up to this point has strongly driven how data systems are developed and operated. For example, different CCSDS link protocols and channel codes are used to support the uplink vs downlink vs proximity link. There are no cross links between relay orbiters. No data is currently exchanged between landed assets without first returning the data to Earth. No opportunistic relay overflights are available to landed assets, i.e., all overflights and data transfers are manually scheduled. The point to point nature of the connectivity between landers and orbiters is driven by the short maximum 10 minute relay over flights. Heritage design of the DFE/DFE path has influenced the relay comm architecture. Since the MRN consists of primarily science orbiters providing secondarily a relay service, the landed asset tunnels its lander frame through the relay orbiter's data system.

## B. Current Mars Relay Network Protocol View

The current protocol view of the MVN is shown in Figure 2 below:

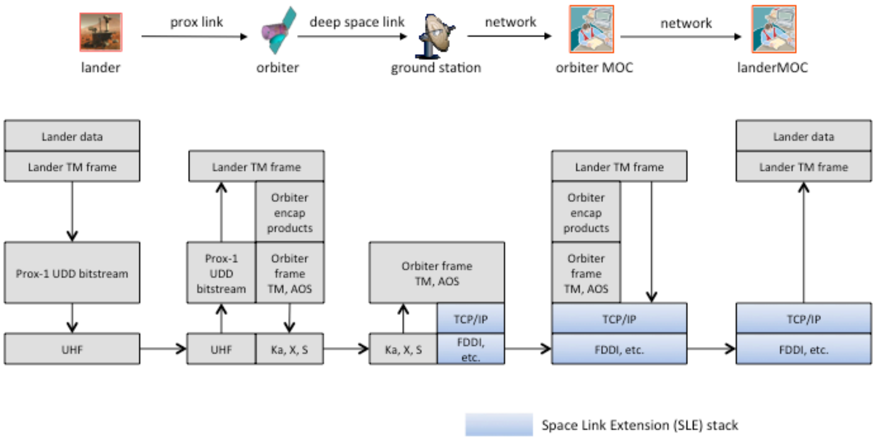

**Figure 2. MRN Protocol View 2016**

This diagram shows which protocols are used by each data system in the End-to-End (E2E) data flow and where their beginnings/end points are. The focus of this diagram is on the E2E downlink path of the lander transfer frame. End-to-End in this case is from the Mars lander to the Lander Mission Operations control Center (MOC) on Earth. The lander transfer frame is tunneled through the relay orbiter over the Proximity-1[5] link as a user defined bit-stream. Although the Proximity-1 standard supports a reliable packet stream interface through which internetworking could be supported, this feature is not currently implemented.

It is important to note that each relay orbiter in the MRN has a different OBDH system. In part, this is because these orbiters are primarily science probes and only secondarily function as relays. Once on the orbiter and ready for downlink, the lander data is stored in the OBDH system as AOS[6] telemetry frames along with separate frames generated by the orbiter itself. A single interface on both the return proximity link and the DTE link is largely driven by the fact that the OBDH does not store data products collected from the science instruments. Instead, the current relay orbiters encapsulate the science packets in AOS frames and pre-store these frames for later downlink, when in fact the framing should only occur during downlink time. As a result, relay orbiters can only transfer data across the proximity link by tunneling frames via reliable bit stream mode. This is a self-inflicted rigidity due to an archaic implementation of these CCSDS standards within the OBDH system and proximity transceivers.

### C. Future Mars Human Era EEIS Architecture

The connectivity view of the MRN in the Mars human era is depicted in Figure 3 below:

