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A Critical Design Evaluation of the Next Generation Space Protocol Architectures

Abstract

In this paper, we first identify eight major design challenges imposed by the next generation space protocols design. Second, we further defined a design evaluation framework based on the space protocol design challenges. Third, we critically evaluate the design of seven leading protocols architectures presented in [RHC 05] [HCP 05] [Bergamo 05] [BCDFHSW 02] [BH 02] [Israel 02] [LB 06] using the design evaluation defined. Finally, it was shown through the critical design evaluation performed in this paper that the currently proposed next generation space protocol architectures lacks a concise description for efficient space addressing schemes, mobile routing protocols, and reliable end-to-end transport protocols.

1. Introduction

In the early and middle twentieth century, space communication was an expensive commodity in the hands of few wealthy nations. The scope of space communication was basically restricted on outer space discovery, earth geography, and multi-purpose intercontinental communication. Moreover, the number of space missions was significantly low due to their extremely high expense, which was only affordable by few wealth governments.

A significant growth has been achieved by space industries since beginning of this millennium. This aspect is clearly seen through the increasing global demand for space communication services in mass telecommunication, defense, scientific explorations, weather forecast, and entertainment. As a consequence, national space agencies in forty-three countries are fiercely competing for exploring the outer space and further for establishing space networks infrastructures to support their future space exploration missions and interplanetary communication within the solar system. In addition, China and India have recently launched a program for sending manned space missions to the moon [SpaceToday 07][SpaceToday2 07]. More future planetary exploration and observation missions are planned by major national space agencies in India and South Korea.

One important aspect in both space exploration and planetary observation missions is handling the communication demands of the space network assets [BH 02]. In the current space missions, communication tasks are performed by industrial-specific **Space Protocols Architectures (SPAs)**. It has been shown that these SNPAs are no loner inadequate for the future space missions and applications as well [RHC 05]. In order to go side-by-side with the future space communication demands, a new generation of standard SNPAs has been proposed by pioneering national space agencies like NASA, CCSDS, BBN and JPL. This generation of SNPAs depicts the layered architectural design of terrestrial communication protocols such as the OSI-ISO reference model [Tanenbaum 03]. Therefore, national space agencies are also competing to provide open-standard space network protocols in order to efficiently facilitate communication for current and future space missions.

The main focus of this paper is critically evaluating the design of the next generation SNPAs in terms of the design requirements constrained by the oddities of space environments. In this paper, we first survey the design of the state-of-art next generation SNPAs proposed by [RHC 05] [HCp 05] [Bergamo 05] [BCDFHSW 02] [BH 02]. Second, we defined the five-tier space network infrastructure as future infrastructure on which next generation SNPAs will operate. Third, through the defined space network infrastructure, we identify eight major design challenges imposed by the next generation SNPA design. Furthermore, we defined a SNPA design evaluation framework on the basis of the space network infrastructure along its design challenges. This framework categorizes these design challenges according to their OSI reference model. These design challenges are categorized according to the data link, network, and transport layers. Fourth, we critically evaluate the design of five leading protocols architectures [RHC 05] [HCp 05] [Bergamo 05] [BCDFHSW 02] [BH 02] through the design evaluation we defined. Finally, it was shown through the critical design evaluation performed in this paper that the currently proposed next generation space protocol architectures lacks a concise description for efficient space addressing schemes, mobile routing protocols, and reliable end-to-end transport protocols.

The rest of the paper is organized as follows, section 2 describes the state of the art next generation SNPAs, section 3 describes our design evaluation framework for space protocol architectures, section 4 provides a critical design evaluation for the proposed space protocol architectures1 section 5 is the conclusion and future work, and finally section 6 lists the references used throughout this paper.

2. The State of the Art Next Generation Space Protocols Architectures

In this paper, space network protocol stacks is named as space protocol architectures. Each layer in the space protocol architecture consists of one or more protocols. A protocol provides one or more services. Space Protocol Architecture SPA is composed of three logical architectures: Earth network protocol architecture, space backbone network architecture and planetary network protocol architecture. Moreover, some SPAs also describe an additional architecture for the on-board spacecraft networks. However, the planetary network protocol architecture is not always existent in a SPA. Moreover, it is assumed that a SPA operates in a space network communication architecture on which the space network assets are distributed.

In this section, we survey seven leading state of the art SPAs proposed in [RHC 05] [HCP 05] [Bergamo 05] [BCDFHSW 02] [BH 02] [Israel 02] [LB 06]. For each SNPA, we first describe its communication architecture. Then we describe the services provided by each of its layers in details. Furthermore we also describe the protocols supported by each of its layers. Finally, we categorize these SPAs according to their architectural design.

2.1. OMNI-based SPA

This protocol architecture is proposed by the **Operating Missions as Nodes on the Internet (OMNI)** project at NASA/GSFC. This SPA provides the simplest and most cost-effective space communication architecture (SCA) for NASA future space missions. The OMNI project adopts standard Internet technologies to create a fertile land for multiple vendor solutions, and hence simplifying the process of future upgrades. In addition this SPA also aims to maximize the use of COTS hardware along with Internet protocols in parallel with future space scientific solutions developments. The use of COTS technologies is a promising key factor in reducing the development time and costs of future space mission development.

Fig. 1 illustrates the OMNI SCA, note that the architecture is broken in to two segments: earth and space. The earth segment is the network backbone shown in Fig.1 earth space network assets consists of three main elements: space missions and control centers, ground base-stations and users all interconnected in to a secure IP backbone network.

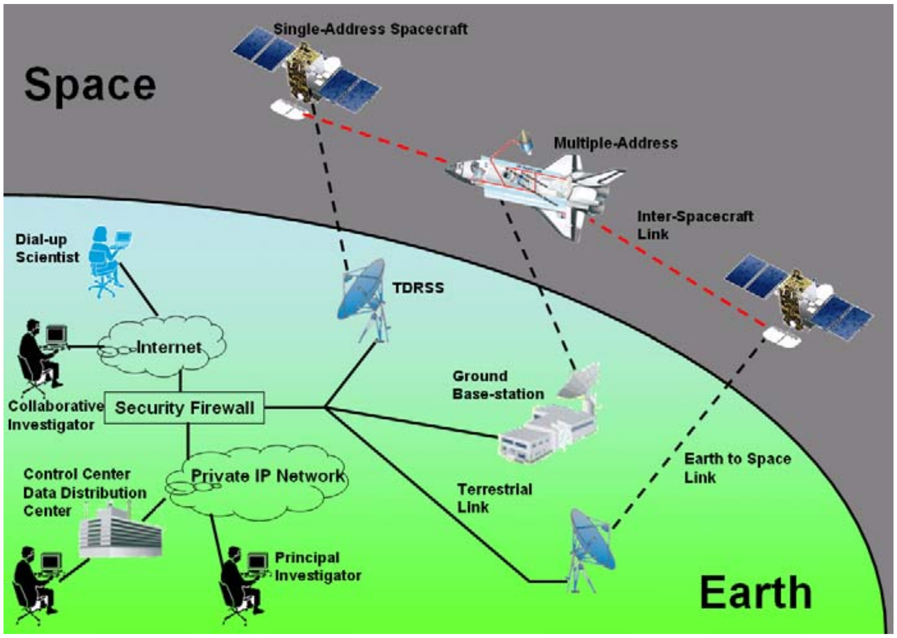

Fig.1: OMNI-based communication architecture.

Users such as scientists, collaborative investigators and principal investigators connect to space missions control and data distribution centers to gain access to on-going space missions. Users connect to these centers through secured private IP networks. The space segment consists of the network assets orbiting around the earth performing various space missions. This segment is consists of two types of spacecrafts: single-address and multiple-address. A single-address spacecraft is accessed along with its science instruments through one unique address. On the other hand, in multiple-address spacecrafts each science instrument is assigned a unique address. Moreover, science instrument can leverage the LAN technologies for their interconnection within the spacecraft. The space segment is spliced to the earth segment by ground base stations. Control data are transmitted to spacecrafts, and telemetry science data are transmitted from the spacecrafts.

The OMNI project proposed a layered SPA illustrated in Fig.2 for future space missions. The layered approach provides is considered allows a clean isolation of special space problems in order to be solved as needed. Moreover, it facilitates modular protocol layer design, which further allows having independent implementations. The design OMNI-based SPA consists of the standard five protocol layers of the OSI-ISO reference model [Tanenbaum 03]. The design of the OMNI-based SPA is described from the bottom up from the physical layer to the application layer.

The mechanisms for delivering bits across media like copper, fiber and RF are provided by the physical layer. This layer also provides modulation, coding and forward error coding services along with the bit delivery mechanisms. This layer applies simple modulation technique, which represents a 1 with high voltage and 0 with low voltage. The transmitted data (bits) are recovered by sampling the data line at each clock cycle, such type of signaling is commonly used in serial line protocols as RS-449/422 and V.35. Moreover, this layer also used a set of reliable coding and modulation techniques the perform data recovery over serial link lines with an embedded clock signal. For instance, Manchester coding is used for 10 Mbps Ethernet, 4B/5B for 100 Mbps FDDI, 8B/10B for Gigabit SONET, and BPSK and QPSK for RF systems. The RF systems of NASA missions are designed to provide 10^{-5} or better BER after coding. Therefore, the following FEC coding is applied: convolutional coding at the bit level, Reed-Solomon coding for block level.

The data link layer handles frame transmission and reception at the earth and space (on-board spacecraft) network segments. The data link layer first puts the upper protocol data units (mostly packets) into frames to be transmitted over the physical layer. It further associates the framed data units with error detection information prior transmission.

Services	Protocol Architecture	Reference Model
Security Simple Data Delivery Reliable File Transfer Time Synchronization Reliable Simple Data Delivery E-mail	PBP, MFTP, CFTP, NFS, CFDP, TFTP NTP, MDP CCSDS COP-1 FTP, HTTP SMPT	APPLICATION
Channel Multiplexing Error Detection Unreliable Packet Delivery Reliable Packet Delivery Real-Time Packet Delivery	UDP TCP RTP	TRANSPORT
Security, VPN Data Packetization Datagram Routing Mobile Routing Data Prioritization	IP IPSec Mobile IP (MIP)	NETWORK
On Board Ethernet Framing RF Link High-rate RF Link Framing	IEEE-1355 (Space Wire), IEEE-1394 (Fire Wire) HDLC HDLC over HSSI, SONET, ATM	DATA LINK
Bit Delivery Modulation and Coding Separation of Framing and Coding Forward-error-correction Coding	Fiber, Copper, RF, SONET Reed-Solomon Coding Manchester, 4B/5B, 8B/10B, BPSK, QPSK RS 449/422, V.35	PHYSICAL

Fig.2: OMNI-based SPA.

For frame reception, this layer extracts frames from the bitstream coming from the physical layer and then passes them to the upper layer. Prior passing a frame to its upper layer it performs the error detection on the information associated with the frame. This layer supports IEEE-1394 and Ethernet for ground and on-board links, HDLC for RF links, and HDLC over ATM and SONET high rate links.

Global end-to-end addressing, datagram routing, data prioritization and security services are provided at the network layer. This layer uses Internet IP-based protocols such as Routing Information Routing (RIP) [RIP 98], Open Shortest Path First (OSPF) [OSPF 98] and Border Gateway Protocol (BGP) for end-to-end packet and datagram routing at the earth network segment. In addition, Mobile IP (MIP) [MIP 96] is supported to continuously communicate with spacecrafts since they orbit around the earth in different velocities. When a spacecraft in its orbit course it crosses over different ground base-stations, the spacecraft is assigned a home agent the rest of base-stations are considered foreign-agents. When a spacecraft is accessed through a foreign-agent base-station, its home-agent establishes an IP tunnel with that foreign-agent. Authentication and packet encryption services are provided by IPSec protocol [IPSec 98] suite.

Channel multiplexing, error detection and end-to-end packet delivery services are the responsibility of the transport layer. This layer uses UDP for unreliable end-to-end data delivery, while it uses TCP for reliable end-to-end data delivery. UDP is a connectionless transport protocol operates on the top of IP. Its main functions are channel multiplexing and error detection, but it does not guarantee ordered packet delivery. UDP is strongly recommended when the timeliness is more critical than guaranteeing the delivery of each packet. This can be sensed when transmitting spacecraft engineering data, health and safety telemetry, and blind commanding. UDP is also a "send-and-forget" transport protocol where connection setup or handshaking phase is inexistent. This has both bright and dark sides. At the bright side, UDP works well with asymmetric or unidirectional links, is delay in-sensitive and supports multicasting. Therefore, UDP would be convenient for deep-space missions. At the dark side, UDP does not provide any sort any flow control mechanisms hence TCP is instead. TCP is a connection-oriented transport protocol, which provides reliable data delivery. TCP also provides the feature of multiplexing multiple data streams on the same host. Being a connection-oriented protocol, connection setup phase exists in TCP. For the purposes of reliability and flow control, TCP mandates status information to be sent with each packet and acknowledgement to be received back. Moreover, TCP supports data recovery and ordered packet delivery, and hence is recommended when data delivery must be guaranteed. In spite of its reliability characteristics, TCP still suffer from a number of limitations. TCP handshaking and flow control requires bi-directional link that moderately exhibits link asymmetry approximately 50:1 before the throughput is affected. In addition, TCP is a windowed and a buffered protocol, it is sensitive to long Round Trip Time (RTT) delay, hence larger buffer to maintain throughput. However, larger buffer penalizes performance in case of packet loss and retransmission. Therefore, TCP would not be convenient for deep-space missions, but would be suitable for lunar missions.

E-mail, reliable files transfer, web access, time synchronization and other user application services are provided by the application layer. This layer supports two types of applications: UDP-based and TCP-based applications. UDP-based applications include simple data delivery protocols, reliable file transfer protocols and time synchronization protocols. Simple file delivery is performed through warping custom user application data in a self-defined protocol. Reliable file transfer protocols used by this layer include Pacsat Broadcast Protocol (PBP) [Price 90], Multicast File Transfer Protocol (MFTP) [Miller 96], CCSDS File Delivery Protocol (CFDP) [CFDP 99], Network File System (NFS) [NFS 89] and Trivial File Transfer Protocol (TFTP) [TFTP 92]. PBP, MFTP and CFDP are particularly used by deep-space missions because they can operate over directional links. Time synchronization protocol (NTP) [NTP 92] is used for synchronizing the time of a client computer or server to another server or reference time path. On the other hand, TCP-based application protocols include reliable simple data delivery, reliable file transfer, and E-mail. Reliable simple data delivery is similarly implemented as the UDP-based with additional feature of guaranteed byte-by-byte data delivery; hence automatic packet retransmission is supported in case of data loss or damage. Two main file transfer protocols supported by TCP: FTP [FTP 85] and HTTP [HTTP 99]. The e-mail service is performed by the Short Mail Transfer Protocol (SMTP) [SMTP 82], which is specified for sending electronic mails among TCP/IP hosts. SMTP enables scientists and spacecraft operators to communicate with spacecrafts when they are not contact. This also enables space mission scientists and operators can send commands and receive telemetry data in an offline fashion. In addition, such solution can be implemented using COTS applications without the need for implementing “space-specific” protocols.

A wide gap exists between the proposed SPA and the reality. Currently, the SPAs employed by scientific space missions do not implement a standard network layer that provides network-wide addressability. Therefore, other mechanisms such as dedicated circuits are used for directing data to the next destination. Further, the space link, the transport, and the network layer are non-existent. On other hand, the session layer is defined on the bases of Acquisition of Signal (AOS), Loss of Signal (LOS), and transmission control commands sent by end-users. For the ground link, both of the network and transport layer are satisfied with custom NASA data formats that eventually delivered over IP protocols.

2.2. GPM IP-based SPA

The focus of this architecture is to provide a potential communication protocol to be used by **Global Precipitation Missions GPM** spacecrafts. GPM aims to provide a complete understanding of the global hydrological cycle and estimation of various sizes of precipitation particles. GPM aims to achieve serve public and private organizations involved in agriculture, public health, water resource management and aviation safety [GPM-SITE 05]. The GPM communication architecture is illustrated in Fig. 3.

Similarly to the OMNI-based SCA, the GPM-based SCA shown above is also broken into two network segments: earth (ground) and space [Bundas 05]. The earth segment consists of the GPM mission space network assets that include NASA and its partner base stations, NASA mission operation center, core and constellation spacecrafts launch vehicles, and GPM science teams. One the other hand, the space network segment consists of diversity of spacecrafts, which includes TDRSS, GPM core observatory, NASA constellation observatory, NASA partner constellation and planned existing spacecrafts. At the ground segment, users such as GPM scientists have access to three data sources: precipitation processing systems, NASA partner database and ground validation systems. Note precipitation processing systems obtains the GPM mission instrument data from NASA partner ground (base) stations and ground validation systems obtain their data from precipitation processing systems. NASA white sands ground-station are connected to NASA mission operation centers, while NASA partner ground stations are connected to their own ground centers. Moreover, NASA white sands ground stations exchange command and science data with NASA missions operation centers. One the other hand, GPM mission spacecrafts communicate and coordinate among other by exchanging command and science data. As shown, both NASA GPM core and constellation observatory spacecrafts exchange command and science data with the TDRSS spacecraft that is in-place connected with NASA white sands ground-station. Besides NASA GPM spacecrafts, NASA partner constellation spacecrafts exchange command and instrument data with their corresponding ground station.

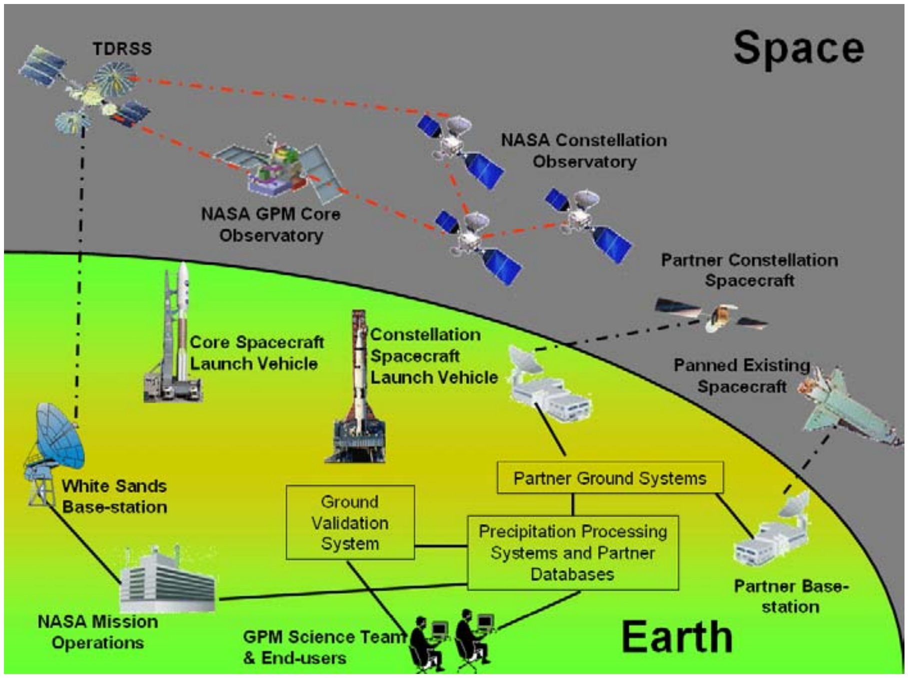

Fig.3: The GPM communication architecture.

In addition, the GPM on-board spacecraft communication architecture is illustrated in Fig.4. This architecture employs standard LAN-based technologies to route data between onboard science instruments, and between the spacecraft and the external world. The figure shown below illustrates two on-board computers OBCs connected to other science instruments through a standard LAN bus topology. Generally, an OBC consists of mass storage devices, science instruments boards, and multiple Ethernet adapters. The mass storage device of the OBC is responsible of storing mission science data (precipitation data). The IEEE 1533 interface connects the OBC with other on-board instruments, while the Ethernet adapters connect the OBC to the on-board LAN. It is shown that the OBC mass storage has bi-directional link with the storage manager and unidirectional links with IEEE 1533 and Ethernet interfaces cards. The storage manager further employs multicast dissemination protocol (MDP), which provides reliable data file delivery over different types of links.

In addition, this communication architecture employs fault-tolerant concepts through the use of dual Ethernet LANs, on-board computers (OBCs), and dual up/down cards. GPM spacecrafts are planned to apply modern operating systems with file system support.

Five years ago, the OMNI Project began an intensive study on the data system concepts for GPM mission [GPM_REFS]. This study aimed to identify and document the use of IP at both earth (ground) and space networks segments. The outcome of this investigation was a proposed IP-based SPA for GPM mission. The sole objective of this SPA is to efficiently route science data between on-board spacecraft science instruments and between spacecrafts and users at mission the earth segment.

The GPM IP-based SPA network infrastructure is illustrated in Fig.5. Since this SPA is an outcome the OMNI Project, this SPA is also based on the layered design approach, which consists of the standard five protocol layers of the OSI-ISO reference model [Tanenbaum 04]. The design of the IP-based GPM SPA is described from the bottom up from the physical layer to the application layer.