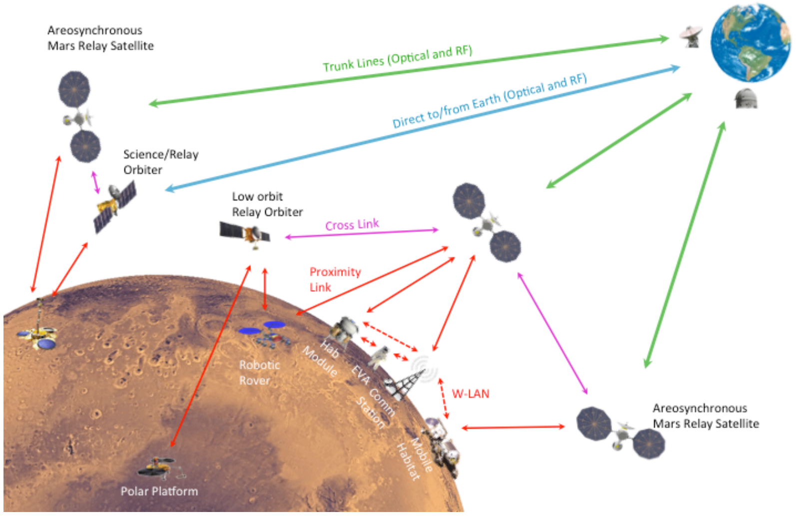

**Figure 3. MRN Connectivity View 2040**

MRN operations in the Mars Human Era will continue to include robotic remote sensing but these operations will be complemented by the activities of astronauts and their vehicles and other deployed space exploration assets. The communication connection fabric will necessarily be vastly richer: robotic sensors will communicate not only with orbiters and with MOCs on Earth but also with astronauts and exploration assets, which in turn will communicate among themselves and with a wide range of entities on Earth: mission operations systems and personnel, science experiment investigators, family members, data resources to which astronauts will require access, and more. The concept of link directionality ("forward" and "return") will disappear: communicating entities will be peers and communication pathways will be functionally symmetrical (even if data rate asymmetry persists). Science orbiters may continue to serve data relay functions at some level, but the volume of communication required to sustain these missions will mandate the far higher service levels that can only be provided by dedicated communication satellites, nominally in areostationary orbits. Communication opportunities on the surface will no longer be limited to the overflights of satellites in low Mars orbit, but end-to-end communications with Earth may still be punctuated by the communication satellites own orbital movement, depending on the availability of communication satellite cross-links.

### D. Future Mars Relay Network Protocol View

The future protocol view of the MVN is shown in Figure 4 below:

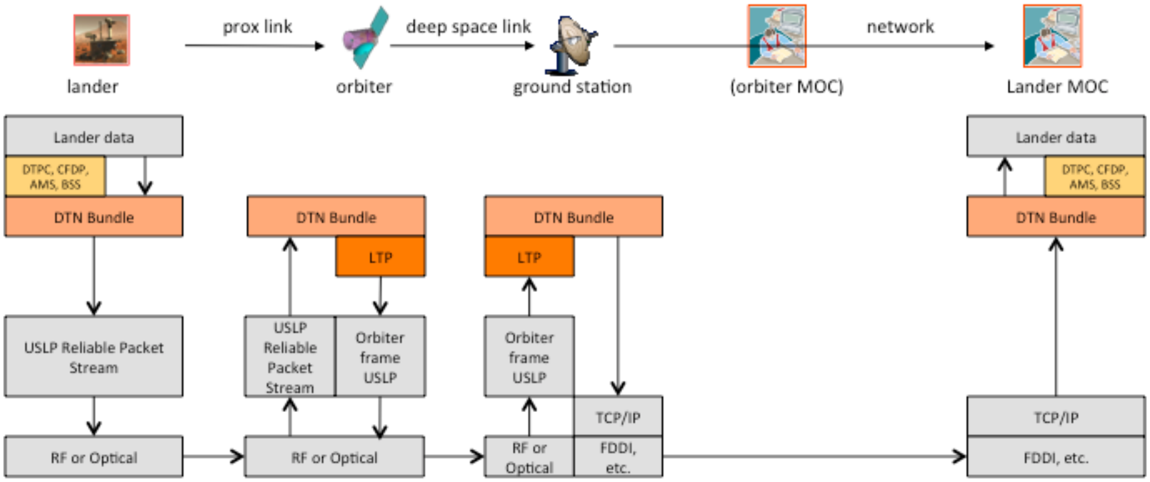

**Figure 4. MRN Protocol View 2040**

Clearly the complexity of the Mars communication environment in this era is orders of magnitude greater than in today's regime, but technology is already at hand to manage that complexity.