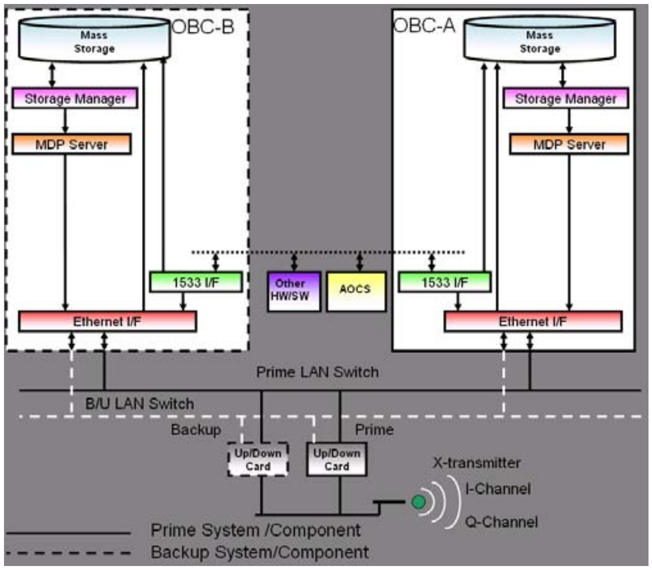

Fig.4: The GPM mission spacecraft on-board communication architecture.

The physical layer provides three standard services: bitstream delivery, modulation and coding, and Forward Error Coding FEC. Various types of physical media that include copper, fiber, SONET and RF are used for bitstream delivery at both segments. Similarly to the OMNI-based SPA, this layer also employs a set of reliable coding and modulation techniques the perform data recovery over serial link lines with an embedded clock signal. For instance, Manchester coding is used for 10 Mbps Ethernet, 4B/5B for 100 Mbps FDDI, 8B/10B for Gigabit SONET, and BPSK and QPSK for RF systems. The RF systems of NASA missions are designed to provide 10^{-5} or better BER after coding. Therefore, the following FEC coding is applied: convolutional coding at the bit level, Reed-Solomon coding for block level.

Services	Protocol Architecture	Reference Model
Reliable File Transfer Reliable Simple Data Delivery Data Storage Management	NTP, MDP FTP, HTTP	APPLICATION
Channel Multiplexing Error Detection On-board Data Transport Unreliable Packet Delivery Real-Time Commanding Commanding in the Blind	UDP TCP	TRANSPORT
Security Data Packetization Datagram Routing Mobile Routing Real-Time Commanding Commanding in the Blind	IP IPSec Mobile IP (MIP)	NETWORK
On Board Ethernet Framing RF Link	Ethernet, 1553 I/F HDLC HDLC over HSSI, SONET, ATM	DATA LINK
Bit Delivery Modulation and Coding Forward-error-correction Coding	Fiber, Copper, RF, SONET Reed-Solomon Coding	PHYSICAL

Fig.5: The IP-based GPM SPA

The data link layer handles frame transmission and reception at the earth and space (on-board spacecraft) network segments. The data link layer first puts the upper protocol data units (mostly packets) into frames to be transmitted over the physical layer. It further associates the framed data units with error detection information prior transmission. For frame reception, this layer extracts frames from the bitstream coming from the physical layer and then passes them to the upper layer. Prior passing a frame to its upper layer it performs the error detection on the information associated with the frame. This layer supports IEEE-1394 and Ethernet for ground and on-board links, HDLC for RF links, and HDLC over ATM and SONET high rate links.

The network layer provides two types of services, standard and specialized services. The standard services include addressing, data packetization, end-to-end datagram routing and security at both network segments. This layer uses Internet protocols for end-to-end packet and datagram routing at the earth network segment. Authentication and packet encryption services are provided by IPSec protocol suite. One the hand, the specialized services includes real-time commanding and commanding in the blind. Real-time commanding is planned to be performed by the use of Mobile IP. Under this configuration, the router is located at the ground station in earth segment and will be have both mobile IP and IP security enabled. When the GPM spacecraft is inaccessible by its home-agent (the mission operation center MOC), the base-station accessible by that spacecraft advertises its availability, so it becomes its foreign agent. The foreign-agent setup takes place few seconds before the forward link is scheduled to begin. Within a matter of few seconds the spacecraft and MOC establish a secured tunnel with the foreign agent, so the MOC would be able to uplink data to the spacecraft. The uplink data consists of command data, MDP ACK and MDK NACK list. Commanding in the blind proposed by this layer is shares the similar concepts with CCSDS blind commanding. Unlike Mobile IP, blind commanding requires only the forward link to be established with the spacecraft in order to uplink data (commands). Therefore, the MOC manually established a secure tunnel with a specific ground station router instead of the agent advertisement procedure preformed by the ground station router. The blind commanding link can be setup prior contacting the spacecraft by several minute. Once the tunnel is established between the MOC and ground station (foreign agent), MOC transmits command data in UDP packets.

The transport layer also provides two classes of services: standard and specialized. The first class includes (data stream) channel multiplexing, error detection, and on-bard data delivery and end-to-end data delivery. For on-board end-to-end data delivery, UDP is used since it operates on the top of IP. UDP performs channel multiplexing and error detection, but it does not guarantee ordered packet delivery. Based on the strong timeliness feature of UDP, its use is recommended for transmitting spacecraft engineering data, health and safety telemetry, and blind commanding. TCP is a connection-oriented transport protocol, which provides reliable data delivery. TCP also provides the feature of multiplexing multiple data streams on the same host. Being a connection-oriented protocol, connection setup phase exists in TCP. For the purposes of reliability and flow control, TCP mandates status information to be sent with each packet and acknowledgement to be received back. Moreover, TCP supports data recovery and ordered packet delivery, and hence is recommended when data delivery must be guaranteed. In spite of its reliability characteristics, TCP still suffer from a number of limitations. TCP handshaking and flow control requires bi-directional link that moderately exhibits link asymmetry approximately 50:1 before the throughput is affected. In addition, TCP is a windowed and a buffered protocol, it is sensitive to long Round Trip Time (RTT) delay, hence larger buffer to maintain throughput. However, larger buffer penalizes performance in case of packet loss and retransmission. Both of TCP and UDP provide end-to-end data delivery at the earth segment. Moreover, UDP is used for end-to-end data delivery between MOC and GPM spacecrafts. In addition, the second class includes real-time commanding and commanding in the blind supported by the network layer. Real-time commanding uses TCP on the top of Mobile IP, while commanding in the blind uses UDP.

The application layer provides three standard services: reliable file transfer, reliable simple data delivery and data storage management. Science and telemetry data is transmitted by FTP, which operates on the top of TCP. Reliable simple data delivery is supported through HTTP, which also operates on top of TCP/IP. Finally, data storage management of science data is supported by RAID system.

2.3. CCSDS-based SPA

Recently, the growing demand for standard interplanetary internet (IPN) architecture has become significant for serving the current and future space mission communication requirements. The fundamental concept of IPN stems from the fact that Internet is an interconnection of networks and hence it is a "Network of Networks". IPN extends this concept to higher level of abstraction, which visualizes the entire Internet on a planet as single network, and the interconnection among these disconnected planetary Internets constitutes the IPN [IPN-SIG]. The major goal of IPN is to expand the use of standard Internet protocols to serve in space and deep space missions. The process of extending Internet protocol to space-compatible Internet process is the specialization of the **Consultative Committee for Space Data Systems (CCSDS)**. CCSDS is also responsible of standardization.

The space communication architecture of CCSDS is illustrated in Fig.6. The CCSDS-based SCA consists of three segments: earth, space and deep space. The first and the second segments are similar to the ones that belong to OMIN and GPM-based SPAs. The deep space segment consists of "store-and-forward" relay satellites, communication and science spacecrafts (orbiters) and planetary colony networks (in-situ Internet). The SCA asserts on a planet surface (other than earth) consists of rovers, base-stations, sensors (a sensor web of motes) and other science instruments. The planetary in-situ Internet connects the SCA assets on the surface of the planet, and further with spacecrafts orbiting at its proximity.

Since the beginning of this millennium, CCSDS has been proposing an integrated IPN SPA. The sole concept behind the CCSDS-based SNPA is in the incremental use of "internationally standardized" space data communication protocols in space missions [BCDFHSW 02]. The main goal of this SPA is to provide a design of internationally standardized IPN, which integrates itself with current terrestrial Internet protocols for future space missions. Each of its layers is contains a set of CCSDS standards implementing its corresponding functionalities. The CCSDS -based SPA network infrastructure is illustrated in Fig.7. We next describe each protocol layer from the bottom-up.

The CCSDS physical layer provides the standard bitstream delivery service, which consists of bitstream transmission, modulation, coding, and error detection. The bitstream is intuitively service is performed at three segments of the CCSDS-based SCA using various types of physical media. The physical media supported by this layer covers copper, RF (Ka and Q), and fiber optics. Modulation and coding, and error detection and correction services are provided by Proximity-1[PROXIMITY-1 04] physical protocol. Proximity-1 specifies the data modulation and coding techniques for transmitters, receivers and carriers.

For error detection, Proximity-1 uses CRC-32 procedure for error detection. On the other hand convolution codes, turbo coding and R-S coding are used for error correction.

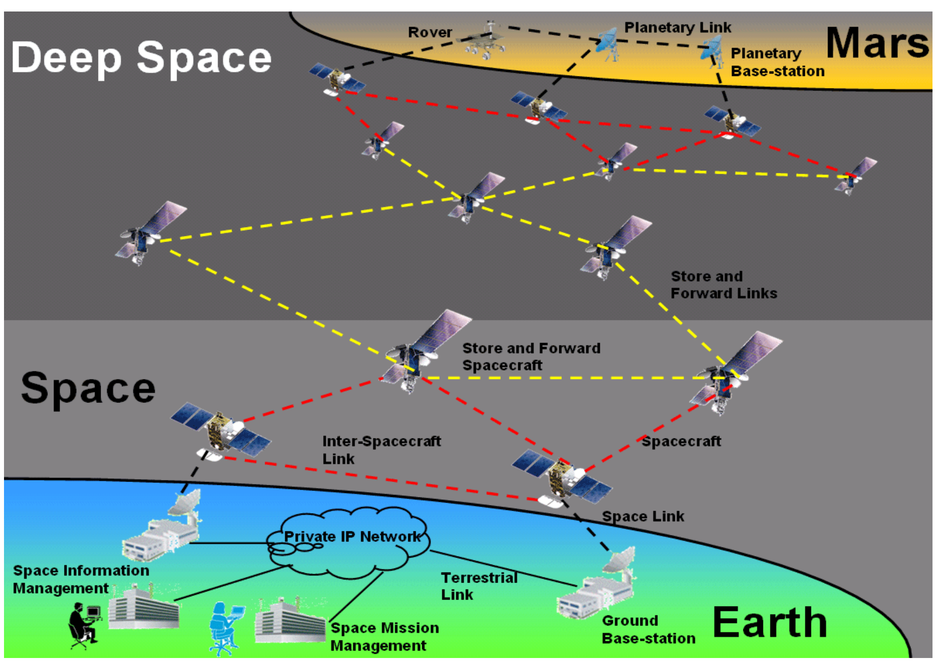

Fig.6: CCSDS space communication architecture.

Services	Protocol Architecture	CCSDS Reference Model
Reliable File Transfer Data Compression Security (End-to-End Data Protection)	SCPS-FP FTP Lossless Data Compression	APPLICATION
Channel Multiplexing Security (End-to-End Data Protection) End-to-End On-board Data Transport End-to-End Reliable Packet Delivery	UDP TCP SCPS-TP, SCPS-SP	TRANSPORT
Addressing Security (End-to-End Data Protection) Data Packetization Datagram Routing On-board Packet Routing End-to-End Routing	IPv4, IPv6 Space Packet Protocol, SCPS-NP IPSec	NETWORK
Frame Transfer Framing (Packet Encapsulation) Synchronization and Channel Coding Error Detection and Correction Security (End-to-End Data Protection)	Ethernet ,HDLC, SONET, ATM TM, TC, AOS Proximity-1 Data Link	DATA LINK SYNCH AND CHANNEL CODING
Bit Delivery Modulation, Synchronization, Coding Error Detection	Fiber, Copper, RF, SONET Reed-Solomon Coding, Convolutional, Proximity-1 Physical	PHYSICAL

Fig.7: CCSDS SNPA.

The CCSDS data link layer provides standard data transfer along with security services to the three segments of the CCSDS SCA. This layer is further broken into two sublayers: synchronization and channel coding, and data link protocol. Standard data transfer services implemented by Proximity-1 Data Link [PROXIMITY-1 04], TM [TM_REF], TC [TC 03] and AOS [AOS 06]. At the earth segment, this layer applies IEEE-1394 and Ethernet for ground and on-board links, HDLC for RF links, ATM and SONET for high rate links. On the other hand, at both of the space and deep space segments, Proximity-1 data link, TM, TC, and AOS protocols are used.

First, Proximity-1 data link protocol provides three types of services: CCSDS packet delivery, user-defined delivery and timing services. In addition, Proximity-1 provides two types of services: sequence-controlled and expedited. Sequence-controlled services apply "Go Back N GBN" sequence control mechanism at both of the transmitter and receiver ends, while expedited services are not reliable and do not provide any guarantees about the data delivery. Second, TM space link protocol supports two types of data transmission services: synchronous and periodic. Third, TC space link protocol provides two types of data transfer services: sequence-controlled (Type-A) and expedited (Type-B). Fourth, Advanced Orbiting System (AOS) data link protocol provides three types of data transfer services: asynchronous, synchronous and periodic. Asynchronous service does not constrain any timing relationship between the transferred data units and the transmission of the Transfer Frames generated by the service provider. One key feature of this type of services is that all data units transferred by the user are transferred once. Unlike asynchronous services, asynchronous services necessitate timing relationship between the transferred data and the transmission of the Transfer Frames generated by the service provider. Therefore, time-division multiplexing is applied. Periodic services are considered a special type of synchronous services, which requires the data unit transmission rate to be constant. Besides, the standard data transmission service, CCSDS data link layer also supports security mechanisms at the space link level.

The CCSDS network layer provides four standard services to the three SCA segments. These services include data unit packetization, addressing, end-to-end packet routing and security. At the earth segment, CCSDS performs data unit packetization, addressing and end-to-end routing through IPv4 and IPv6 and further supports security through IPSec. At the space and deep space segments, CCSDS uses space packet protocol SPP, SCPS network protocol SCPS-NP, IPv4 and IPv6. The main use of SPP is transmitting and routing processed telemetry data efficiently using variable length data units generated by on-board spacecraft science instruments. SCPS-NP aims to provide support for connectionless and managed connections operations, priority-based handling, datagram lifetime control, and multiple routing operations [SCPS-NP 99]. SCPS-NP further supports three addressing families: SCPS-NP, IP and IPv6. In addition, end-to-end data security mechanisms of are implemented by SCPS security protocol SCPS-SP [SCPS-SP 99]. SCPS-SP provides four types of security mechanisms: confidentiality, integrity, authentication and access control.

The CCSDS transport layer is responsible of provided end-to-end data delivery along with security to thee SCA segments. For the earth segment, TCP and UDP are used for end-to-end data delivery. TCP is applied for reliable data delivery, while UDP is applied for unreliable datagram delivery. For both of space and deep space segments, CCSDS applies SCPS-TP protocol for end-to-end data delivery. For security services, SCPS-TP is used.

The CCSDS application layer has three services to provide the users at three segments. These services include reliable data transfer, lossless data compression and security. For reliable files transfer service, CCSDS has proposed SCPS-FP [SCPS-FP 99], which handles all file transfer operations (primitives). Moreover, FTP can be used on the top of SCPS-TP, TCP and UDP.

2.4. High-Throughput Distributed Spacecraft Network (Hi-DSN) SPA

The Hi-DSN SPA [Bergamo 05] integrates both space and terrestrial networks with each other to provide an ad hoc space communications infrastructure. This infrastructure is intended to support a wide range of space missions and spacecraft configurations. Hi-DSN infrastructure will be relevant for integrating various space missions to share their assets and mission data. Hi-DSN is planned to be applied for establishing communication with ground base-stations, planet rovers and low-flying probes. Hi-DSN is also applied for inter-spacecraft networking that include formation and clusters. In addition, Hi-DSN will provide support for real-time applications and multiple self-forming space network topologies.

The Hi-DSN space communication architecture SCA is illustrated in Fig.8. The Hi-DSN SCA consists of a collection of planet-vicinity networks linked together through an interplanetary backbone network, which usually includes relay satellites placed in the Earth-Moon and Earth-Sun Lagrange points to provide high throughput backbone capabilities to deep space missions.

Similar to CCSDS SCA, Hi-DSN SCA is also three-segment architecture. The first segment (lowest) is the Earth tier which consists of space network assets on Earth such as base-stations. The second segment (middle) is the space network that consists of the spacecraft network, which consists of the spacecrafts that within the vicinity of the Earth and the Moon. The third tier (highest) is the deep space network, which consists the interplanetary relay satellites that relay data among different planets in the solar system.

The Hi-DSN SPA is the outcome of the collaboration project between NASA and BBN that aims to provide future Internet-friendly planet vicinity architecture. The main focus of this SPA is only on the space and deep space segments; hence the proceeding discussion does not include the earth segment.

The key layer of this SPA is the physical layer, which is uniformly deployed at spacecrafts. This layer provides two types of services standard and specialized. Standard services include bitstream delivery, modulation and coding, and error detection. Specialized services include digital beam forming and, constant burst transmission and reception. Bitstream transmission is performed at the Ka-band, which allows high data rate transmission, spatial reuse of the available spectrum, and the use of high gain antenna arrays. This layer assumes that transmit-and-receive antennas are spatially isolated in order to achieve full reuse of the spectrum. One significant capability of this layer is the predictability of arbitrary network topologies, which in place facilitates the use of null-steered digital beam-forming to establish a variable number of cross-links per spacecraft. In addition, two types of null-steered beam forming are supported: broadcast and point-to-point. To cope with the long inter-spacecraft distances, a novel BBN-based multi-code multi-bit modulation-and coding technique is used. This multi-code modulation-and-coding technique is used on each cross link in order to achieve high bit rates up to four-order-of-magnitude.

The Hi-DSN data link layer is responsible of controlling the use and access to the shared media (space link) among multiple spacecrafts. Therefore the services of this layer are focused on multiple access control functionalities, since this layer has proposed a novel multiplexing called TCeMA as combination of spatial, time, and code multiplexing. This layer also performs two classes of services: standard and specialized, Standard services include frame transmission and reception, channel coding, and error detection and correction. Hi-DSN defines a space link frame structure, which supports for space-and-time synchronization and intermittent (bursty) traffic.

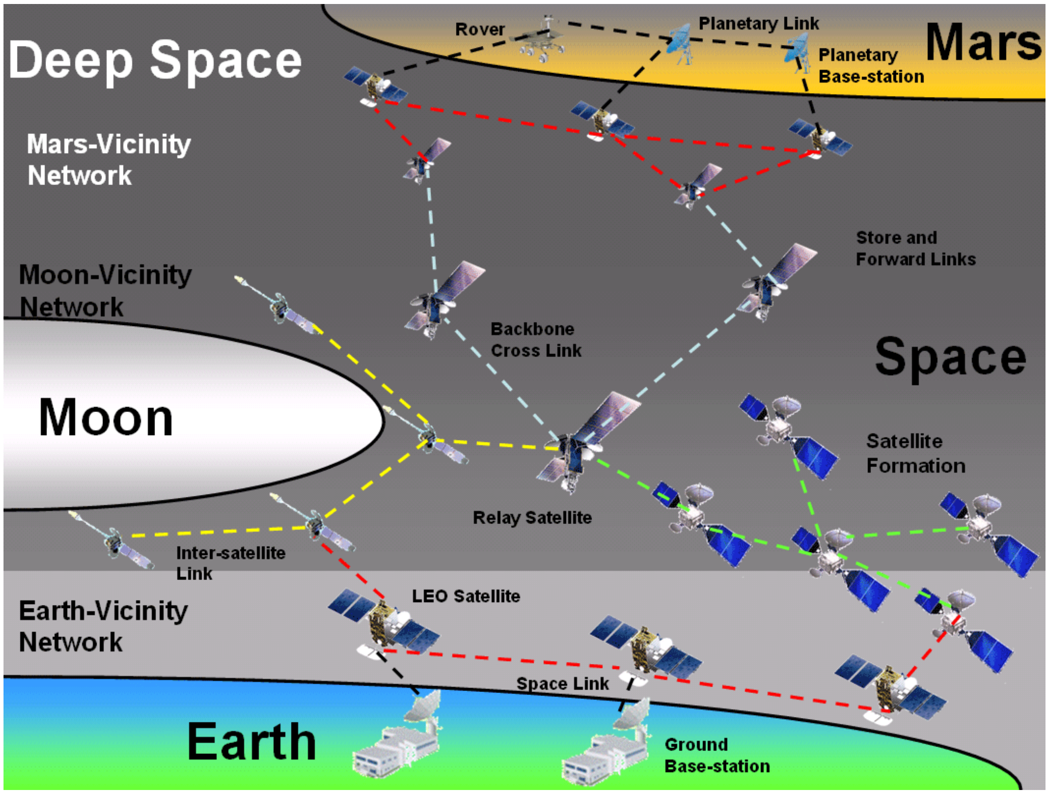

Fig.7: The Hi-DSN Hierarchal SNPA.