We envision communication opportunities will employ the CCSDS Unified Space Data Link layer protocol (USLP) currently in development by CCSDS. It is compatible with a wide variety of coding and modulation schemes and physical media (radio bands and light frequencies) operating at sharply varying data rates based upon operational need. In order for network protocols to route user data products across the MRN, USLP supports a reliable packet stream delivery mode.

The DTN protocols are designed to enable automation of virtually all aspects of mission communication channel operations, including many elements of data management. The DTN "Bundle Protocol" (BP)[7] encapsulates complete user data products in protocol data units called "bundles" containing the information that any receiving relay entity would need in order to properly forward the data toward its destination, subject to application-specified quality-of-service parameters. This functionality is preserved end-to-end regardless of variation in the characteristics of the communication links at the underlying "convergence layer". The non-volatile data buffering performed by BP automatically mediates between inbound and outbound data flows at different rates and even at different times. Data that are lost or corrupted in transmission are efficiently detected even over very long signal propagation latencies and are automatically retransmitted by the DTN "Licklider Transmission Protocol"[8] over the link on which the error occurred, or over a later opportunity if that link has been closed by the time the error is detected. Data retained in buffers to support automatic retransmission are automatically deleted (subject to application control) upon successful reception. All communication processes are symmetrical (wherever bidirectional communication is supported), and extensive security measures – termed the "Bundle Security Protocol" (BSP)[9] – to protect the integrity and/or confidentiality of data are available on all links.

The richer connectivity of the MRN will in many cases offer multiple alternative end-to-end paths by which a given data product might reach its destination. Selecting the optimum path for each bundle is challenging in concept, but DTN includes a "route" computation mechanism, "Contact Graph Routing" (CGR)[10], that automatically makes this determination based on the characteristics of the bundle (size, destination, priority), the current backlogs of data awaiting transmission to neighboring network nodes, and the schedule of future communication opportunities planned by mission operations teams and the operators of the Deep Space Network. When a planned opportunity is canceled or interrupted for some reason, DTN will automatically re-route to the next best opportunity all bundles currently allocated to that contact. Since the DTN protocols are international standards, cross-support is simplified: recovery from a missed communication opportunity may be easily and automatically provided by a different mission operated by a different space agency.

## III. Key Technical Considerations of the Future EEIS Architecture

### A. Optical and Radio Frequency Communication

In the past decade, optical communications have matured substantially for use in deep space exploration. It is expected that optical communications would be ready for operational use within 5 to 10 years. Optical links enable higher data rates than RF, yet they are more susceptible to external perturbations such as spacecraft pointing and weather effects. RF links, on the other hand, support lower data rates, but they have less demaining pointing requirements and are more immune to weather effects. It is expected that future spacecraft would carry both optical and RF systems to ensure high-capacity and robust communications. The concept of operation is to utilize optical link for bulk science data that can tolerate high-latency and occasional loss, and use the RF link for time-critical engineering and telemetry data. The onboard data management system would implement standard data and network protocols to ensure smart and efficient data delivery through different communication channels.

### B. Low latency QoS issues for Voice, Video, and Security

In the Mars human era, we expect the areosynchronous[1] Mars relay orbiters to act as access points providing continuous relay coverage to astronauts and to manned and robotic assets in the Mars vicinity. The MRN supports Earth relay services as well as in-situ relay services, which includes voice and video communications. We expect the introduction of these new data types would affect the MRN architecture in the following ways:

1) Voice and video communications are real-time in nature. This imposes stringent latency requirements (QoS) on data transport in the MRN, which in turn drives the in-situ relay architecture toward “amplify-and-forward” rather than “decode-and-forward”.
2) Due to privacy requirements on voice and video data, the in-situ Mars relay links must employ authentication and/or encryption that ensure secure communications between astronauts, and between Mars surface assets and Earth.