On the other hand, specialized services include neighbor discovery, spatial-temporal synchronization, spatial multiplexing control, cross-link level control, and receiver-direct burst synchronization. First, neighbor discovery service is performed by exchanging HELLO and FOUND_YOU busts in the discovery DISC time-slot. This operation further incurs a series of computation-intensive measurements for relative spatial direction, frame-time alignment and carrier frequency synchronization. Second, spatial-temporal synchronization service maintains both the spatial and frame alignment of each node is synchronized with the other nodes. Third, spatial multiplexing control service is supervises the spatial alignment between nodes and the negotiation that takes place between them (aligned nodes) for creating a non-interfering cross-links. Fourth, cross-link level control service performs two tasks: post bust-reception measurements of link performance and of the relative frequency, and using these measurements to monitor the quality of cross-links. The quality of cross-links determines the achievable throughput as a function of the BER encoding and the required PER. Fifth, receiver-direct burst synchronization service schedules burst transmission between the nodes (between a node and its neighbors). Burst transmission schedule is required to guarantee that nodes transmissions do not overlap at the transmitter and the burst is received time-aligned with the both of the receiver's time-slots and carrier frequency.

Similar to the SPAs described previously, global addressing, data packetization and end-to-end routing are handled by the Hi-DSN network layer. This layer is further extended to an additional sublayer which provides more specialized services to include neighbor discovery, network synchronization and terminal affiliation. The end-to-end routing service provided by this layer covers the routing at the on-board spacecraft, formation, intra-constellation, and inter-constellation topological levels. BBN has proposed five related protocols to serve this purpose. First, the neighbor discovery protocol handles node self-advertisement and time-slot synchronization with other nodes within its range. Second, global node frame-epoch synchronization is performed by the network synchronization protocol. Third, end-to-end routing is performed by the distributed routing protocol, which maintains the network topological information database and manages the link state information for each destination node. Fourth, the decisions a node takes to forward a packet to specific destination node is performed by the packet forwarding protocol. Finally, the node affiliation protocol enables an endpoint router to find affiliate routers on the path to a destination node and dynamically handover network topological information over time.

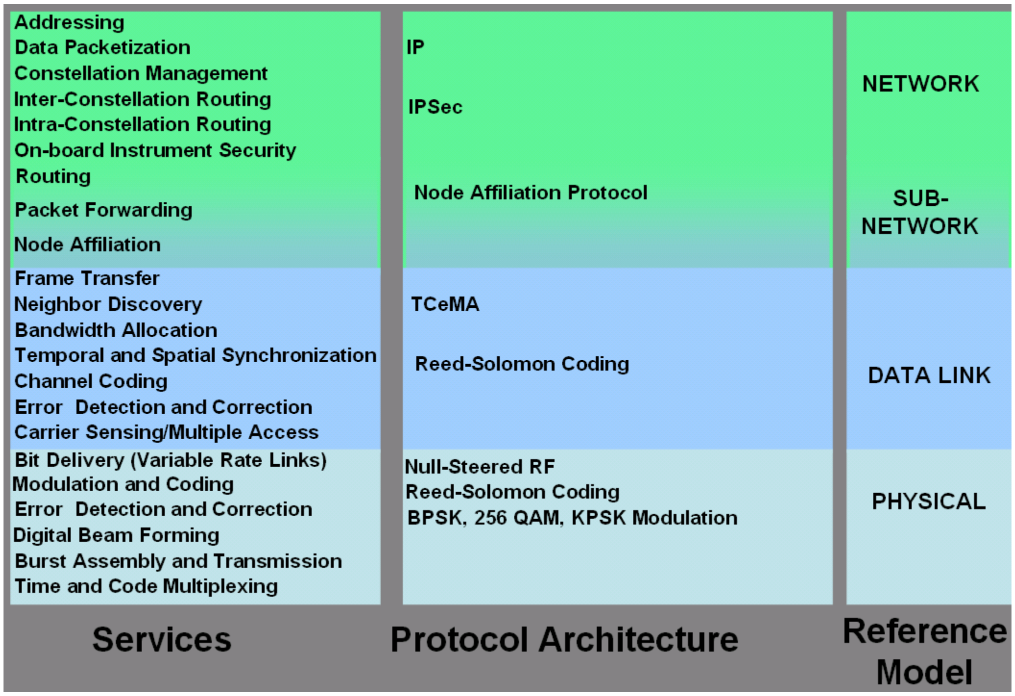

Fig.8: The Hi-DSN SNPA.

2.5. NASA Enterprise SPA

Recently NASA has become aware that the future communication requirements of its missions beyond year 2010 will impose a new set of service demands. The imposed demands include high data rates, high capacity, security, real-time data delivery, and interoperability between space entities. It is anticipated that layered space protocol design will be responsive enough to the future demands. The advantages gained from such protocol design are gained through the quality of data handled and the simplicity of data delivery.

NASA has also realized that Internet-based architectures will have the strong potential to be utilized by future space mission. One primary advantage of the Internet is in its horizontal structure, which allows global connectivity through its flexible and diverse set of open interoperable standards.

This main contribution of this work is the provision of an integrated design for the next generation NASA space communication infrastructure.

This design of the future NASA enterprise SCA is illustrated in fig. 9. This SCA consists of thee segments: earth, space and deep space. The NASA future space network infrastructure integrates four basic network architectures to support NASA enterprise space applications.

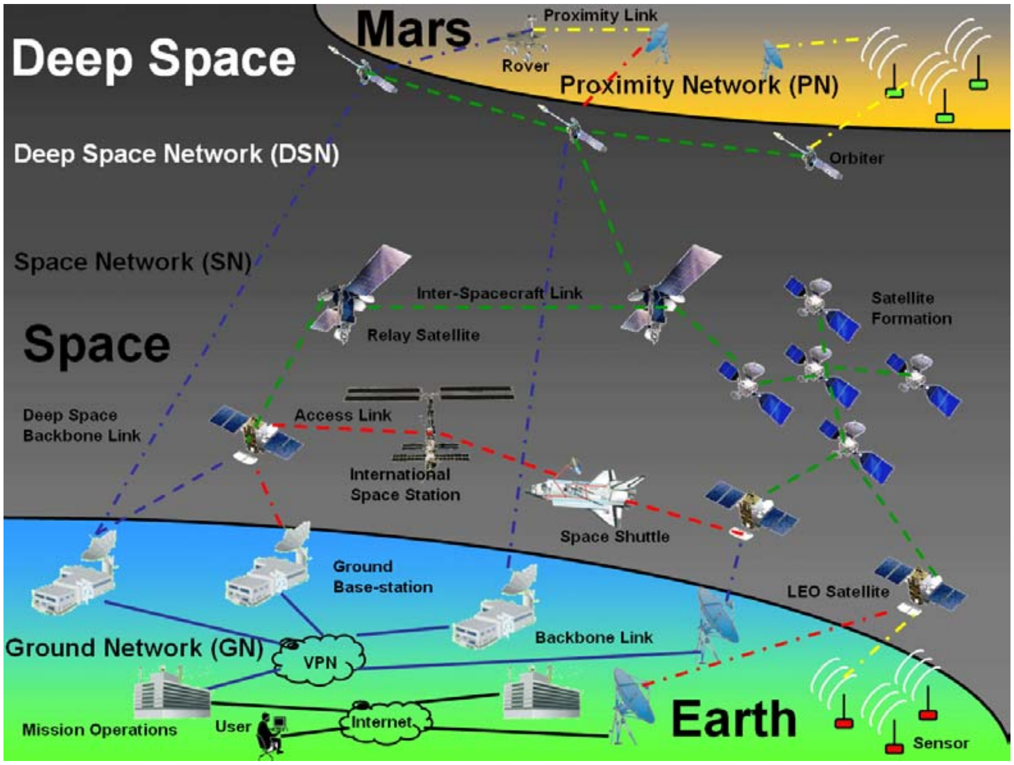

Fig.9: NASA future enterprise communication architecture.

First, the backbone network (BN) architecture integrates the segments with the both NASA's Intranets and virtual private networks. The backbone links are colored in blue. In the earth segment, the BN links ground base-station to mission operations centers that are further connected to users by secured VPNs. In the space segment, BN links ground-base stations to spacecrafts orbiting around the earth. In the deep space segment, BN links both the earth segment and planetary (Mars) proximity network to the spacecrafts orbiting around Mars.

Second, the access network (AN) architecture provides communication linkage among space backbone networks, mission spacecrafts, and local area network (LAN's) on-board spacecrafts of vehicles. ANs links (colored in red) apply both radio and optical communication links.

Third, the Inter-space network (ISN) is responsible of providing connectivity (shown in green lines) between spacecrafts flying within a constellation, formation, or cluster.

Fourth, proximity network (PN) architecture provides low range connectivity to the space network assets at earth and planet surface networks. At the earth level, PN architecture links the sensor web on the earth surface to a LEO satellite orbiting with the earth's proximity. Besides the earth segment, PN also provide connectivity among vehicles, landers, and sensor ad hoc network at the planetary surface level.

Next, we provide a detailed description of each of the four architectures described above.

2.5.1. Backbone Networks (The Backbone Network Architecture)

The future NASA BN architecture integrates the three NASA SCA segments into a global back bone network. This architecture provides a global access to the entire SCA, since it connects the three network segments.

The abstract NASA backbone is SCA is illustrated in Fig. 10. The earth segment consists of ground stations, mission operation centers and users. These network assets belonging to NASA ground networks (GN) domain are responsible of handling all communication services among end-users, space centers, and base stations on earth. The space segment consists of space networks (SNs) that link both earth and space segments to each other. The space craft orbiting in the space segment would include satellites (LEO, MEO and GEO), the International Space Station (ISS), NASA space shuttle and GPM spacecrafts. The deep space network segment contains the DSN networks that connect the earth segment to the deep space segment.

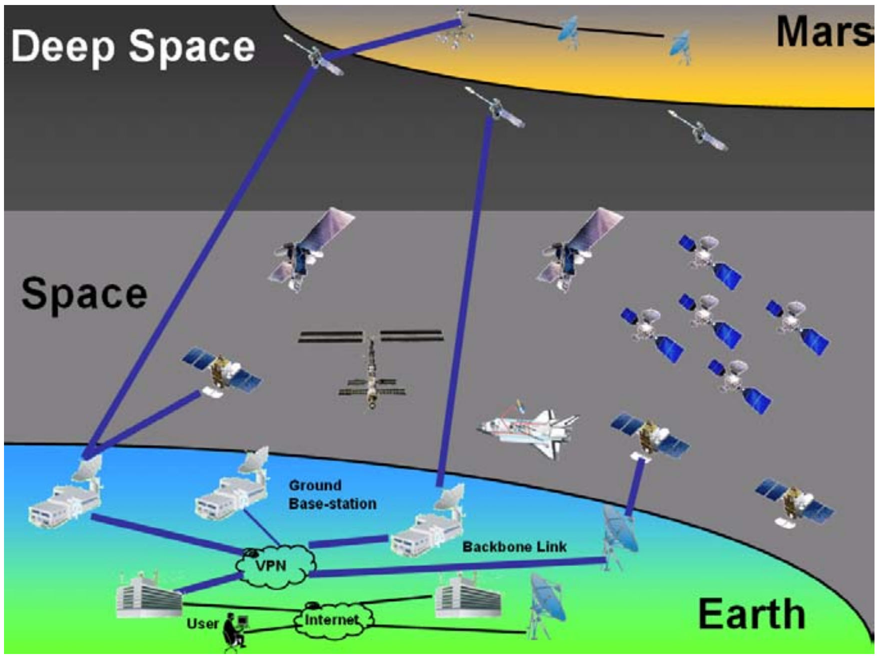

Fig.10: The Abstracts NASA Backbone Networks Communication Architecture.

The services and protocols used by NASA backbone network (BN) architecture are elaborated through its SPA shown in Fig.11. The design of the BN SPA corresponds to the standard OSI reference model. The services and protocols supported by the BN architecture covers the three network elements described above. The detailed description of the BN SPA is given from the bottom up, from the physical layer to the application layer.

The standard bitstream delivery, modulation, coding, error detection and correction are provided by the physical layer. These services are all uniform at the ground, space and deep space networks. Bitstream delivery is performed by a wide verity of physical media is used such as copper, fiber (FDDI) and RF (Ka/Q/V bands). Modulation is performed by standard procedures applied by the supported physical media. Coding is performed by the Reed-Solomon coding. Error detection and correction (not specified) would be performed by standard CRC-32 procedure.

The data link layer services include packet encapsulation (framing), frame transfer, error detection and correction. These services are supported at the three networking levels. This layer applies standard link layer protocols such as Ethernet, IEEE 1394 (Fire Wire), 1355 (Space Wire), ATM, SONET and HDLC. Ground networks (GNs) employ Ethernet, IEEE 1394, ATM and SONET. One the other hand, both space and deep space networks employ IEEE 1355 and HDLC.

Fig.11: The Abstract NASA Backbone Network Protocol Architecture.

Global addressing, data encapsulation (packetization), end-to-end routing and security service are specialization of the network layer. The services of this layer are only provided to GNs and SNs. Ground networks apply both IPv4 and IPv6 for global addressing, data encapsulation, real-time tunneling and end-to-end packet routing. GNs also use IPsec to provide security services. In addition, SNs use IPv4 and IPv6 to provide global addressing end-to-end packet routing (including on-board routing).
Standard data delivery services are provided by the transport layer, which include channel multiplexing, security, end-to-end data delivery. These services are only supported at the ground network level. This layer applies UDP for unreliable datagram delivery, while TCP is applied for reliable end-to-end data delivery.
Mission data storage management, remote access, security, file transfer and web access are all services provided by the application. At the GN level, standard Internet-based protocols such as HTTP, FTP, SSH and SMPT to provide web access, file transfer, remote access and e-mail services. At the SN and DSN level, custom science and image processing applications are used.

2.5.2. Access Network Architecture

The access network (AN) architecture provides communication services to the outer edges of backbone networks for mission spacecraft, vehicles, and other entities. The (AN) SCA is illustrated in Fig.12. It is shown that this SCA is involved in the segments. In earth segment, (AN) architecture enable ground stations to gain access to the spacecrafts orbiting around the earth. In space segment, (AN) enables spacecrafts to gain access to other spacecrafts and earth ground stations. In the deep space segment, AN enables Mars in-situ networks to communicate with spacecrafts (orbiters) that are within their proximity range. It can be noted that this architecture does not integrate the three segments unlike to the BN architecture.

In addition, the next generation on-board networks are planned to be compliant with terrestrial LAN's. Therefore, the future on-board spacecraft LAN will be a part of the access network that provides the interfaces for the science instrument to access information and services from the on-board recourses.

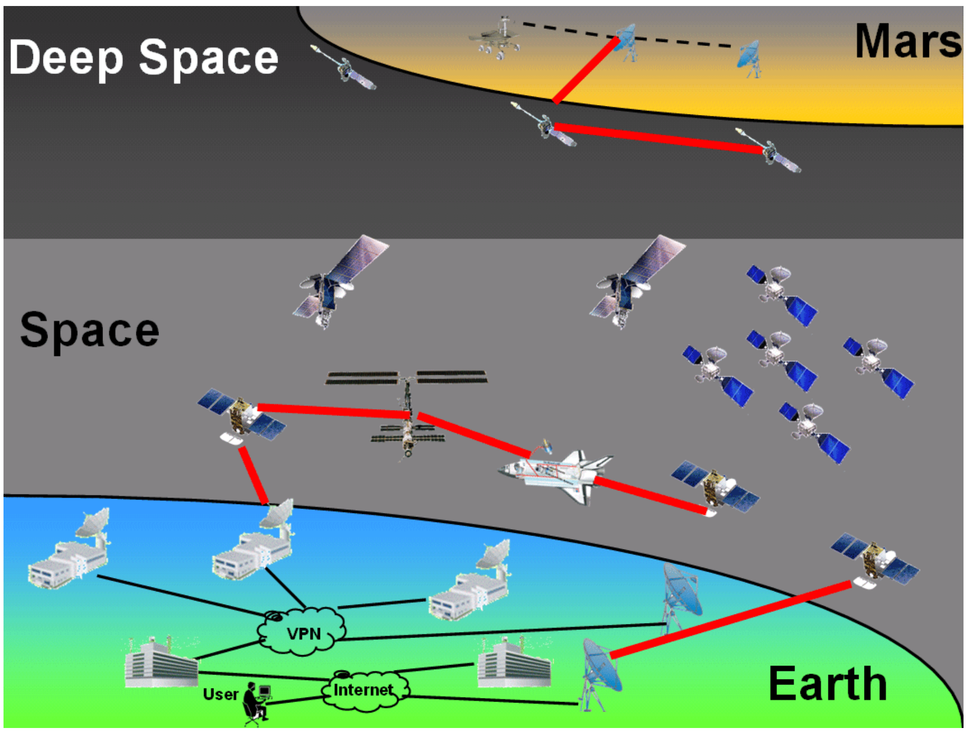

Fig. 12: Access Networks Communication Architecture.

The services and protocols used by NASA access network (AN) architecture are elaborated through its SPA shown in Fig.13. The design of the AN SPA follows the standard OSI reference model. The services and protocols supported by the AN architecture covers the GNs and SNs.

The standard bitstream delivery, modulation, coding, error detection and correction are provided by the physical layer. These services are all uniform at the ground, space networks. Bitstream delivery is performed by a wide verity of physical media is used such as copper, fiber (FDDI) and RF (Ka/Q/V bands). Modulation is performed by standard procedures applied by the supported physical media. Coding is performed by the Reed-Solomon coding. Error detection and correction (not specified) would be performed by standard CRC-32 procedure.

The data link layer services include packet encapsulation (framing), frame transfer, error detection and correction. These services are supported at the three networking levels. This layer applies standard link layer protocols such as Ethernet, IEEE 1394 (Fire Wire), 1355 (Space Wire), ATM, SONET and HDLC. Ground networks (GNs) employ Ethernet, IEEE 1394, ATM and SONET. One the other hand, space networks employ IEEE 1355, ATM, Gigabit and HDLC.

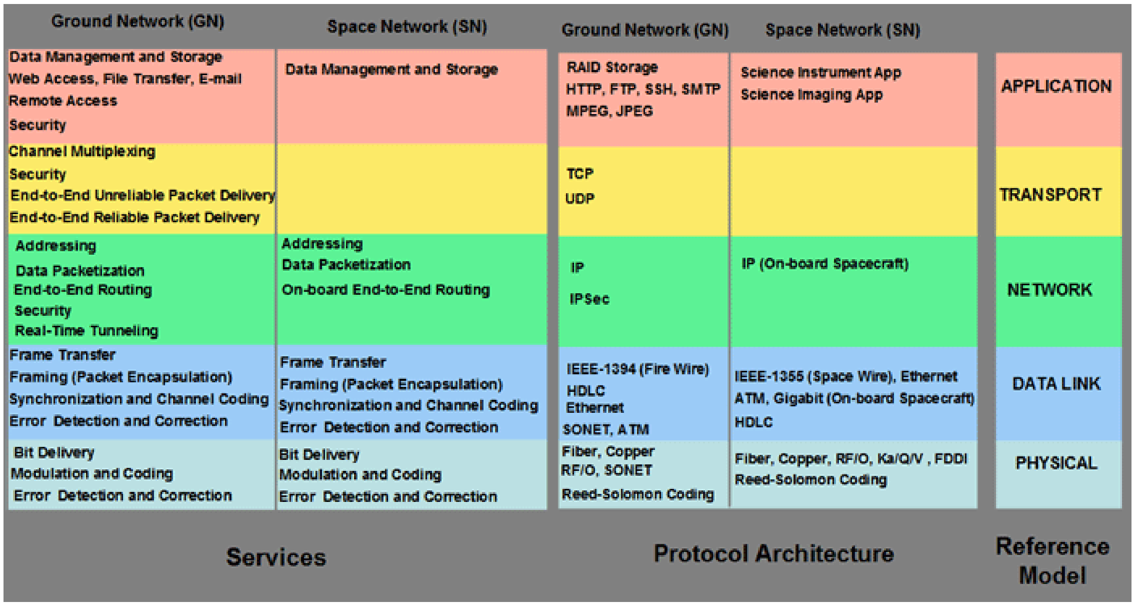

Fig. 13: Access Network SNPA.

Global addressing, data encapsulation (packetization), end-to-end routing and security service are specialization of the network layer. The services of this layer are only provided to GNs and SNs. Ground networks apply both IPv4 and IPv6 for global addressing, data encapsulation, real-time tunneling and end-to-end packet routing. GNs also use IPsec to provide security services. In addition, SNs use IPv4 and IPv6 to provide global addressing end-to-end packet routing (including on-board routing).

Standard data delivery services are provided by the transport layer, which include channel multiplexing, security, end-to-end data delivery. These services are only supported at the ground network level. This layer applies UDP for unreliable datagram delivery, while TCP is applied for reliable end-to-end data delivery.

Mission data storage management, remote access, security, file transfer and web access are all services provided by the application. At the GN level, standard Internet-based protocols such as HTTP, FTP, SSH and SMPT to provide web access, file transfer, remote access and e-mail services. At the SN level, custom science and image processing applications are used.

2.5.3. The Inter-Spacecraft Architecture

The purpose of inter-space network ISN architecture is handling the local communication and coordination tasks for spacecrafts flying within constellations, tight formations, or loose clusters. ISNs network are applied in measuring the relative positions between spacecrafts. The ISN SCA illustrated in Fig. 14, consists of several ground stations connected to three satellite formations via RF/O links. These formations include of three types of spacecraft network topologies: ad hoc cluster, ad hoc formation, and star formation. ISN architecture supports concurrent missions control and coordination through allowing multiple ground stations at the earth segment to communicate with different satellite formations simultaneously. It can be noted that the ISN architecture ties the space and deep space segments to each other. This is achieved through multiple levels of inter-spacecraft interconnection. At the formation level, all spacecrafts correspond to an intra-formation network topology. At the segment, different formations are linked by relay satellites, therefore inter-formation networks can be the interconnection between two or more formations. At the inter-segment level, segments are interconnected by relay satellites.

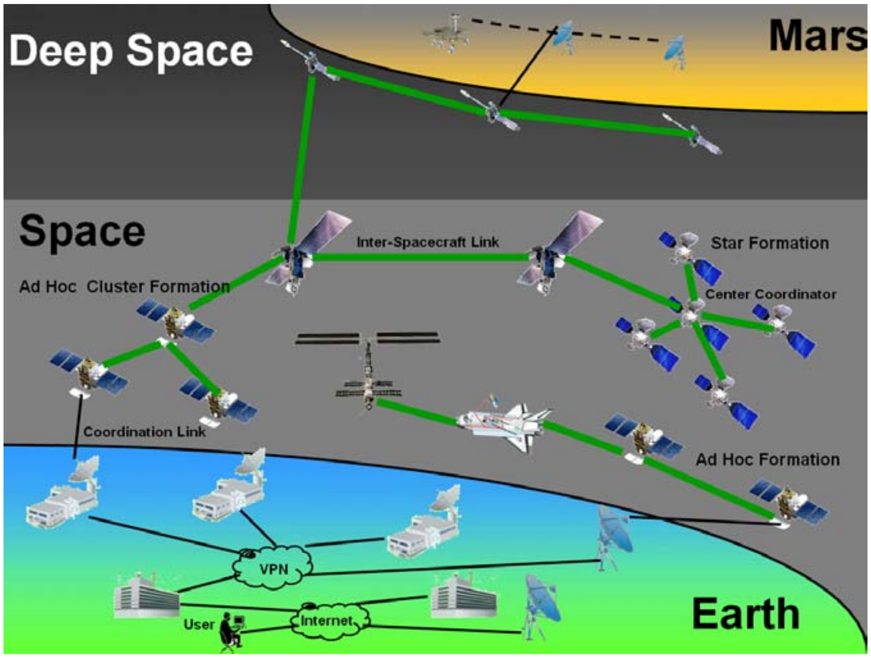

Fig. 14: Inter-spacecraft Communication Architecture.

Services: Backbone Network (BN)	Services: Inter-Spacecraft Network (ISN) Member Spacecraft	Protocol Architecture: Ground Network (GN)	Protocol Architecture: Inter-Spacecraft Network (ISN) Member Spacecraft	Reference Model
Data Management and Storage Satellite Formation Coordination	Data Management and Storage Science App	RAID Storage	Science Instrument App Science Imaging App	APPLICATION
		TCP UDP		TRANSPORT
Addressing Data Packetization End-to-End Routing Security Real-Time Tunneling	Addressing Data Packetization On-board End-to-End Routing On-board Real-Time Tunneling	IP IPSec	IP (On-board Spacecraft)	NETWORK
Frame Transfer Framing (Packet Encapsulation) Synchronization and Channel Coding Error Detection and Correction	Frame Transfer Framing (Packet Encapsulation) Synchronization and Channel Coding Error Detection and Correction	IEEE-1394 (Fire Wire) HDLC Ethernet SONET, ATM	IEEE-1355 (Space Wire), Ethernet ATM, Gigabit (On-board Spacecraft) HDLC	DATA LINK
Bit Delivery Modulation and Coding Error Detection and Correction	Bit Delivery Modulation and Coding Error Detection and Correction	Fiber, Copper RF/O, SONET Reed-Solomon Coding	Fiber, Copper, RF/O, Ka/Q/V , FDDI Reed-Solomon Coding	PHYSICAL

Fig. 15: Inter-spacecraft Network SNPA.

The services and protocols used by NASA inter-spacecraft network (ISN) architecture are elaborated in details through its SPA shown in Fig.13. The design of the ISN SPA is based on the OSI reference model. The services and protocols supported by the ISN architecture are motivated towards the GNs, ISNs and on-board spacecraft (member in a formation).

The standard bitstream delivery, modulation, coding, error detection and correction are provided by the physical layer. These services are all uniform at GNs, ISNs and on-board spacecrafts networks. Bitstream delivery is performed by a wide verity of physical media is used such as copper, fiber (FDDI) and RF (Ka/Q/V bands). Modulation is performed by standard procedures applied by the supported physical media.

Coding is performed by the Reed-Solomon coding. Error detection and correction (not specified) would be performed by standard CRC-32 procedure.

The data link layer services include packet encapsulation (framing), frame transfer, error detection and correction. This layer applies standard link layer protocols such as Ethernet, IEEE 1394 (Fire Wire), 1355 (Space Wire), ATM, SONET and HDLC. Ground networks and on-board spacecrafts networks employ Ethernet, IEEE 1394, IEEE 1355, ATM and SONET. Besides GNs, ISNs employ IEEE 1355, ATM, Gigabit and HDLC.

Global addressing, data encapsulation (packetization), end-to-end routing and security service are specialization of the network layer. Ground networks apply both IPv4 and IPv6 for global addressing, data encapsulation, real-time tunneling and end-to-end packet routing. GNs also use IPsec to provide security services. In addition, SNs use IPv4 and IPv6 to provide global addressing end-to-end packet routing (including on-board routing). However, this architecture does not specify what protocols are used for intra- and inter-formation routing.

Standard data delivery services are provided by the transport layer, which include channel multiplexing, security, end-to-end data delivery. The ISN SPA does not provide these services, and hence the transport layer is inexistent.

Mission data storage management, spacecraft coordination and on-board science instruments services are all services provided by the application layer. The application layer at the GN level provides data storage and spacecraft formation control. At the ISN level, the application layer

2.5.4. Proximity Network Architecture

The proximity network PN architecture provides flexible low-power communication services to closely spaced, landed, and airborne entities in an ad hoc fashion. As shown in Fig.16, the services of the PN architecture are utilized at the earth and deep space segments, since it only supports short range communication capability among the space network assets. At the earth segment, the wireless sensor-web is exchange data with LEO satellites for various purposes. At the deep space segment, the PN architecture enables Mars in-situ networks to communicate with each other and with the satellites. Note that the Mars in-situ network consists of ground-stations, rovers and sensors.

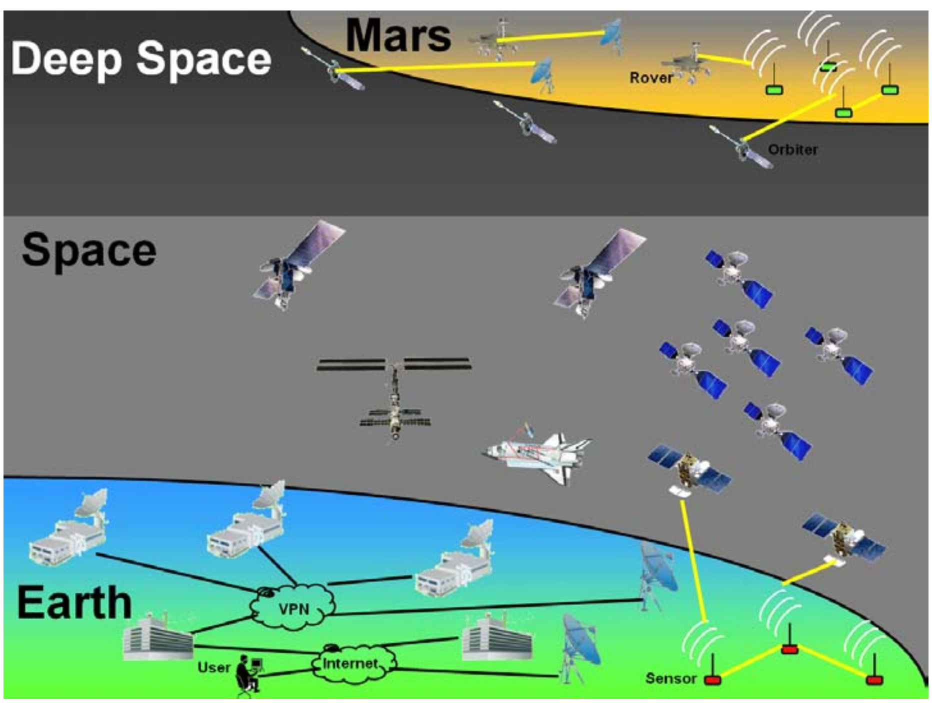

Fig. 16: Proximity Network SCA.

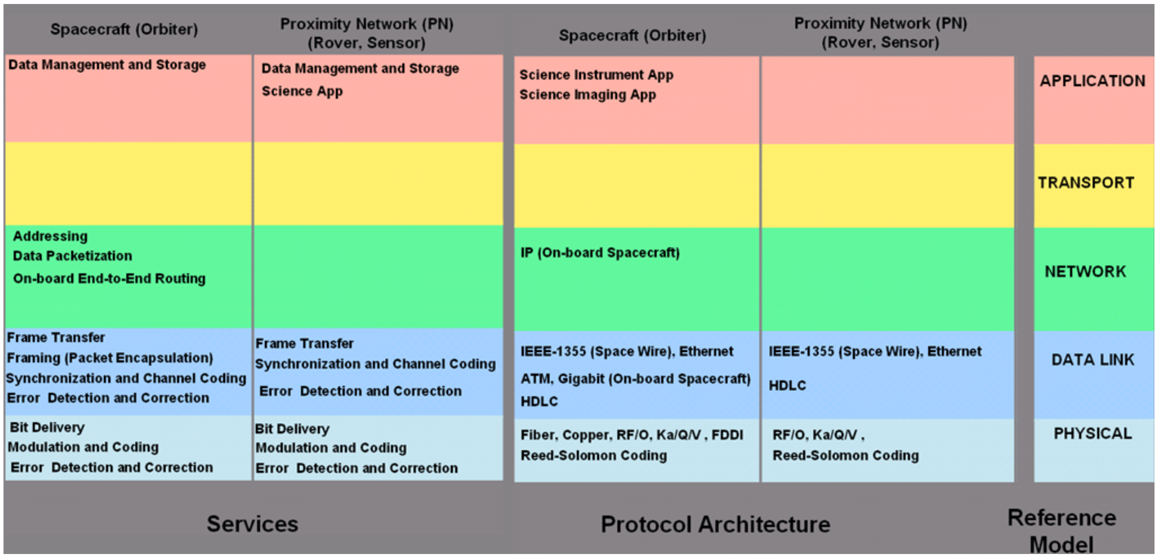

Fig. 17: Proximity Network SNPA.

The services and protocols used by NASA proximity network (PN) architecture are elaborated in details through its SPA shown in Fig.15. The design of the ISN SPA is based on the OSI reference model. The services and protocols supported by the PN architecture are motivated towards the on-board spacecraft (orbiter) , and planetary (in-situ) networks.
The standard bitstream delivery, modulation, coding, error detection and correction are provided by the physical layer. Bitstream delivery is performed by a wide verity of physical media is used such as copper, fiber (FDDI) and RF (Ka/Q/V bands). Modulation is performed by standard procedures applied by the supported physical media. Coding is performed by the Reed-Solomon coding. Error detection and correction (not specified) would be performed by standard CRC-32 procedure.
The data link layer services include packet encapsulation (framing), frame transfer, error detection and correction. This layer applies standard link layer protocols such as Ethernet, IEEE 1394 (Fire Wire), 1355 (Space Wire), ATM, SONET and HDLC. Planetary surface networks and on-board spacecrafts networks employ Ethernet, IEEE 1394, IEEE 1355, ATM, SONET and HDLC.
Global addressing, data encapsulation (packetization), on-board routing services are specialization of the network layer. This layer only exists at the on-board spacecraft end. On-board spacecrafts uses both IPv4 and IPv6 for global addressing, data encapsulation, real-time tunneling and end-to-end packet routing.
Standard data delivery services are provided by the transport layer, which include channel multiplexing, security, end-to-end data delivery. The ISN SPA does not provide these services, and hence the transport layer is inexistent.
Finally, the application layer provides mission data storage and management. At the on-board spacecraft network, the application layer manages the science data storage and controls the on-board science instruments. At the planetary network level, the application layer constitutes and data storage and science applications on-board science instruments (rovers, base-stations and wireless sensors).

2.6. Communication And Navigation Demonstration On Shuttle (CANDOS) SPA

The CANDOS protocol architecture is proposed by the OMNI project at NASA/GSFC as phase V. This SPA provided an IP-based end-to-end architecture as a part of the CANDOS experiment deployed on-board STS-107. CANDOS experiment was a part on the Fast Reaction Experiments Enabling Science, Technology, Applications and Research (FREESTAR) Hitchhiker Payload of the Columbia space shuttle that catastrophically destroyed while re-entry in 2003 [Israel 02]. Similarly to the OMNI-based SPA, this architecture is also leverages both the performance and commercial benefits of the industrial COTS technologies. The corresponding SCA of the CANDOS experiment is illustrated in Fig.18.

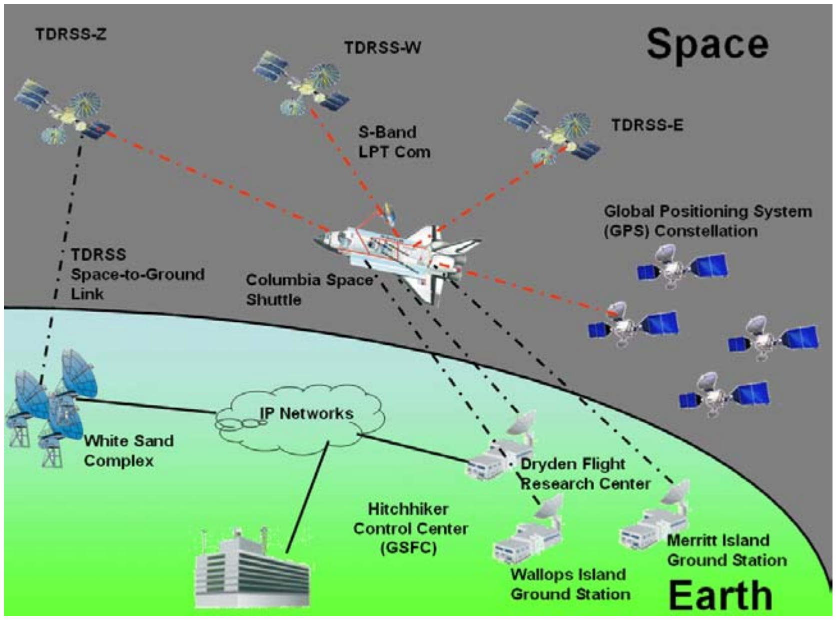

Fig. 18: The CANSOS Experiment SCA.

It can be noted that the SCA on which CANDOS experiment operated resembles OMNI-based SCA, since the CANDOS experiment is one of the final stages of the OMNI project. Therefore, this SCA is a two-segment architecture. The earth segment consists of ground stations and mission control centers. Ground stations include white sand complexes, Dryden flight research center, Merritt Island and Wallops Island. These ground stations are linked with the Hitchhiker control center (GSFC) through a common IP network backbone. One the other hand, the space segment consists of the Columbia space shuttle, TDRSS satellites and GPS satellites constellation. During the course of the CANDOS experiment (sixteen days), six payload objectives were accomplished. These objectives include TDRSS Communications, STDN Communications, GPS Navigation, On-Orbit Reconfiguration, Space Based Range Safety, and Mobile IP.

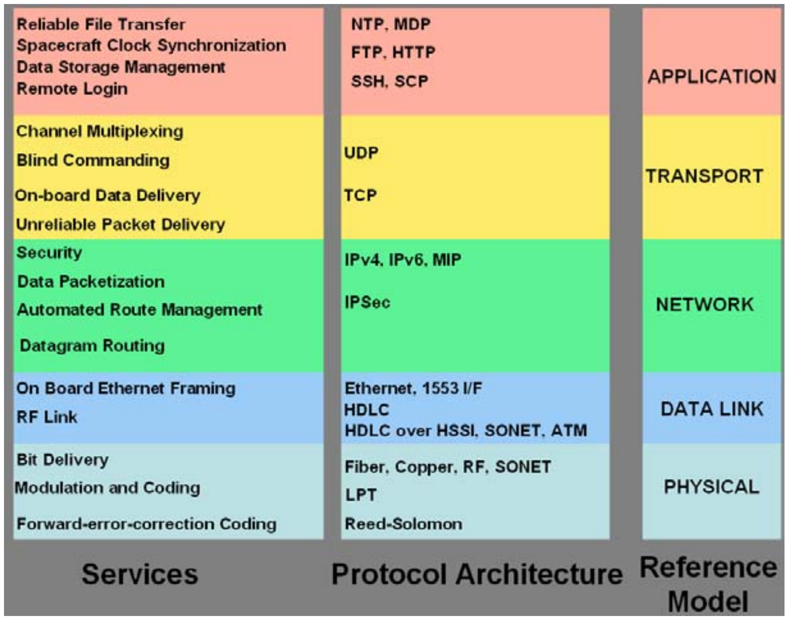

Fig. 19: CANDOS Experiment SCA.

All contacts between the Hitchhiker and the STS-107 CANDOS payload were established through the TDRSS satellites and the ground stations located in the earth segment.
The control operations of the CANDOS experiment were made accessible through special computers called Attached Shuttle Payload Control Center (ASPC) from the GSFC center. ASPC workstations operate Linux systems utilizing commercial Internet processes. In addition to the workstations, a set workstations connected into a common IP-based LAN are responsible of managing and sharing the telemetry data analysis.
The communications established between the GSFC center and the STS-107 CANDOS payload were conducted over Hitchhiker/Shuttle TDRSS links or directly through the CANDOS experiment antennas and RF links from TDRSS or ground stations.
The design of the CANDOS SPA shown in Fig. 19 is described from the bottom up from the physical layer to the application layer.
The physical layer provides three standard services: bitstream delivery, modulation and coding, and Forward Error Coding FEC. Various types of physical media that include copper, fiber, SONET and RF are used for bitstream delivery at both segments. Furthermore, a special type of RF transceiver called Low Power Transceiver (LPT) [LPS 01] was integrated into the flight computer hardware. LPT transceiver functions with four types of antennas: S-band high gain, S-band low gain, S-band receiver and GPS receive. Similarly to the OMNI-based SPA, this layer also employs a set of reliable coding and modulation techniques the perform data recovery over serial link lines with an embedded clock signal. For instance, Manchester coding is used for 10 Mbps Ethernet, 4B/5B for 100 Mbps FDDI, 8B/10B for Gigabit SONET, and BPSK and QPSK for RF systems. The RF systems of NASA missions are designed to provide 10^{-5} or better BER after coding. Therefore, the following FEC coding is applied: convolutional coding at the bit level, Reed-Solomon coding for block level.
The services provided and the protocols supported by the data link, network and transport layers are similar to ones corresponding to the OMNI-based SPA.
The services provided by the application layer include reliable file transfer using FTP and SCP, clock synchronization NTP, remote login using SSH, and data storage management of science data using RAID systems.