## IV. CCSDS Future Protocol Stack Supporting MRN

Figure 5 shows what we envision to be the future CCSDS protocol stack in the MRN. The left hand arrow shows how the Protocol Data Units (PDUs) traverse the various protocols supporting the receive side until received as a Service Data Unit (SDU) i.e., a file by the application. The right hand arrow depicts how a SDU e.g., a file is provided by the application at the highest layer and transferred as PDUs of each successive protocol layer on the sending side. A short discussion of the functionality of each layer is provided below.

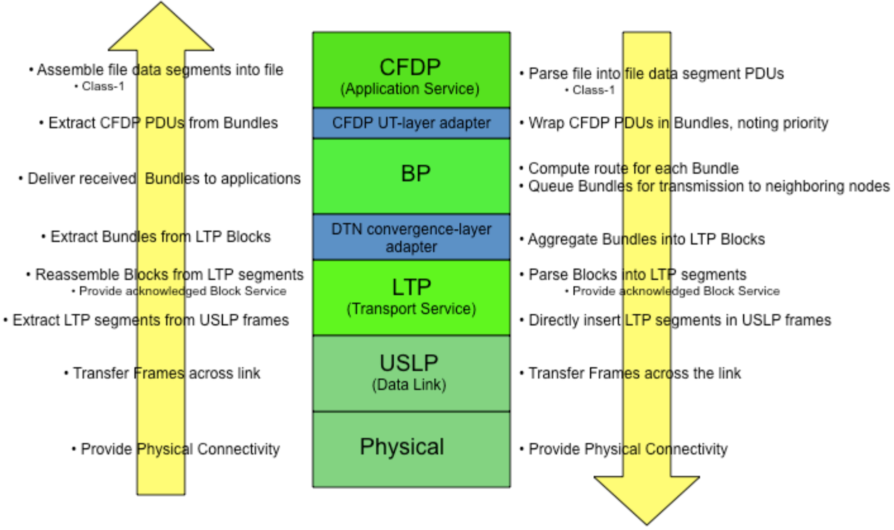

**Figure 5. CCSDS Layered Protocol Stack for MRN**

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[1] The Mars areosynchronous orbit altitude is 17000 km.

### A. Physical Layer

The **physical layer** is layer one i.e., the lowest **layer** in the seven **layer** OSI (open system interconnection) reference model.

*RF communications* Traditional deep space communication systems employ power-efficient modulation techniques like Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK), and operate in lower frequency bands like S-band and X-band. Due to the lack of available RF spectrum allocation and the mission demand for higher data rates, a higher frequency band like Ka-band, and spectral-efficient modulation schemes like Gaussian Minimum Shift Keying (GMSK) and high-order Quadrature Amplitude Modulation (QAM) are being considered. On the DTE link, the MVN network is considering moving to Ka-band, coupled to high-power transmitters, enabled by the high power available from Solar Electric Propulsion (SEP) delivered orbiters, and large deployable antennas. These technologies combined could offer up to a magnitude of telecom performance improvement over the current state of the art. Over the proximity link, operations has been restricted to uHF band via omni antennas. Several orders of magnitude improvement could be realized by moving to higher-frequeny directional links.

*Optical communications* Optical communications can broadly be divided into two basic types – direct detection and coherent detection. Direct detection extracts transmitted information just from the power variation of the received field. Coherent detection, on the other hand, requires a locally generated field to optically mix with the received field through a front-end mirror, and the combined wave is photo-detected. One commonly used direct detection scheme for deep space optical communications is Pulse Position Modulation (PPM), which was first proposed by Pierce in 1978 for the photon counting channel[11]. Theoretically the PPM scheme has unbounded transmission efficiency that can be increased infinitely by merely increasing the number of pulse positions or time slots in the noiseless case. PPM combined with forward error correcting codes can be used to obtain high transmission efficiencies at tolerable bandwidth expansion[12]. However recent analysis indicates that PPM exhibits $1/r^4$ roll off in channel capacity at low signal-to-noise ratio[13]. Coherent detection schemes like M-PSK and M-QAM have lower transmission efficiency compared to direct detection schemes, but they shows $1/r^2$ roll off in channel capacity across the whole range of signal-to-noise ratio.

The CCSDS is currently standardizing optical communications for both near earth and deep space environments.

### B. Data Link Coding Sublayer

The Data-Link layer is layer 2 in the Open Systems Interconnect (OSI) model. The lower portion of this layer is the Channel Coding sublayer. Channel coding ensures reliable communication of digital data, typically as a stream of “ones” and “zeros”, between a source and a destination separated by a noisy channel. The channel encoder maps k information bits to n channel bits, where $k < n$, and produce a modulating waveform for transmission through the noisy channel. The receiver/decoder accepts the corrupted channel waveform, and attempts to reconstruct the original binary data. A well-designed coding scheme is one that meets the error rate and spectrum expansion requirements of the communication system, while using less energy per information bit than the uncoded system.

The error-correction coding schemes recommended by the CCSDS standards are: a) convolutional codes[14], b) Reed-Solomon (R-S) Codes[14], c) concatenated codes[14], d) turbo codes[14], e) Low Density Parity Check (LDPC)[14] codes, f) Serially Concatenated Convolutional Codes (SCCC)[15] and the g) Digital Video Broadcasting - Satellite (DVB-S2)[16] code.

### C. Data Link Protocol Sublayer – USLP

The upper portion of the Data-Link layer is the data protocol sublayer consisting of the data link protocol. USLP has been designed to meet the requirements of space missions for efficient transfer of space application data of various types and characteristics over all space-to-ground and/or space-to-space communications links. It transfers a variable-length protocol data unit called the Transfer Frame between adjacent network nodes in a network. USLP addresses the three major deficiencies in the current set of CCSDS link layer protocols: 1) Transfer frame size and accountability are too limited for CCSDS’ agencies envisioned future mission set. This is largely due to advances in forward error correction coding algorithms and advances in microelectronic technology allowing improved uplink and crosslink performance to be achieved for space-borne systems; 2) There are inadequate spacecraft ID assignments available in the current CCSDS link layer protocols; 3) We believe the development of a single data link protocol for all links will reduce development and implementation costs for future missions that must communicate over multiple types of space links.

### D. Network Layer – End to End DTN Bundle Protocol with reliability aspects

The Network layer is layer 3 in the Open Systems Interconnect (OSI) model. As discussed earlier, the DTN Bundle Protocol operating at the Network layer, supported by the Bundle Security Protocol, the retransmission procedures of the Licklider Transmission Protocol, and the path selection capability provided by Contact Graph Routing, enables automatic, reliable, efficient, secure conveyance of data products from the entity at which they are created to the entity at which they are to be processed, regardless of data loss, round-trip communication latency, lapses in connectivity, and variation in data rates and transmission media.

### E. Transport Layer – Data Tolerant Payload Conditioning

The Transport layer is layer 4 in the Open Systems Interconnect (OSI) model. The base DTN protocols convey data products from source to destination reliably and securely but not necessarily in the order in which they were issued. For some applications, the order of arrival of data products must be the same as the order of transmission. Where functionality analogous to Transmission Control Protocol (TCP, the Transport-layer protocol of the Internet)[17] is required, DTN's "Delay-Tolerant Payload Conditioning" (DTPC)[7] protocol may be invoked. An application that uses DTPC presents outbound data products to DTPC for transmission rather than directly to BP. DTPC aggregates small data products into larger DTPC protocol data units (DPDUs), as necessary; strips redundant data products out of the aggregate DPDUs as appropriate, under application control; and presents sequentially tagged DPDUs to BP for transmission. The destination DTPC entity receives DPDUs from BP, possibly out of order, and re-sequences them for in-order delivery to the destination application. In addition, the sequential numbering of DPDUs enables the destination DTPC entity to detect discontinuities in data arrival and send end-to-end positive and negative acknowledgments back to the source DTPC entity to trigger end-to-end retransmission as needed.