2.7. SpaceVPN SPA

The focus of the Hi-DSN SPA is centered at the provision of self-forming multi-hop space network. Hi-DSN integrates the predictability of orbital movement for the purpose of establishing and maintaining cross-links and multi-hop routes. Hi-DSN also utilizes ad hoc networking neighbor discovery techniques to autonomously discover new and recurring neighbors. Moreover, a novel multiplexing technique, which integrates spatial, time, and encoding was proposed to maximize the connectivity under large inter-spacecraft distances. However, Hi-DSN does not provide architectural specification for the earth segment, which securely connects user to different space missions.
The SpaceVPN SPA extends the Hi-DSN SPA with the architectural specifications of the earth segment, which focuses on enabling both secured real-time access to both onboard spacecraft resources. According the contest of SpaceVPN, the spacecraft resources include science data, instruments and sensors.
The SpaceVPN SCA illustrated in Fig.20 extends the Hi-DSN SCA shown in Fig.10 through the earth network segment by which users (experimenters) gain access to space missions. Given that fact that SpaceVPN is based on the Hi-DSN SPA, SpaceVPN is a three segment SPA. Moreover, the space and deep space segments on this SPA are equivalent to the ones belonging to the Hi-DSN. Therefore, the preceding discussion only describes the earth segment.
The main task of the earth segment is to provide experimenters (users) secure and real-time access to spacecraft resources. Generally experimenters gain access to different space missions through Missions Operations Centers (MOC) using secure Internet connections. These centers host network access servers securely connected to ground stations. The earth segment shown in Fig.20 illustrates the scenario by which an experimenter is transparently linked to the on-board spacecraft sensor hardware through an encrypted tunnel.
The SpaceVPN SPA is illustrated in Fig. 21, note that the lower four layers corresponds to the Hi-DSN SPA described previously. However, the network layer of this SPA additionally provides security services through IPSec protocol suite. Therefore we only describe the transport and application layers of the SpaceVPN SPA.
The standard channel multiplexing and data delivery services are provided by transport layer. For unreliable end-to-end data transport UDP is used, while TCP is used for reliable end-to-end data transport. Reliable file transfer and secured remote login services are provided by the application layer, which supports FTP and SCP for file transfer services and SSH for remote login to on-board spacecraft computers.

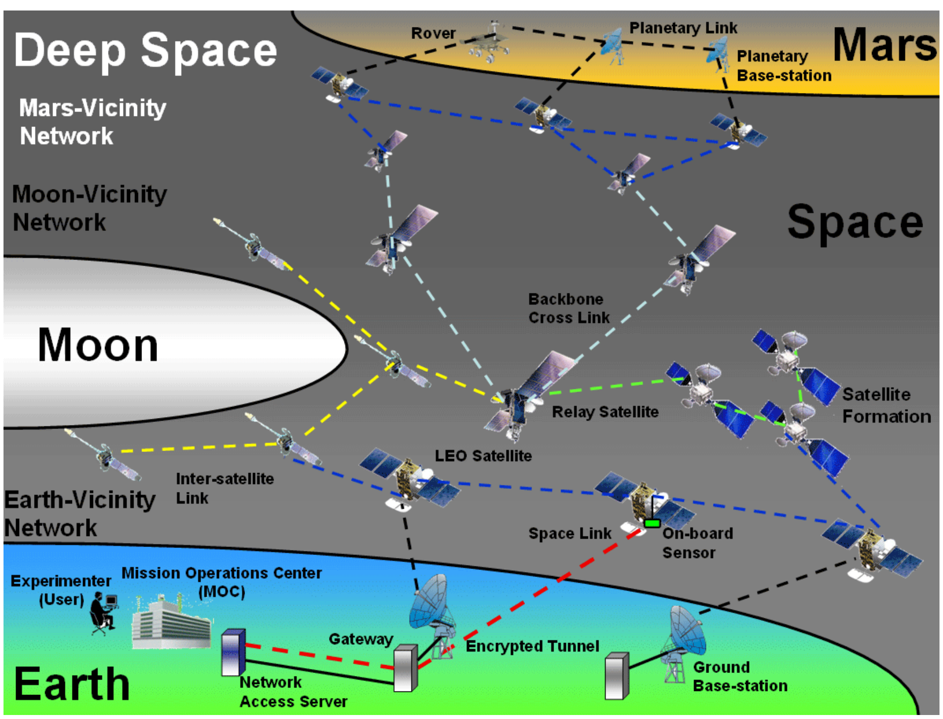

Fig. 20: SpaceVPN SCA.

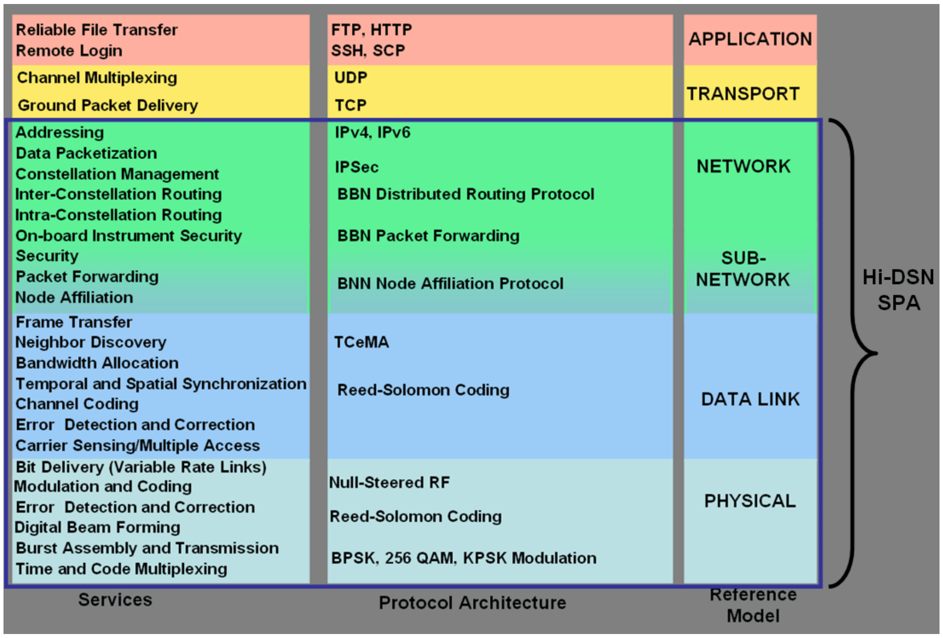

Fig. 21: SpaceVPN SPA.

2.8. Summary

The next generation space protocol architectures surveyed in this section can be further broken into three categories: Space OSI, Interplanetary, and Deep Space Network (DSN). The categorization is based on the SPA design model, number of core layers, services provided by each layer and the protocols supported by each layer. The SPA-centric classification of the seven SPAs is given by Table 1.

Space OSI	Interplanetary Internet	Deep Space Networking (DSN)
OMNI-based	CCSDS-based	Hi-DSN
GPM IP-based		SpaceVPN
NASA Enterprise		
CANDOS		

Table 1: SPA categorization

The Space OSI category contains OMNI, GPM, NASA Enterprise, and CANDOS SPAs. The design of Space OSI SPAs is based on the standard OSI reference model. The services provided by each layer along with their corresponding protocols are summarized in Table 3.

Protocol Layer	Services	Protocols
Application	• Reliable file transfer • Remote login • Web access • Network synchronization and • Email • Data storage management.	• FTP, SCP • SSH, Telnet • HTTP • NTP • SMTP • RAID
Transport	• Channel multiplexing	• TCP

	• End-to-end data delivery	• UDP, RTP
Network	• Global addressing • End-to-end routing • Security • Real-time commanding • Commanding in the blind	• IPv4, IPv6 • OSPF, RIP, BGP • IPSec. • MobileIP (MIP)
Data Links	• Packet encapsulation (Framing) • Frame transmission and reception • Error detection and correction • Forward error coding (FEC) • Carrier multiple access	• Ethernet, Space Wire, Fire Wire. • ATM, SONET, HDLC • CRC-32 • R-S coding • TDMA, CDMA
Physical	• Bitstream delivery • Coding and modulation • Error detection and correction	• Fiber, Copper, RF. • Manchester coding • R-S coding • RS 449/422, B.35

Table 2: Space OSI services and protocols

Second, the IPN category includes the CCSDS and NGI SPAs. The design CCSDS classification is also based on the OSI. However, the protocols supported by CCSDS layers are based on CCSDS protocols standards. The services provided by each layer along with their corresponding protocols are summarized in Table 4.

Protocol Layer	Services	Protocols
Application	• Reliable file transfer • Lossless data compression • Security	• SCPS-FP • FTP • LDC
Transport	• Channel multiplexing • End-to-end data delivery • Security	• TCP, UDP • SCPS-TP • SCPS-SP
Network	• Global addressing • End-to-end routing • Security • Real-time commanding • Commanding in the blind	• IPv4, IPv6 • IPSec. • SCPS-NP
Data Link	• Packet encapsulation (Framing) • Frame transmission and reception • Error detection and correction • Security.	• Ethernet, ATM, SONET, HDLC • Advanced Orbiting System (AOS) • TM, TC • Proximity-1 Data Link
Physical	• Bitstream delivery • Coding and modulation • Error detection and correction	• Fiber, Copper, RF. • R-S coding • Proximity-1 Physical

Table 3: Interplanetary Internet services and protocols

Third, the DSN category includes two SPAs: Hi-DSN and SpaceVPN. Both architectures are designed and prototyped at BBN technologies. It was given that SpaceVPN is based on the Hi-DSN. This class of SPA also follows the layered design approach. However, the DSN protocol design implements the physical, data link and network layers. The DSN classification focuses on the inter-spacecraft networks at the space and deep space segments. The DSN architectures provide a novel RF transmission and multiplexing techniques at the physical and data links layers respectively. Moreover, the DSN network layer is broken into two sublayers: sub-network and network layers. The sub network layer performs specialized tasks, where the network layer handles the standard networking tasks. The services provided by each layer along with their corresponding protocols are summarized in Table 5.

Protocol Layer	Services	Protocols
Network	• Global addressing • Security • Ground end-to-end routing	• IPv4, IPv6 • IPSec.
Sub-Network	• Constellation management • Intra-Constellation routing • Inter-Constellation routing • Packet Forwarding • Node Affiliation	• BBN Distributed Routing Protocol • BBN Packet Forwarding • BNN Node Affiliation Protocol
Data Link	• Packet encapsulation (Framing) • Frame transmission and reception • Error detection and correction • Neighbor Discovery • Temporal and Spatial Synchronization • Carrier Sensing/Multiple Access • Bandwidth Allocation	• Spatial multiplexing • Time multiplexing • Code multiplexing • TCeMA • R-S coding
Physical	• Bit delivery (variable rate links) • Modulation and coding • Error detection and correction • Digital beam forming • Burst assembly and transmission • Time and code multiplexing • Burst assembly and transmission	• Null-Steered RF • Reed-Solomon Coding • BPSK, 256 QAM, KPSK Modulation

Table 4: DSN services and protocols

3. Next Generation Space Protocol Architectures Classification

In the previous section we surveyed the seven most leading next generation space protocol architectures. These architectures were presented in terms of the space communication architecture (SCA) on which they operate, and the space protocol architecture (SPA) they provide. Moreover, the SPA corresponding to each of these architectures was further elaborated in terms of the services each layer provides along with the protocols it supports.

First, the OMNI-based SPA adopts standard Internet technologies to create a fertile land for multiple vendor solutions, and hence simplifying the process of future upgrades [OMNI-PRES_REF]. Moreover, this SCA also maximizes the use of COTS hardware along with Internet protocols in parallel with future space scientific solutions developments. The use of COTS technologies is a promising key factor in reducing the development time and costs of future space mission development.

Second, GPM is to provide a complete understanding of the global hydrological cycle and estimation of various sizes of precipitation particles. GPM aims to achieve serve public and private organizations involved in agriculture, public health, water resource management and aviation safety [GPM-SITE 05].

Third, CCSDS has been recently proposed as an integrated IPN SPA. The sole concept behind the CCSDS-based SNPA is in the incremental use of "internationally standardized" space data communication protocols in space missions [BCDFHSW 02]. The main goal of the CCSDS-based SPA is to provide a design of internationally standardized IPN, which integrates itself with current terrestrial Internet protocols for future space missions. Each of its layers is contains a set of CCSDS standards implementing its corresponding functionalities.

Fourth, the Hi-DSN SPA [Bergamo 05] integrates both space and terrestrial networks with each other to provide an ad hoc space communications infrastructure. Hi-DSN is intended to support a wide range of space missions and spacecraft configurations. It will be relevant for integrating various space missions to share their assets and mission data and is also planned to be applied for establishing communication with ground base-stations, planet rovers and low-flying probes. The main focus of Hi-DSN is to be applied for inter-spacecraft networking that include formation and clusters. Furthermore, Hi-DSN will provide support for real-time applications and multiple self-forming space network topologies.

Fifth, the NASA [KH 05] enterprise architecture is intended to serve the future NASA enterprise applications. The design of this SPA integrates four architectural elements: backbone (BN), access (AN), inter-spacecraft (ISN) and proximity (PN) networks. BN consists of the space network (SN), the ground network (GN), NASA's Intranets and virtual private networks (VPN's), the Internet, and commercial communication systems. ANs provide connectivity among space backbone networks, mission spacecrafts, and local area network (LAN's) on-board spacecrafts of vehicles. ANs use both radio and optical communication links. ISNs provide connectivity between spacecrafts flying in a constellation, formation, or cluster. PNs use both radio and optical communication links to interface between vehicles, landers, and sensor ad hoc network.

Sixth, The CANDOS protocol architecture is proposed by the OMNI project at NASA/GSFC as phase V. This SPA provided an IP-based end-to-end architecture as a part of the CANDOS experiment deployed on-board STS-107. CANDOS experiment was a part on the Fast Reaction Experiments Enabling Science, Technology, Applications and Research (FREESTAR) Hitchhiker Payload of the Columbia space shuttle that catastrophically destroyed while re-entry in 2003 [Israel 02]. Similarly to the OMNI-based SPA, this architecture is also leverages both the performance and commercial benefits of the industrial COTS technologies.

Seventh, The SpaceVPN SPA extends the Hi-DSN SPA with the architectural specifications of the earth segment, which focuses on enabling both secured real-time access to both onboard spacecraft resources. According the contest of SpaceVPN, the spacecraft resources include science data, instruments and sensors.

The next generation space network architectures operate in two classes of space communication architectures: two- and three segment architectures. The two-segment SCAs consists the earth and space (includes the loaner system), while three-segment SCAs additionally consists of the deep space segment. In addition, the SPAs provided by the next generation architectures fall into three classes: OMNI (Space OSI), CCSDS, and Deep Space Networks (DSN). In this section, we provide two classifications for these architectures. The first is SCA-centric and protocol centric.

3.1. SCA-Centric Classification

The next generation space protocol architectures supports two classes of SCAs: two- and three-segment architectures. The purpose of this classification is to specify the network resources and communication demands of the future space missions.

The earth segment generally contains three main elements: space missions and control centers, ground base-stations and users all interconnected in to a secure IP backbone network. Users such as scientists, collaborative investigators and principal investigators connect to space missions control and data distribution centers to gain access to on-going space missions. Users connect to these centers through secured private IP networks. The space segment consists of the network assets orbiting around the earth performing various space missions. The space segment is spliced to the earth segment by ground base stations. Control data are transmitted to spacecrafts, and telemetry science data are transmitted from the spacecrafts. The deep space segment consists of "store-and-forward" relay satellites, communication and science spacecrafts (orbiters) and planetary colony networks (in-situ Internet). The SCA assets on a planet surface (other than earth) consist of rovers, base-stations, sensors (a sensor web of motes) and other science instruments. The planetary in-situ Internet connects the SCA assets on the surface of the planet, and further with spacecrafts orbiting at its proximity. The SCA-centric classification is given in Table 1 shown below.

Two-Segment SPA	Three-Segment SPA
OMNI	CCSDS
GPM IP-based	Hi-DSN
CANDOS	NASA Enterprise
	SpaceVPN

Table 5: SCA-centric classification

By thoroughly observing at the design of the seven SPAs surveyed in section 2, it can be inferred that the two-segment SCA classification contains three SPAs: OMNI-based, GPM IP-based and CANDOS. On the other hand, the three-segment consists of four SPAs: Hi-DSN, CCSDS-based, NASA enterprise and SpaceVPN.

Two-segment SCAs are relevant to the space mission and explorations whose range is within the earth' and Moon's vicinities. Two-segment SCAs provide the strong potential to be applied in earth science enterprise applications [KH 05] that gathers data from specialized environmental monitoring and forecasting systems deployed at the earth and space segments. On the other hand, three-segment SCAs facilitate deep space exploration missions and are relevant for space science enterprise applications.

In spite of the fact that the design of three-segment SPAs is more extensive than its two-segment counterparts, the design two-segment SPAs have reached the level of maturity. The OMNI project was launched in the 2001 and its concepts were successfully applied to the CANDOS experiment in the 2003. The GPM IP-based SPA is currently under research and development and will be deployed in the next generation of satellite-based earth missions.

The design of three-segment SPAs is currently under research and development. The CCSDS SPA completed the research phase its design recommendations are currently under development and prototyping. The BBN Hi-DSN SPA completed the both the design and simulation phase and is currently under development. Besides the Hi-DSN SPA, SpaceVPN extends Hi-DSN with the earth segment communication services. Recently, BBN technologies has implemented an inter-spacecraft testbed [SpaceVPN_REF] for the purpose of evaluating the performance of Hi-DSN and SpaceVPN. The NASA enterprise architecture is currently under research. However, the GN and SN components are currently implemented by the means of OMNI-based architecture.

3.2. Protocol-centric classification

In this section we classify the seven space protocol architectures according to the protocols they support at the network, transport and application layer. The network layer protocol-centric classification given by Table 6 is based on the common protocols supported by each segment. These protocols include IP (IPv4 and IPv6), Mobile IP (MIP), SCPS-NP and IPSec. At the earth segment, all SPAs except Hi-DSN support IP including both IPv4 and IPv6 as standard addressing and routing protocol. Hi-DSN does not specify the network layer services at the earth segment; hence we assumed that IP is not supported there. On the other hand, the SCPS-NP is exclusively supported by CCSDS-based SPA. At the space segment, IP is not supported by CCSDS-based, Hi-DSN and SpaceVPN SPAs. CCSCS-based SPA supports SCPS-NP, while Hi-DSN and SpaceVPN apply industrial specific (provided by BBN technologies) distributed routing protocols suite. At the deep space segment, IP is supported by none of the three-segment SPAs. The CCSDS will support SCPS-NP, and both Hi-DSN and SpaceVPN will support BBN-based distributed routing protocols suite.

The transport layer-centric classification is given by Table 7. This classification based on the common protocols supported by this layer at each segment. At the earth segment, both TCP and UDP are supported by all SPAs except Hi-DSN, since Hi-DSN does not provides a transport layer through its design.

Furthermore, both SCPS-TP and LTP are exclusively supported by the CCSDS-based SPAs, while RTP is exclusively supported by OMNI-based and CANDOS SPAs. At the space segment, TCP and UDP are not supported by the Hi-DSN, SpaceVPN and CCSDS-based SPAs. The CCSDS-based SPA will support both SCPS-TP and LTP, while Hi-DSN and SpaceVPN does not provide transport layers through their design. At the deep space segment, the only SPA that provides a transport layer through its design is the CCSDS-based, since it will support both SCPS-TP and LTP. Although Hi-DSN and SpaceVPN both belong to the three-segment classification, but their design is restricted on the lower three layers. Therefore no such transport protocol will be supported by Hi-DSN and SpaceVPN unless future architectural modifications are to be applied.

The application layer-centric classification given by Table 8 is based on the set of common protocols supported by this layer at the different segments. The commonly supported protocols supported by the application layer includes HTTP, FTP, SSH, NTP, SMTP and SCPS-FP. At the earth segment, HTTP and FTP are supported by all of the SPAs except Hi-DSN. The SSH protocol is also supported by OMNI-based and CANDOS SPAs and SCPS-FP is exclusively used by the CCSDS-based SPA. At the space segment, OMNI-, GPM IP-based and CANDOS SPAs provide an application layer that supports HTTP, FTP, SSH, NTP, SMTP. Furthermore, the CCSDS-based SPA provides an application layer which only supports SCPS-FP and lossless compression protocol (LCP). None of the SPAs except the CCSDS-based provide an application layer at the deep space segment. Finally, the CCSDS-based application layer supports both SCPS-FP and LCP protocols.

Space Protocol Architecture	Earth Segment				Space Segment				Deep Space Segment			
	IP	MIP	SCPS-NP	IPSec	IP	MIP	SCPS-NP	IPSec	IP	MIP	SCPS-NP	IPSec
OMNI-based	YES	YES	NO	YES	YES	YES	NO	NO				
GPM IP-based	YES	YES	NO	NO	YES	YES	NO	NO				
NASA Enterprise	YES	NO	NO	NO	YES	NO	NO	NO				
CANDOS	YES	YES	NO	YES	YES	YES	NO	NO				
CCSDS-based	YES	YES	NO	YES	NO	NO	YES	YES	NO	NO	YES	NO
Hi-DSN	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
SpaceVPN	YES	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO

Table 6: Network layer classification

Space Protocol Architecture	Earth Segment						Space Segment						Deep Space Segment					
	UDP	TCP	RTP	SCPS-TP	SCPS-SP	LTP	UDP	TCP	RTP	SCPS-TP	SCPS-SP	LTP	UDP	TCP	RTP	SCPS-TP	SCPS-SP	LTP
OMNI-based	YES	YES	YES	NO	NO	NO	YES	YES	YES	NO	NO	NO						
GPM IP-based	YES	YES	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO						
NASA Enterprise	YES	YES	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO						
CANDOS	YES	YES	YES	NO	NO	NO	YES	YES	NO	NO	NO	NO						
CCSDS-based	YES	YES	NO	YES	YES	YES	NO	NO	NO	YES	YES	YES	NO	NO	YES	YES	YES	YES
Hi-DSN																		
SpaceVPN	YES	YES	NO	NO	NO	NO												

Table 7: Transport layer classification

Space Protocol Architecture	Earth Segment						Space Segment						Deep Space Segment					
	HTTP	FTP	SSH	NTP	SMTP	SCPS-FP	HTTP	FTP	SSH	NTP	SMTP	SCPS-FP	HTTP	FTP	SSH	NTP	SMTP	SCPS-FP
OMNI-based	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	NO	NO						
GPM IP-based	YES	YES	NO	NO	NO	NO	YES	YES	YES	YES	NO	NO						
NASA Enterprise	YES	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO						
CANDOS	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	NO	NO						
CCSDS-based	YES	YES	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	YES
Hi-DSN	NO	NO	NO	NO	NO	NO												
SpaceVPN	YES	YES	NO	NO	NO	NO												

Table 8: Transport layer classification

SpaceVPN implements both transport and application layers. However, these layers are only implemented at the earth segment and not precisely described in it literature.

4. Space Network Protocol Design Evaluation Framework

In this section we provide a detailed description of the design framework we defined for evaluating the proposed next generation space protocol architectures. We first provide a general description for two classes of space communication architectures on which next generation SPAs will operate. Second, we describe the communication demands expected to be provided by both communication architectures. Third, based on these communication demands we identify eight major design challenges posed by next generation space network architectures.

4.1. The Space Communication Architectural Model

The primary task of the space network infrastructure is to provide an efficient and yet reliable end-to-end communication paths among various space assets on Earth, space, and other planets. We characterize the space network infrastructure as a model of five interconnected logical tiers. This model is further illustrated by means of the two- and three segment space communication architectures shown in Figs.10-12. For the two-segment architectures, we illustrate two configurations.

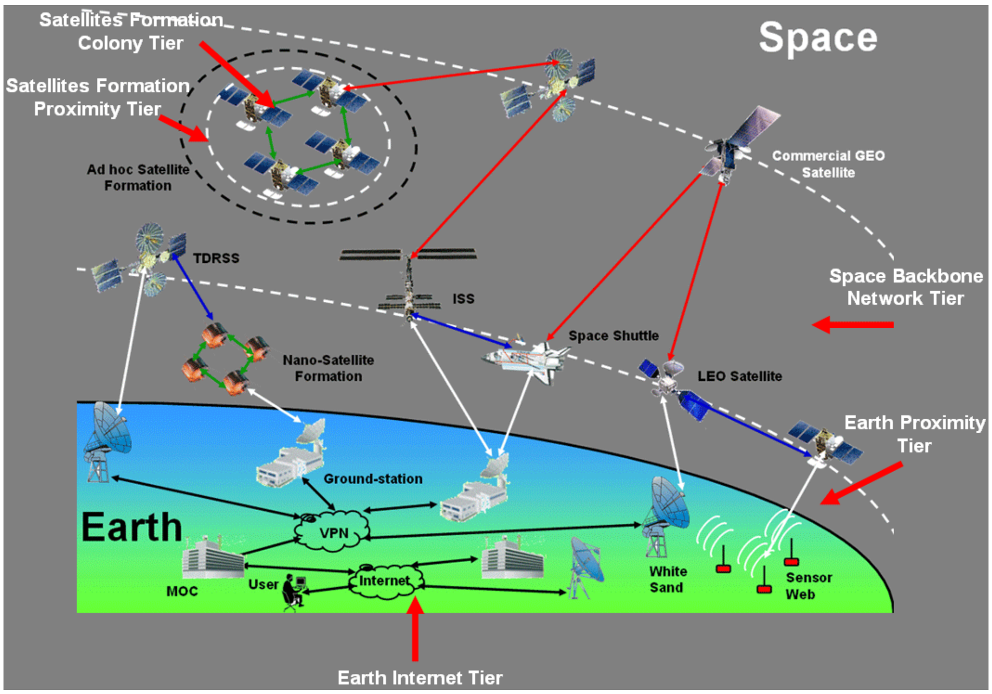

Fig.10: The five-tier Space Network Infrastructure Model for Two-Segment Architectures.

The configuration illustrated in Fig.10 describes the five-tier two-segment SCA. First, lower most tier represents the earth Internet, which consists of the of space network assets in Earth, note that these assets are interconnected through Internet. Second, the satellites orbiting in the Earth vicinity along with Earth Internet tier form the Earth proximity tier consists is space assets form the Earth proximity-tier. Third, the space backbone network consists of TDRSS and commercial GEO satellites. This tier stands as an interplanetary relay backbone network, which relays data among different planets. Forth, the communication range within the ad hoc satellites formation represents the formation proximity network. Fifth the interconnection among of the members of the satellite formation represents the colony network tier.

The second configuration shown in Fig. 11 illustrates the five-tier two-segment SCA, which emphasizes on the interconnectivity between the space shuttle and the International Space Station ISS. The Earth Internet, Earth proximity and the space backbone tiers are similar previous configuration. The fourth tier represents the proximity of the space shuttle, which includes the ISS. The fifth tier in the configuration is represented by the on-board of the shuttle network.

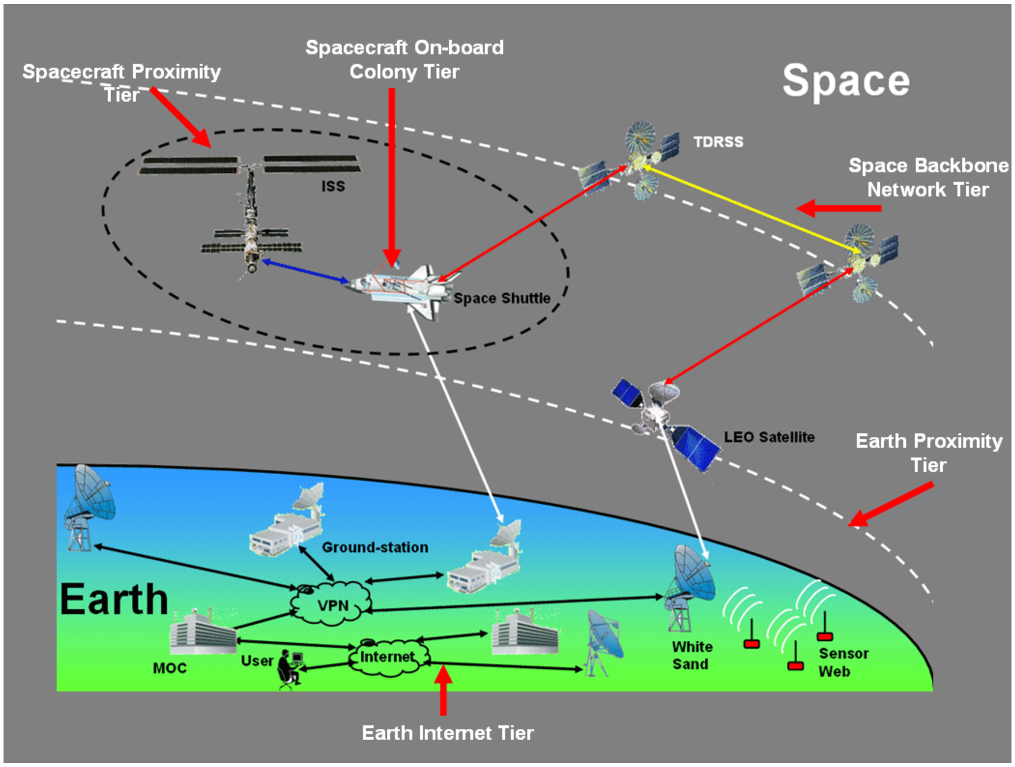

Fig.11: The five-tier Space Network Infrastructure Model for Two-Segment Architectures.

The five-tier space network infrastructure for three-segment SCAs is illustrated in Fig. 12. First, the Earth Internet tier consists of all the space network assets connected to each other via Internet. Second, the satellites orbiting in the Earth vicinity along with Earth Internet tier form the Earth proximity tier consists is space assets form the Earth proximity-tier. Third, the space backbone network consists of the relay satellites that forward data between Earth and Mars planets. Therefore, the space backbone network acts as an interplanetary relay backbone network, which relays data among different planets. In addition, it can be noted the space shuttle at the right most of Fig. 10, has an onboard colony network. This colony network interconnects onboard computers and scientific equipments with each other. Furthermore, space shuttle proximity network consists of the space lab only, while planetary proximity network such as Earth and Mars would contain different types of spacecrafts. Fourth, the Mars proximity network is similar to the Earth proximity network, whereas the satellites are orbiting in the Martian proximity.

Finally, the Mars colony network consists of the space assets on the surface of Mars that includes rovers, landers, and ground stations. We next provide a detailed description for each design challenge posed by space network protocols model described in this section.

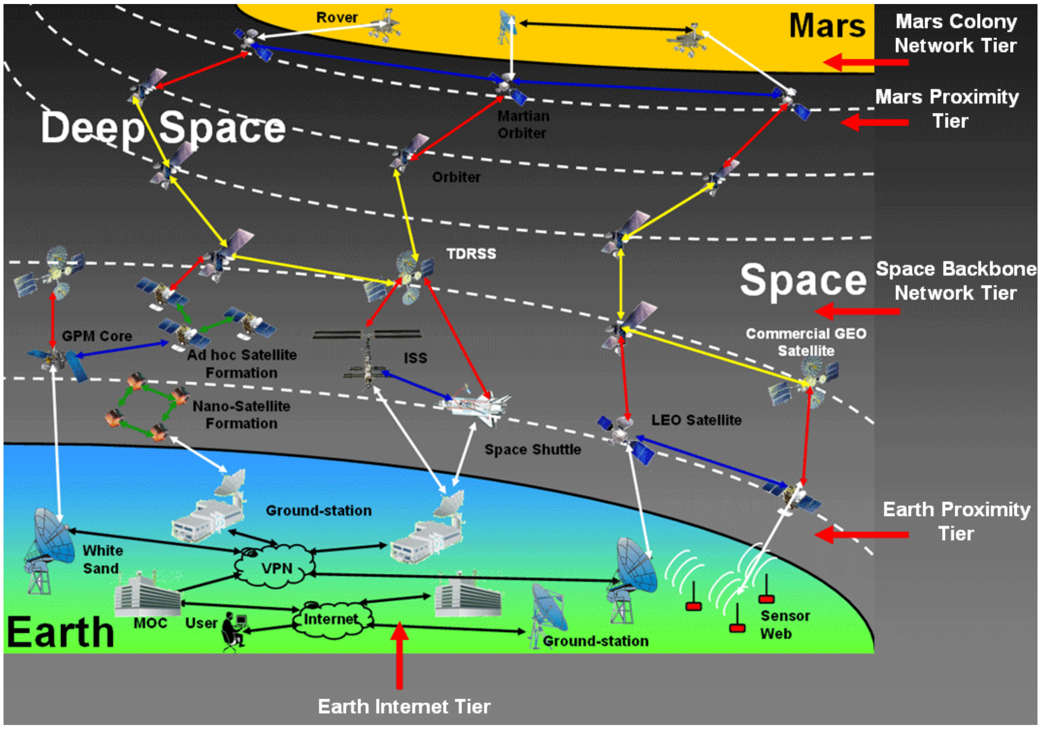

Fig.12: The five-tier Space Network Infrastructure Model Three-Segment Architectures.

4.2 Handling long propagation delay

This challenge is related to the connectivity established under a wide range of propagation delays and relative velocity. By referring to the space network infrastructure shown at Fig. 14, it can be noticed that the inter-tier distances (listed in Table 1) are remarkably long.

Inter-Tier	Distance (Km)
Earth Internet-Earth Proximity Network	250-2000 [Christopher 99]
Earth Proximity Network-Space Backbone Network	1-2800 [Christopher 99]
Space Backbone Network-Mars Proximity Network	1-100,000 [BH 02]
Mars Proximity Network-Mars Colony Network	800 [BCEET 00]

For a spacecraft in low-altitude orbits, the inter-spacecraft distances may range from 1 meter to 100,000 kilometers [26] and that requires aggregate throughput maximization that ranges between 100 Kbps to 1 Gbps. For instance, the average distance between the Earth and the Moon is 84,399 kilometers [WikiMoon 07], whereas the average distance between the Earth and Mars is approximately 200 million kilometers [28]. These large inter-spacecraft distances have a major impact on the space network performance. The propagation delay becomes a significant factor impacting the choice of medium access technique [Bergamo 05] [CGJO 05]. Extremely long propagation delay results two implications [FJ 05] [GPBG 05]. First, the delay will negatively impact the system responsiveness. Second, long round-trip delay will cause sharp link bandwidth degradation.

4.3 Dynamic Network Topologies

The dynamicity characteristic of upper levels of space network architecture described above pose five crucial design challenges described as follows:

- **The overall space network interconnection**: According to the five-tier space network infrastructure illustrated. The overall network topology is the interconnection between Earth colony networks with other planetary colony networks through the space backbone network. This interconnection is performed by *space network splicing*, which defines the splicing areas between adjacent tiers. The notion of space network splicing is elaborated in Fig. 11. It is shown that four splicing areas exist between the following tiers: (1) Earth colony-proximity splicing area, (2) Earth proximity-backbone splicing area,(3) Mars proximity-backbone splicing area, and (4) Mars colony-proximity splicing area. Note that the splicing areas are an intersection between the networks two adjacent tiers. Therefore, it can be inferred that the overall space network interconnection can be given in terms of a chain of intersections between the tiers.
However, the overall network interconnection described clearly corresponds to the three segment architectures. On the other hand, in two-segment architectures, the colony network would be either a flying satellites formation within the earth vicinity or a network colony deployed on Moon surface. Therefore, the third splicing area corresponds to the area between the backbone network and the proximity of either the satellites formation or the Moon colony. Moreover, the fourth splicing area corresponds to the colony network proximity and the colony network itself.
The notion of space network splicing raise two main issues, the first is related to the addressing scheme resolution among different tiers, and the other is related to the splicing approach used by the space network infrastructure.
First, Earth Internet and planetary colony network topologies are static and yet deterministic, where the space backbone network topology can be dynamic and thus undeterministic. Therefore, two possible space topologies are resulted: fully static or semi-dynamic. Second, space network splicing can be performed either manual or automatic. If splicing is done manually all information is sent the earth colony network, and disseminated to the entire space network. On the other hand, if it is done automatically space assets at each tier performs the inter-tier splicing operations. It is anticipated from the next generation space network layer to support the concept of network splicing along with its issues.

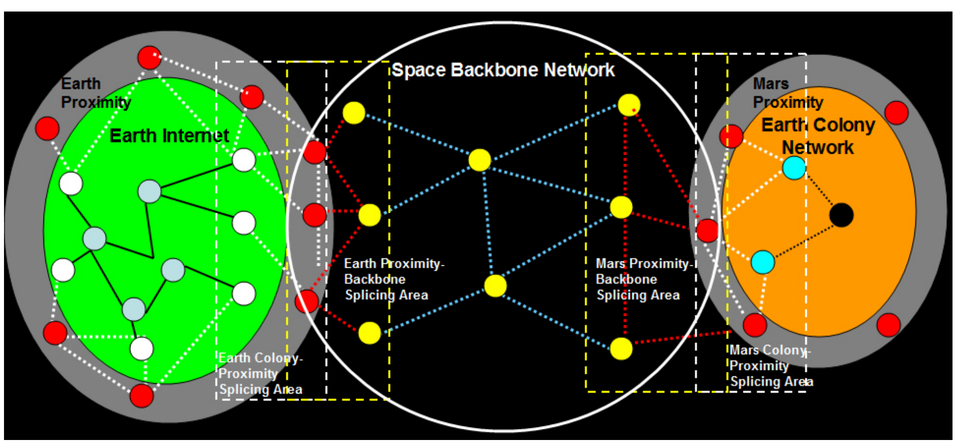

Fig. 11: The Abstract model of the five-tier Space Network with splicing areas

- **Topological Information Dissemination**: When a change is made at any tier, the rest of space network topology is required to tune itself according to the changes made. In order to maintain efficient connectivity, all the three tiers of the space network infrastructure must be update periodically. Therefore, a mechanism for disseminating network topological information periodically is required [refs]. Furthermore, this mechanism can be done either manually or automatically. If the former approach is used topological information is computed and distributed from the Earth colony network. On the other hand, if the second is applied space assets at different tiers are responsible to periodically compute and disseminated this information.

- **Addressing**: Based space infrastructure model, both of Earth Internet and planetary colony network apply IP-based addressing since their corresponding network topologies are static. On the other hand proximity and space backbone networks may use different addressing schemes such as flat addressing, Attribute-based addressing [Warthman 03], Delay Tolerant Network (DTN) addressing [Fall 03], and Hierarchal addressing [BK 07]. As a consequence, the design of the next generation network layer is expected to provide efficient mechanisms for address translation, resolution, and integration among the three tiers of the space network infrastructure.

- **Routing:** Routing in space networks is distinguished from routing in terrestrial network by four aspects: nature of the network topology, path establishment, shortest path computation, and next-hop packet forwarding. First, the overall space network topology described in Fig. 11 is combination of static and dynamic network topology spliced with one another. Colony network topologies are static and, where the backbone network topology and the network topologies at the splicing areas are either dynamic or semi-dynamic. Second, one crucial issue related to space network topology is route establishment, which is strongly depends on the network topology. According to the five-tier model described, two route establishment scenarios would exist in this context: fully static, semi-dynamic, and fully dynamic. Third, based on the route information disseminated, nodes at the five tiers periodically compute the shortest path to all the nodes in the space network. Because of dynamicity characteristic of the space network infrastructure, conventional shortest path algorithm such Dijkstra or Floyd-Warshal are inapplicable. Therefore, it is necessary to apply modified versions of the conventional shortest path algorithms that consider the rapid changes (evolution) of the space network topology [DGV 03]]. Moreover, route computation can be also done either manually or automatically. Fourth, the decision which a space router takes for the forwarding packet to the next hop is based on route information maintained in the node's route table, which can hold the entire route to the destination node or only the next hop-hop towards the destination [SRBJ 04] [BK 07]. It has to be noted that it is very difficult or near impossible to have the complete route to a destination node due to the constant routers mobility and rapid network topology evolution, and hence nodes are required to store a huge volume of information to track states of all possible routes in the network topology. As a consequence, a node would only be aware of the next hop towards the destination, and hence the entire packet routing is done in terms of a chain of localized packet forwarding. Finally, when local packet forwarding is used, link temporal information must be carefully considered, because an optimal route of packet at time ***t*** would not be equivalent to one at ***t'***.

- **Routing Quality of Service (QoS):** Is the reliability of routes computed in the space networks that reflect the level of packet delivery guarantee. The context level of packet delivery guarantee is that a packet is delivered to its corresponding destination within the expected transmission time delay. The reliability of space routers plays a major role in determining the degree packet delivery guarantee. The reliability of space router can evaluated in terms of computation and storage capabilities. First, space routers should have adequate storage capacity to maintain the route table and buffer incoming traffic. Second, space routers are required to support the notion of *schedulablity of packet delivery* in order to guarantee a reliable packet delivery. Moreover, the route QoS depends on the quality to the frequency and the accuracy of the temporal link state information disseminated. Finally, design of the next generation space network protocol layer is required to satisfy these storage and computation requirements.

Based on the design challenges posed by the space routing architecture, it can be inferred that conventional mobile routing algorithms are inapplicable for such space routing architectures. It can be also noticed that existence of End-to-End route between communicating peers is almost impossible to achieve. Therefore, neither proactive nor reactive MANET routing algorithms such neither Destination-Sequence Distance Vector (DSDV) [PH 94] and Ad hoc On-demand Distance Vector (AODV) [Perkins 97] would be applicable in space networks. Furthermore, terrestrial mobile networks involve human intervention, which makes ad hoc and unpredictable. On the other hand, space networks are unmanned and are predictable.

4.4 Resource Allocation

Efficient communication recourse allocation to multiplex traffic originated from different applications with different QoS requirements. Moreover, handling the related aspects of traffic flow control is performed in terms of admission control, packet scheduling, and link QoS for different traffic patterns [Bergamo 05]. In space networks, resource allocation has to be planned in advance in order to satisfy the resource demands of the current and future missions.