### F. Application Layer

The Application layer is the highest layer in the Open Systems Interconnect (OSI) model. A variety of service protocols at the application layer will be available for use by future MRN users. Among these are:

1) The CCSDS File Delivery Protocol (CFDP), which enables efficient transmission of a file of arbitrary size, together with extensive metadata, from any MRN entity to any other. Individual portions of the transmitted file, encapsulated in individual DTN bundles, may take different paths through the network and arrive at the destination entity at different times, but reassembly and delivery of the file and all associated metadata is automatic; this ensures that file delivery latency is minimized, subject to the priorities of other transmissions.
2) The CCSDS Asynchronous Message Service (AMS)[18], which enables the efficient publication of brief messages to multiple subscribers at any number of physical locations in the network. AMS publication utilizes DTN to ensure reliability and security in message delivery.
3) The Bundle Streaming Service (BSS)[19], which delivers streaming video and telemetry data in transmission order – possibly with some data loss – for review in real time at the destination, while concurrently retransmitting lost data and storing these out-of-order transmissions in a database for error-free later replay.

## V. Conclusion

By comparing the current vs the potential future EEIS views of the MRN, we see an enormous increase in connectivity at Mars in only 15 to 25 years. All of the CCSDS protocols supporting this connectivity view are either currently ISO CCSDS standards today e.g., BP, LTP, CFDP or they are well into development e.g., DTN, USLP. Given the 3 to 5 year average CCSDS standard development time from beginning (white book) to end (blue book), we can safely estimate that the entire protocol suite will be available and compatibility tested well beforehand. Therefore the good news from a technology point of view is that the international space agencies providing resources in the Mars Human Era will be able to base their EEIS architecture on proven CCSDS standards. These protocols and their supported application service protocols will provide MRN users with the tools to automate routine communications of virtually all science, mission operations, medical, logistical, and other human support applications in the Human Era at Mars. This automation will help to minimize cost and risk in Human Era Mars missions, aiding humans at Mars and in mission and science support centers on Earth in making the best possible use of their valuable time.

# Appendix A
## Acronym List

| | |
|---|---|
| **AMS** | Asynchronous Messaging Service |
| **AOS** | Advanced Orbiting Systems |
| **BP** | Bundle Protocol |
| **BPSK** | Binary Phase Shift Keying |
| **BSS** | Bundle Streaming Service |
| **BSP** | Bundle Security Protocol |
| **CCSDS** | Consultative Committee for Space Data Systems |
| **CFDP** | CCSDS File Delivery Protocol |
| **CGR** | Contact Graph Routing |
| **DFE** | Direct-From-Earth |
| **DI** | Data Integration |
| **DM** | Data Management |
| **DPDU** | DTPC protocol data unit |
| **DT** | Data Transport |
| **DTE** | Direct-To-Earth |
| **DTN** | Delay Tolerant Networking |
| **DTPC** | Delay-Tolerant Payload Conditioning |
| **E2E** | End-to-End |
| **EEIS** | End to End Information System |
| **EHA** | Engineering Housekeeping and Accountability |
| **ESA** | European Space Agency |
| **FDDI** | Fiber Distribution Data Interface |
| **GMSK** | Gaussian Minimum Shift Keying |
| **IP** | Internet Protocol |
| **ISO** | International Organization for Standardization |
| **LTP** | Licklider Transmission Protocol |
| **MOC** | Mission Operations control Center |
| **MOS** | Mission Operations System |
| **M-PSK** | M-ary Phase Shift Keying |
| **MRN** | Mars Relay Network |
| **NASA** | National Aeronautics and Space Administration |
| **OSI** | Open Systems Interconnection |
| **OBDH** | On-Board Data Handling |
| **PDU** | Protocol Data Unit |
| **PPM** | Pulse Position Modulation |
| **QAM** | Quadrature Amplitude Modulation |
| **QoS** | Quality of Service |
| **QPSK** | Quadrature Phase Shift Keying |
| **RF** | Radio Frequency |
| **SDU** | Service Data Unit |
| **TCP** | Transmission Control Protocol |
| **UHF** | Ultra High Frequency |
| **USLP** | Unified Space Link Protocol |

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