4.5 Intermittent communication link

4.5.1 The notion of link intermittency

Link intermittency is a direct consequence of the dynamicity of the space network topology. This aspect is can be clearly observed at the space backbone network tier, where communication links have limited age. In other words, links are active only for a limited period of time due to the constant node mobility. The concept of link intermittency is elaborated for a time-varying connected graph in Fig. 12.

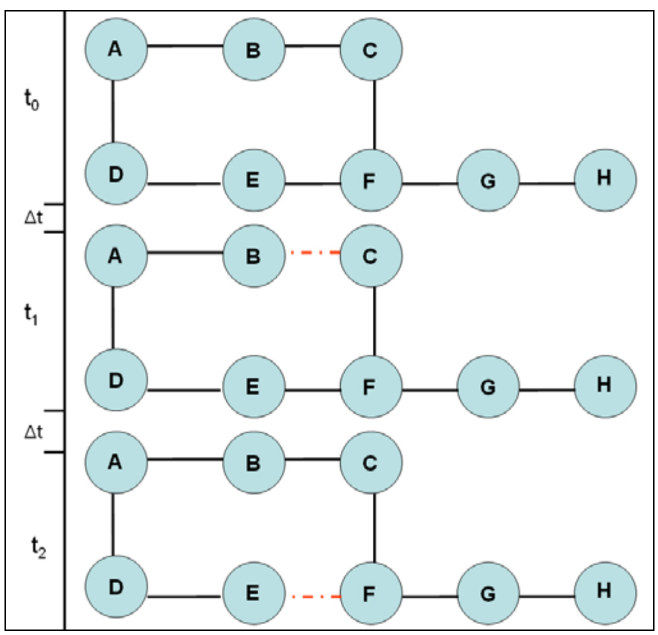

Fig. 12: Link Intermittency Scenario in Time-Varying Graphs

By observing the time line at Fig, 12, the entire set of edges are intact in initial graph at time t_0, at t_1 the edge (B,C) went down, and time t_2 the edge (B,C) became intact while (E,F) went down. Note that the transition time duration between time-adjacent graphs is Δt. Based on the link intermittency scenario described above, when A wants to send a message to H, at time t_0 the message can take either paths p_1 = {(A,B),(B,C), (C,F),(F,G),(G,H)} or p_2={(A,D),(D,E), (E,F),(F,G),(G,H)}. However, at time t_1 when the edge (B, C) went down the p_1 is no longer a valid path to H, and the same applies to p_2 when the edge (E, F) went down at time t_2.

4.5.2 Link intermittency at the entire space network infrastructure

According to the space network infrastructure model, link intermittency occurs at space backbone network tier and the splicing areas. We illustrate the link intermittency in the space network infrastructure through space network topology shown in Fig. 13. Note that the initial network topology is given at time t_0 and Δt topology evolution time.
Since, link intermittency does not occur in the Earth Internet and planetary colony tiers, the space network infrastructure shown in Fig.13 only elaborate the Earth proximity, space backbone, and Mars proximity tiers. The Earth proximity network consists of the set of LEO satellites $S_{Earth} = \{S_1, S_2, S_3\}$ and Mars proximity consists $S_{Mars} = \{S_5, S_6\}$. In addition, The Earth proximity-backbone splicing area consists of the set S and the set of Earth relay satellites $E = \{E_1, E_2, E_3, E_4\}$, while Mars-backbone slicing area consists of the satellites in and set of Mars relay satellites $M = \{M_1, M_2, M_3, M_4\}$. Lastly, the space backbone network consists of the set of backbone relay satellite $R = \{R_1, R_2, R_3, R_4\}$, and the relay satellites in E and M. By observing the time line in Fig.14, it can be noticed that the satellites in sets S_{Earth} and S_{Mars} changes their positions every Δt, satellites in the sets E and M change their positions every 2 Δt. The rate of positional evolution of the satellites in S_{Earth} and S_{Mars} is Δt , 2Δt the satellites in E and M, and 3Δt for satellites in R. The link availability time table of the space network scenario shown in Fig. 13 is listed in Table1.

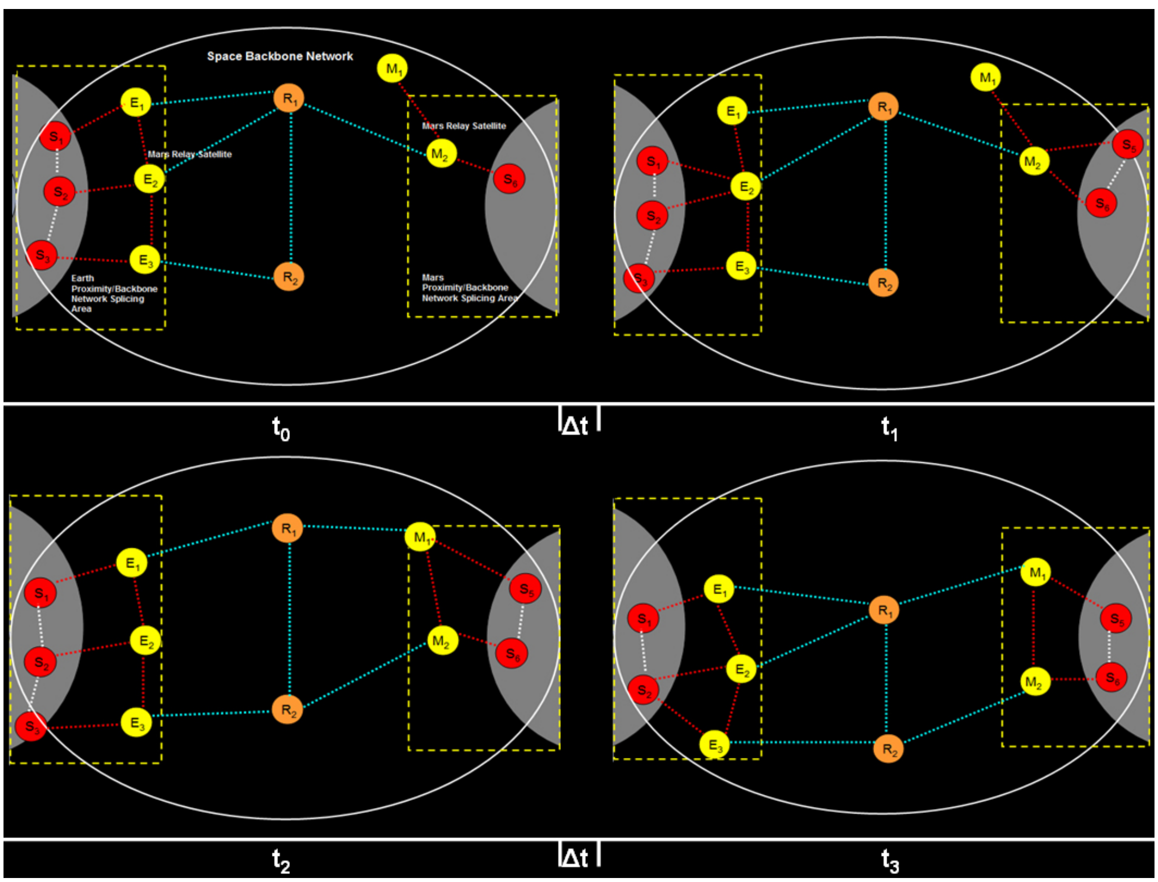

Fig.13: Link Intermittency at the entire space network infrastructure.

Based on the space network topologies shown in Fig. 13 and link availability table listed in table 1, the next example describes the effect of link intermittency on end-to-end paths between satellites in the space network infrastructure.

	S_1	S_2	S_3	E_1	E_2	E_3	R_1	R_2	M_1	M_2	S_5	S_6
S_1		t_0, t_1, t_2 , t_3		t_0, t_2, t_3	t_1							
S_2	t_0, t_1, t_2, t_3		t_0, t_1, t_2,		t_0, t_1, t_2, t_3	t_3						
S_3		t_0, t_1, t_2				t_0, t_1, t_2						
E_1	t_0, t_2, t_3`				t_0, t_1, t_2, t_3		t_0, t_1, t_2, t_3					
E_2	t_1	t_0, t_1, t_2, t_3		t_0, t_1, t_2, t_3		t_0, t_1, t_2, t_3	t_0, t_1, t_3					
E_3		t_3	t_0, t_1, t_2		t_0, t_1, t_2, t_3			t_0, t_1, t_2, t_3				
R_1				t_0, t_1, t_2, t_3	t_0, t_1, t_3			t_0, t_1, t_2, t_3	t_2, t_3	t_0, t_1,		
R_2						t_0, t_1, t_2, t_3	t_0, t_1, t_2, t_3			t_2, t_3		
M_1							t_2, t_3			t_0, t_1, t_2, t_3	t_2, t_3	
M_2							t_0, t_1	t_2, t_3	t_0, t_1, t_2, t_3		t_1	t_0, t_1, t_2, t_3
S_5										t_1, t_2, t_3		t_1, t_2, t_3
S_6										t_0 t_1, t_2, t_3	t_1, t_2, t_3	

Table 1: The link availability time table to the space network scenario shown in Fig.13.

When satellite S_3 intends to send a message to satellite S_5, S_3 should consider the end-to-end path availability to S_5 over time t_0 to t_3. At time t_0, no end-to-end path leading to S_5 exists, hence no message transmissions to S_5 can be scheduled. At time t_1, two possible end-to-end paths to S_5: $p_1 = \{(S_3, E_3), (E_3, R_2), (R_2, R_1), (R_1, M_2), (M_2, S_5)\}$ and $p_2 = \{(S_3, S_2), (S_2, E_2), (E_2, R_1), (R_1, M_2), (M_2, S_5)\}$. Moreover, at time t_2, p_2 becomes no longer leading to S_5, where another two possibly existent paths are $p_3 = \{(S_3, E_3), (E_3, R_2), (R_2, R_1), (R_1, M_1), (M_1, S_5)\}$. However, it has to be noticed that S_5 become no longer connected to the space network topology at time t_3. S_3 can not schedule message transmissions to any satellite of the space network topology during at time t_3. When more than one end-to-end path exists to a destination, the transmitter node should specify which path is the optimal. Furthermore, If S_3 has a long message that cannot be sent in a single time slot. Therefore, S_3 must break the message into smaller message fragments, each is sent in a single time slot. In this case, S_3 must consider different end-to-end paths reachable to S_5 over time because of link intermittency. As a consequence, S_3 should schedule the transmission of these smaller message fragments into different paths by using the link availability table shown above. Finally, it can be inferred that the task of routing converges to transmission scheduling over time.

4.5.3 Link intermittency design issues

The issue of link intermittency poses a set of design challenges described as follows:

- **Support for Link Availability dissemination**: Is the issue related SNPA support for handling link intermittency by distributing link availability information among the nodes in each tier. In this context, three possible methods would exist to address this challenge: Ostrich, manual, and automated.

  - **The Ostrich method**: The issue of link intermittency is completely ignored, and nodes in the space network are only aware of a single route for each node in the network. Therefore when a message is transmitted via a disconnected path, nodes along path may buffer that message until the path becomes intact. One advantage of this method is no additional computation overhead would be resulted. One the other hand, this option has two crucial drawbacks. First, large amount of storage is required at each space routing node, and further computation overhead is incurred for storage management. Second, message buffering periods would be very long so messages would not arrive to their corresponding recipients within the expected latencies. It can be inferred that this method would result low QoS, and thus would be irrelevant for space network infrastructures.
  - **Manual Method**: The issue of link intermittency is handled at the Earth colony network. All link state information are sent base-stations and national space agencies at the Earth colony network, where future link intermittency events are predicted and next disseminated to entire space network. This method has two key advantages. First, all link availability information would be predicted a head of time, so nodes in the space network would have a complete knowledge about the space network topology over time. Therefore, space nodes would route messages more efficiently since they would become aware of path availability over time. Second, this method provides an enhanced QoS, since nodes in the space networks can efficiently schedule data transmissions over intermittent links, so data messages would arrive to their corresponding recipients within the expected delay. One main drawback this method suffers is being centralized, which causes single-point of failure bottleneck.
  - **Automatic Method:** The issue of link intermittency is automatically handled by at three tiers of space network. Space assets at each tier exchange link availability information among each other and further exchange them with their neighboring tiers at the splicing areas. This method has two main advantages. First, similar to the centralized nodes in the space network would have a complete knowledge about the space network topology, and hence and enhanced QoS would be provided. Second, unlike the manual method this method is distributed, and hence this method overcomes the single-point of failure. However, this method has two main disadvantages. First, in order to guarantee the awareness of network topological changes, the duration in which link availability information are disseminated must be shorter enough than Δt. If the value of Δt is low, then link availability information must be distributed in high frequency. Second, a considerable amount of computation, storage, and communication overhead incurred by link availability dissemination.

- **Optimal End-to-End Shortest Route Computation:** Based on the temporal link state information disseminated, space nodes can compute time-varying graph of the entire space network topology. This facilitates space nodes to compute the time-varying shortest path to all nodes in the space network. Computing the end-to-end shortest routes further arises two issues. The first is related to method of computation, which can be centralized or distributed. The centralized method would suffer from the single-point of failure bottleneck, whereas the distributed method must be optimal and transparent. The other issue is related to the shortest path algorithm applied. It was previously given that conventional shortest path algorithms are not relevant for space network topologies in the context of constant node mobility. This issue can also be regarded from the link intermittency point, and thus link intermittency is considered instead of the positions of nodes in the network. Therefore, shortest path computation provided by the next generation network protocol layer must provide optimal algorithms that consider spatial and temporal information. This issue has been recently addressed by the Space OSPF routing protocol [Bantan 07] [BK 07] through the use of the Shortest Delay Intermittent Pathway (SDIP) algorithm. SDIP algorithm uses the routing information to build and populate route tables that handles link intermittency [Bantan 07][BK 07].

- **Optimal Flow Control:** Is the process of scheduling incoming traffic relatively with the both spatial and temporal link state information. Based on the time-varying graphs, the space node is capable of precisely scheduling an incoming traffic to its corresponding destination. Moreover, packet scheduling at the transport layer can be done either offline or online. In addition, it is necessary to determine the packet arrival behavior, delivery deadline, and other scheduling metrics in order to guarantee packet delivery within their deadlines. This issue is more severe, when online packet scheduling is performed aperiodic incoming traffic. Determining the packet schedulablity is an NP problem [ref]. Therefore, the design packet scheduling algorithms of next generation transport protocol layer is required to address temporal facts of communication links and the real-time(ness) of data traffic.

3.6 High link asymmetry

This is related to the fact that most spacecrafts have a higher downlink bandwidth the uplink bandwidth. This is due to their limited power and weight budgets that limit their ability to support large steerable high-gain antennas. The link asymmetry aspect is resulted from the nature of most space missions, where the up link is used to transmit control signal to spacecrafts and down links for telemetry data transmission from mission spacecrafts to base-stations. The future space missions will pose additional bandwidth requirements on the uplinks so that high quality multimedia data could be streamed to spacecrafts.

4.7 Bit error rates

Due to the long distances between spacecrafts that reach up to 10,000 kilometers and the noisy environment, the transmitted signals would have stronger likelihood to be lost or attenuated. Hence, this will result a higher Bit Error Rate (BER). The error correction applied by NASA achieves BER down to 10^{-7}, where handshaking protocols like TCP/IP functions properly [RHC 05].

4.8 Extreme Protocol Reliability

Is the level of reliability guaranteed by the space protocol to deliver mission data and control signals between base-stations and spacecrafts, and among spacecrafts themselves. Moreover, reliability in this context is also related to degree to fault-tolerance and self-stabilization the protocol provides in the cases of sudden failures or crashes. In space networks, the degree of protocol reliability is required to be extremely high due to the extremely high expense of mission redeployment. For instance, loosing control of a spacecraft orbiting around a specific planet would incur a prohibitive cost in the order of millions of dollars, and hence it would be in tolerable. Conventional standard terrestrial network protocol architectures do not provide this degree of fault tolerance. Therefore, this issue poses a design challenge must be considered by the next generation SNPAs.

4.9 Security

The mechanisms and the procedures applied for protecting the space network-wide assets from unauthorized access. These mechanisms are necessary to be applied in levels of space networks that include ground networks, space networks and deep space networks. Furthermore, security mechanisms must provide a high degree of restriction and protection due to sensitivity of information being transmitted. Therefore, it is anticipated that next generation SNPA have strong data security services integrated in their protocol layers. In space so far the communication assets are within one administrative domain, the main threats will be eavesdropping.

The principle mechanism needed to thwart such threat is authentication and encryption. However, unlike earth, some information cannot be hidden. The orbit and location information of most of the assets along with overall routing and topology scenario will remain exposed. It will be vulnerable to jamming, denial of service attacks or even physical destruction. It is likely that different countries (or agencies within a country) will have complementary assets, and there will be mission scenarios under which communication routes have to be established using assets from multiple administrative domains. BGP like selective asset advertisement and filtered asset disclosure protocols have to be developed to support such scenarios. The current BGP have to be extended to include schedulablity and dynamic topology support. Further, two sub-scenarios might arise in inter agency information exchange. Like earth, the information may be filtered and exchanged directly in space. However, it is also possible that the agencies will exchange all such information via a gateway server on earth, where proper filtering and security checks enforced here.

5. Design Evaluation of the Next Generation Space Protocol Architectures

This section critically evaluates the seven next generation space protocol architectures surveyed in this paper. These protocol architectures are evaluated in terms of the approaches and solution they provide to tackle each design challenge addressed by our framework. The previously given design challenges can be categorized according to their corresponding layers. The space protocol design challenges categorization is shown in Fig.14.

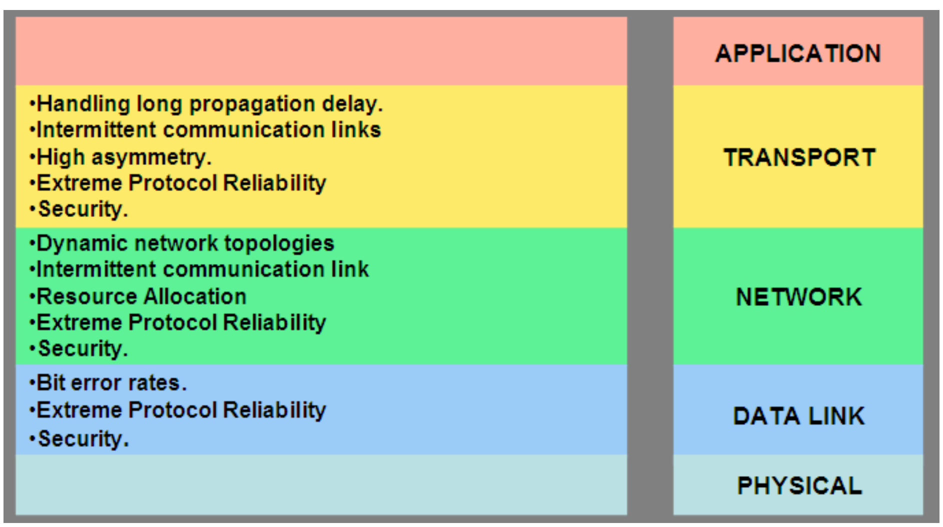

Fig.14: The layered categorization of the space network protocols design challenges.

Based on the space communication architecture classification, the design evaluation conducted in this section will break these seven SPAs into two classes two-segment and three-segment SPAs.

5.1 Design evaluation of the next generation two-segment SPAs

The two-segment class consists of four architectures: OMNI-based, GPM IP-based, and CANDOS. The scope of the design challenges identified in this paper covers the ground and space segments.

5.1.1 The OMNI-Based Protocol Architecture

1. Data Link Layer

A. Handling bit error rates (BER)

This layer supports IEEE-1394 and Ethernet for ground and on-board links, HDLC for RF links, and HDLC over ATM and SONET high rate links. It is given that HDLC framing provides link layer quality close to terrestrial networks, and hence this layer provides a mature solution to this challenge.

B. Extreme protocol reliability

This layer supports reliability at both segments through the error detection and correction procedures along with frame retransmission supported by IEEE-1394, Ethernet, HDLC, and HDLC over SONET.

C. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the OMNI research group.

2. Network Layer

A. Dynamic network topologies

The network topology at the ground segment is static, and hence deterministic. On the other hand, it was previously shown that the space network assets at the space segment consist of all spacecrafts within the geostationary range. The network topological changes are tracked by the OMNI missions operations centers (MOCs), hence the entire network topology is deterministic. Therefore this design challenge is mitigated through the static nature of the OMNI communication architecture.

B. Link intermittency

Based on the fact that network entire network topology is both deterministic and tractable. Link intermittency is handled using the static approach, where the link states of all links are deterministic. However, this layer does not specify the any procedures for handling link intermittency. Therefore this design challenge remains as an open question to the OMNI research team.

C. Resource allocation

This layer does not specify any procedures for network resource allocation. However, the resource allocation procedures might be implied in the layer protocols. Therefore, this design challenge remains as an open question to the OMNI research team.

D. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols it supports. Therefore this design challenge remains as an open question to the OMNI research team.

E. Security

This layer supports security through IPSec protocol suite that provides authentication and packet encryption services. Therefore, this layer provides a mature solution to this challenge.

3. Transport Layer

A. Dynamic network topologies

The network topology at the ground segment is static, and hence deterministic. On the other hand, it was previously shown that the space network assets at the space segment consist of all spacecrafts within the geostationary range. The network topological changes are tracked by the OMNI missions operations centers (MOCs), hence the entire network topology is deterministic. Therefore this design challenge is mitigated through the static nature of the OMNI communication architecture.

B. Link intermittency

Based on the fact that network entire network topology is both deterministic and tractable. Link intermittency is handled using the static approach, where the link states of all links are deterministic. However, this layer does not specify the any data transport procedures for handling link intermittency. Therefore this design challenge remains as an open question to the OMNI research team.

C. Resource allocation

This layer does not specify any procedures for network resource allocation such as admission control procedures. However, the resource allocation procedures might be implied in the layer protocols. Therefore, this design challenge remains as an open question to the OMNI research team.

D. Handling link asymmetry

This does not consider any approached to link asymmetry despite of its importance in future applications were both of up and down streams would be nearly equal. Therefore, this design challenge remains as an open question to the OMNI research team.

E. Extreme protocol reliability

This layer supports reliable data transport through TCP by means of acknowledged packet transmission, packet retransmission, and congestion control. The reliability provided by this layer suffices the scale of OMNI communication architecture.

F. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the OMNI research group.

5.1.2 GPM IP-based SPA

1. Data Link Layer

A. Handling bit error rates (BER)

This layer supports IEEE-1394 and Ethernet for ground and on-board links, HDLC for RF links, and HDLC over ATM and SONET high rate links. It is given that HDLC framing provides link layer quality close to terrestrial networks, and hence this layer provides a mature solution to this challenge.

B. Extreme protocol reliability

This layer supports reliability at both segments through the error detection and correction procedures along with frame retransmission supported by IEEE-1394, Ethernet, HDLC, and HDLC over SONET.

C. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the OMNI research group.

2. Network Layer

A. Dynamic network topologies

The network topology at the ground segment is static, and hence deterministic. On the other hand, it was previously shown that the space network assets at the space segment consist of all spacecrafts within the geostationary range. The network topological changes are tracked by the GPM missions operations centers (MOCs), hence the entire network topology is deterministic. Therefore this design challenge is mitigated through the static nature of the GPM communication architecture.

B. Link intermittency

Based on the fact that network entire network topology is both deterministic and tractable. Link intermittency is handled using the static approach, where the link states of all links are deterministic. However, this layer does not specify the any procedures for handling link intermittency. Therefore this design challenge remains as an open question to the GPM research team.

C. Resource allocation

This layer does not specify any procedures for network resource allocation. However, the resource allocation procedures might be implied in the layer protocols. Therefore, this design challenge remains as an open question to the GPM research team.

D. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols it supports. Therefore this design challenge remains as an open question to the GPM research team.

E. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the OMNI research group.

3. Transport Layer

A. Dynamic network topologies

The network topology at the ground segment is static, and hence deterministic. On the other hand, it was previously shown that the space network assets at the space segment consist of all spacecrafts within the geostationary range. The network topological changes are tracked by the GPM missions operations centers (MOCs), hence the entire network topology is deterministic. Therefore this design challenge is mitigated through the static nature of the GPM communication architecture.

B. Link intermittency

Based on the fact that network entire network topology is both deterministic and tractable. Link intermittency is handled using the static approach, where the link states of all links are deterministic. However, this layer does not specify the any data transport procedures for handling link intermittency. Therefore this design challenge remains as an open question to the GPM research group.

C. Resource allocation

This layer does not specify any procedures for network resource allocation such as admission control procedures. However, the resource allocation procedures might be implied in the layer protocols. Therefore, this design challenge remains as an open question to the GPM research group.

D. Handling link asymmetry

This does not consider any approached to link asymmetry despite of its importance in future applications were both of up and down streams would be nearly equal. Therefore, this design challenge remains as an open question to the GPM research group.

E. Extreme protocol reliability

This layer supports reliable data transport through TCP by means of acknowledged packet transmission, packet retransmission, and congestion control. The reliability provided by this layer suffices the scale of GPM communication architecture.

F. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the GPM research group.

5.1.3 The CANDOS Protocol Architecture

1. Data Link Layer

A. Handling high bit error rates (BER)

This layer supports IEEE-1394 and Ethernet for ground and on-board links, HDLC for RF links, and HDLC over ATM and SONET high rate links. It is given that HDLC framing provides link layer quality close to terrestrial networks, and hence this layer provides a mature solution to this challenge.

B. Extreme protocol reliability

This layer supports reliability at both segments through the error detection and correction procedures along with frame retransmission supported by IEEE-1394, Ethernet, HDLC, and HDLC over SONET.

C. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the CANDOS research group.

2. Network Layer

A. Dynamic network topologies

The network topology at the ground segment is static, and hence deterministic. On the other hand, it was previously shown that the space network assets at the space segment consist of all spacecrafts within the geostationary range. The network topological changes are tracked by the OMNI missions operations centers (MOCs), hence the entire network topology is deterministic. Therefore this design challenge is mitigated through the static nature of the CANDOS communication architecture.

B. Link intermittency

Based on the fact that network entire network topology is both deterministic and tractable. Link intermittency is handled using the static approach, where the link states of all links are deterministic. However, this layer does not specify the any procedures for handling link intermittency. Therefore this design challenge remains as an open question to the CANDOS research team.

C. Resource allocation

This layer does not specify any procedures for network resource allocation. However, the resource allocation procedures might be implied in the layer protocols. Therefore, this design challenge remains as an open question to the CANDOS research team.

D. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols it supports. Therefore this design challenge remains as an open question to the CANDOS research team.

E. Security

This layer supports security through IPSec protocol suite that provides authentication and packet encryption services. Therefore, this layer provides a mature solution to this challenge.

3. Transport Layer

A. Dynamic network topologies

The network topology at the ground segment is static, and hence deterministic. On the other hand, it was previously shown that the space network assets at the space segment consist of all spacecrafts within the geostationary range. The network topological changes are tracked by the CANDOS missions operations centers (MOCs), hence the entire network topology is deterministic. Therefore this design challenge is mitigated through the static nature of the CANDOS communication architecture.

B. Link intermittency

Based on the fact that network entire network topology is both deterministic and tractable. Link intermittency is handled using the static approach, where the link states of all links are deterministic. However, this layer does not specify the any data transport procedures for handling link intermittency. Therefore this design challenge remains as an open question to the CANDOS research group.

C. Resource allocation

This layer does not specify any procedures for network resource allocation such as admission control procedures. However, the resource allocation procedures might be implied in the layer protocols. Therefore, this design challenge remains as an open question to the CANDOS research group.

D. Handling link asymmetry

This does not consider any approached to link asymmetry despite of its importance in future applications were both of up and down streams would be nearly equal. Therefore, this design challenge remains as an open question to the CANDOS research group.

E. Extreme protocol reliability

This layer supports reliable data transport through TCP by means of acknowledged packet transmission, packet retransmission, and congestion control. The reliability provided by this layer suffices the scale of CANDOS communication architecture.

F. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the CANDOS research group.

5.2 Design evaluation of the next generation three-segment SPAs

The two-segment class consists of four architectures: OMNI-based, GPM IP-based, and CANDOS. The scope of the design challenges identified in this paper covers the ground and space segments.

5.2.1 NASA Enterprise SPA

This network architecture is composed of four network architectural elements:

1. **The backbone network architecture**: which consists of the space network (SN), the ground network (GN), and Deep Space Networks (DSN).
2. **Access networks network architecture**: that provides connectivity among space backbone networks, mission spacecrafts, and local area network (LAN's) on-board spacecrafts of vehicles.
3. **Inter-spacecraft network architecture**: that provides connectivity between spacecrafts flying in a constellation, formation, or cluster.
4. **Proximity network architecture**: that uses both radio and optical communication links to interface between vehicles, landers, and sensor ad hoc network.

The proceeding design evaluation considers the four architectural elements jointly for the data link, network, and transport layers.

1. Data Link Layer

A. Handling high bit error rates (BER)

It was given that HDLC for the space link at the backbone, access, inter-spacecraft and proximity networks architectures. The BER of HDLC is approximately 10^{-6}, which is close to the BER of terrestrial networks.

B. Extreme protocol reliability

This layer supports reliability through the error detection and correction procedures along with frame retransmission mechanisms supported by its protocols suite. Protocol reliability is achieved through error detection and frame retransmission mechanisms supported by IEEE-1394, Ethernet, HDLC, ATM and SONET protocols at the four network architectures.

C. Security

This layer does not support security at this level. Therefore, this design challenge would remain a recommendation to the CANDOS research group.

2. Network Layer

A. Dynamic network topologies

This design challenge directly corresponds to the inter-spacecraft networks ISNs at the space and deep space segments, since the rest of the network architectures are based on static topologies. ISNs can be found in three organizations: formations, clusters and ad hoc formations. Spacecrafts within a formation communicate and coordinate among each other. Spacecraft formations are directly coordinated by MOCs at the earth segment. This topological organization enables MOCs at the earth segment to track the changes of the entire network topology, which spans the three segments.
However, this SPA does not specify any addressing schemes and routing algorithms to handle communication between formations and between formations and earth ground stations.
In addition, this protocol architecture does not consider the issue related to handling long propagation delays due to the long distances among spacecrafts formations. Therefore these issues would remain an open question to the NASA enterprise SPA research group.

B. Link intermittency

Similar to the previous design challenge, this issue is also related to ISN protocol architecture. The network topologies at the backbone, access and proximity architectures are tractable and thus deterministic. MOCs at the earth segment can determine the space-link state at any time instance. Therefore, static mechanisms for handling link intermittency would be applicable at there architectures. However, this does not apply at the ISN architecture due to frequent state alternations of space links and lack of dynamic mechanisms for handling link intermittency. It has to be noted this protocol architecture does not describe or even specify mechanisms for handling link intermittency at any of the four network architecture. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

C. Resource allocation

None of the four network architectures address this design challenge. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

D. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols it supports. It was shown that backbone and access network architectures employ both IPv4 and IPv6. On the other hand, no protocols are specified for ISN and proximity networks architectures. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

E. Security

This layer supports security through IPSec protocol suite that provides authentication and packet encryption services at the backbone and access network architectures. Moreover, the on-board spacecraft network also applies IPSec for security purposes. However, no security protocols or procedures are specified for ISN and proximity architectures. Therefore, this layer provides a mature solution to this challenge.

3. Transport Layer

A. Dynamic network topologies

This design challenge directly corresponds to the inter-spacecraft networks ISNs at the space and deep space segments, since the rest of the network architectures are based on static topologies. ISNs can be found in three organizations: formations, clusters and ad hoc formations. Spacecrafts within a formation communicate and coordinate among each other. Spacecraft formations are directly coordinated by MOCs at the earth segment. This topological organization enables MOCs at the earth segment to track the changes of the entire network topology, which spans the three segments.
However, this SPA does not specify any addressing schemes and routing algorithms to handle communication between formations and between formations and earth ground stations.
In addition, this protocol architecture does not consider the issue related to handling long propagation delays due to the long distances among spacecrafts formations. Therefore these issues would remain an open question to the NASA enterprise SPA research group.

B. Link intermittency

Similar to the previous design challenge, this issue is also related to ISN protocol architecture. The network topologies at the backbone, access and proximity architectures are tractable and thus deterministic. MOCs at the earth segment can determine the space-link state at any time instance. Therefore, static mechanisms for handling link intermittency would be applicable at there architectures. However, this does not apply at the ISN architecture due to frequent state alternations of space links and lack of dynamic mechanisms for handling link intermittency. It has to be noted this protocol architecture does not describe or even specify mechanisms for handling link intermittency at any of the four network architecture. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

C. Resource allocation

This layer does not specify any procedures for network resource allocation such as admission control procedures beyond the ones used by TCP and UDP at the backbone and access networks architectures. However, no such resource allocations mechanisms are described for ISN and proximity networks architectures. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

D. Handling link asymmetry

This layer does not exploit this design challenge at any of the four networks architectures. However, this issue would be very crucial for future applications where both of up and down streams would be nearly equal. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

E. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols it supports. It was shown that ground network parts of the backbone and access networks architectures employ both TCP and UDP. On the other hand, no protocols are specified for ISN and proximity networks architectures. Therefore this design challenge would remain an open question to NASA enterprise SPA research group

F. Security

This layer does not support security at this level. Therefore this design challenge would remain an open question to NASA enterprise SPA research group.

5.2.2 CCSDS-based SPA Design Evaluation

1. Data Link Layer

A. Handling high bit error rates (BER)

This layer employs HDLC for the space link at both space and deep space segments. It was given that BER of HDLC is approximately 10^{-6}, which is close to the BER of terrestrial networks.

B. Extreme protocol reliability

This layer supports reliability through the error detection and correction procedures along with frame retransmission mechanisms supported by its protocols suite. Protocol reliability is achieved through error detection and frame retransmission mechanisms supported by Ethernet, HDLC, Proximity-Data Link, TM, TC, AOS, ATM, and SONET.

C. Security

Security services are provided by the Proximity-1 Data Link protocol, which implements the end-to-end data protection primitives that include authentication and data encryption. Therefore the CCSDS-based SPA provides a satisfactory solution to this deign challenge.

2. Network Layer

A. Dynamic network topologies

It was shown that the network topology at the earth segment is deterministic; hence IPv4 and 6 would be suitable for handling network topological dynamics. On the other hand, the situation completely differs at the space and deep space segments, where the network topology is dynamic. Similarly to the NASA enterprise ISN architectures, CCSDS organizes these networks into formations and constellations. CCSDS has proposed two protocols to operate in these two segments: SPP and SCPS-NP. SCPS-NP is proposed to handle spacecraft communication in formation and constellation. Moreover, the functional specifications of SCPS-NP address the dynamicity of the network topology at the space and deep space segments. Therefore, it can be inferred that this design challenge is under research and development.

B. Link intermittency

It was shown that the network topology at the earth segment is deterministic; hence static link intermittency handling mechanisms would be suitable for handling network topological dynamics. On the other hand, the situation completely differs at the space and deep space segments, where the network topology is dynamic. Similarly to the NASA enterprise ISN architectures, CCSDS organizes these networks into formations and constellations. CCSDS has proposed two protocols to operate in these two segments: SPP and SCPS-NP. SCPS-NP is proposed to handle spacecraft communication in formation and constellation. Moreover, the functional specifications of SCPS-NP address the link intermittency at the space and deep space segments. However, SCPS-NP does not precisely specify mechanisms for handling link intermittency. Therefore, it can be inferred that this design challenge is under research and development.

C. Resource allocation

This layer does not address the issues related to resources allocation, which includes network resource allocation and management. Therefore this design challenge would remain an open question to the SCPS research group.

D. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols. It was given that CCSDS employs IPv4 and 6 at the earth segment, where the issue of reliability is less crucial. On the other hand, this is issue is crucial at the space and deep space segments due to the significant expense and limitedness of network resources. However, the functional specifications of SPP and SCPS-NP does not address this deign challenge. Therefore this design challenge would remain an open question to SCPS research group.

E. Security

This layer supports security through IPSec protocol suite that provides authentication and packet encryption services at the earth segment. For the space and deep space segments, CCSDS has proposed SCPS-SP which operates between the network and transport layer. SCPS-SP provides standard security services that include: authentication, integrity, access control and confidentiality. Based on functional specifications of SCPS-SP, this layer provides a satisfactory level of security. Finally, SCPS-SP is currently under development by space agency contractors such as MITRE.

3. Transport Layer

A. Dynamic network topologies

It was shown that the network topology at the earth segment is deterministic; hence TCP and UDP would be suitable for handling network topological dynamics. On the other hand, the situation completely differs at the space and deep space segments, where the network topology is dynamic. Similarly to the NASA enterprise ISN architectures, CCSDS organizes these networks into formations and constellations. CCSDS has proposed a transport protocol called SCPS-TP to operate in these two segments. SCPS-TP is proposed to handle spacecraft data transport in formation and constellation. However, the functional specifications of SCPS-TP do not address the dynamicity of the network topology at the space and deep space segments. Therefore, this design challenge remains an open question to the SCPS research group.

B. Link intermittency

It was shown that the network topology at the earth segment is deterministic, where link intermittency is deterministic; hence TCP and UDP would be suitable. On the other hand, the situation completely differs at the space and deep space segments, where the network topology is dynamic. Similarly to the NASA enterprise ISN architectures, CCSDS organizes these networks into formations and constellations. CCSDS has proposed a transport protocol called SCPS-TP to operate in these two segments. SCPS-TP is proposed to handle spacecraft data transport in formation and constellation. However, the functional specifications of SCPS-TP do not address the link intermittency of space link at the space and deep space segments. Therefore, this design challenge remains an open question to the SCPS research group.

C. Resource allocation

This layer does not address the issues related to resources allocation, which includes network resource allocation and management. Therefore this design challenge would remain an open question to the SCPS research group.

D. Handling link asymmetry

This design challenge is not addressed by this SPA. Therefore, this issue would remain an open question to the NASA enterprise SPA research group.

E. Extreme protocol reliability

This layer does not provide any specialized reliability features beyond the reliability supported by the standard protocols it supports. It was shown that ground network parts of the backbone and access networks architectures employ both TCP and UDP. On the other hand, no protocols are specified for ISN and proximity networks architectures. Therefore this design challenge would remain an open question to NASA enterprise SPA research group.

F. Security

This layer does not support security at this level. Therefore this design challenge would remain an open question to NASA enterprise SPA research group.

5.2.3 Hi-DSN-based SPA Design Evaluation

1. Data Link Layer

A. Handling high bit error rates (BER)

Hi-DSN data link layer emphasizes on mitigating signal interference by signal separation provided by spatial and time multiplexing. This in place reduces the bit error rate (BER) and increases the reliability of space link. Moreover, Hi-DSN data link layer provides solutions for maintaining the quality of the cross link as a function BER.

B. Extreme protocol reliability

This layer supports reliability through the error detection and correction procedures along with frame retransmission mechanisms supported by its protocols suite. Protocol reliability is achieved through error detection and frame retransmission mechanisms supported by the TCeMA.

C. Security

This design challenge is not addressed by this SPA. Therefore, this issue would remain an open question to the Hi-DSN research group.

2. Network Layer

A. Dynamic network topologies

It was shown that the network topology at the earth segment is deterministic; hence IPv4 and 6 would be suitable for handling network topological dynamics. On the other hand, the situation completely differs at the space and deep space segments, where the network topology is dynamic. Similarly to the to both NASA enterprise ISN and CCSDS architectures, this SPA organizes these networks into formations and constellations. BBN proposed a sub-network layer, which provides more specialized services to include neighbor discovery, network synchronization and terminal affiliation. BBN has proposed five related protocols to serve this purpose. The services provided by these five protocols have the strong potential to address this design challenge. Therefore, it can be concluded that BBN provides a mature solution to this design challenge.

B. Link intermittency

It was shown that the network topology at the earth segment is deterministic; hence IPv4 and 6 would be suitable for handling network topological dynamics. On the other hand, the situation completely differs at the space and deep space segments, where the network topology is dynamic. Similarly to the to both NASA enterprise ISN and CCSDS architectures, this SPA organizes these networks into formations and constellations. BBN proposed a sub-network layer, which provides more specialized services to include neighbor discovery, network synchronization and terminal affiliation. BBN has proposed five related protocols to serve this purpose. The services provided by these five protocols have the strong potential to address this design challenge. Therefore, it can be concluded that BBN provides a mature solution to this design challenge.

C. Resource allocation

This layer does not address the issue related to resources allocation at this layer, which includes network resource allocation and management. Therefore this design challenge would remain an open question to the BBN research group.

D. Extreme protocol reliability

The issue of extreme reliability

E. Security

This layer supports security through IPSec protocol suite that provides authentication and packet encryption services at the earth segment. For the space and deep space segments, CCSDS has proposed SCPS-SP which operates between the network and transport layer. SCPS-SP provides standard security services that include: authentication, integrity, access control and confidentiality. Based on functional specifications of SCPS-SP, this layer provides a satisfactory level of security. Finally, SCPS-SP is currently under development by space agency contractors such as MITRE.

1. Transport Layer

The Hi-DSN system does not specify a clear separate transport layer. However, it supports some of the transport layer services through the Hi-DSN network layer described in the previous section. According to the transport layer context, Hi-DSN system addresses the design challenge related to inter-spacecraft connectivity. Since the Hi-DSN system provides connectivity under a wide range of propagation delays and relative velocity. For a spacecraft in low-altitude orbits, the infer-spacecraft distances may range from 1 meter to 100,000 kilometer [26] and that requires connectivity and aggregate throughput maximization that ranges between 100 Kbps to 1 Gbps. On the other hand, this layer does not address the security and resource allocation issues, despite of thier sensitivity in space. Finally, on basis of Hi-DSN transport layer serviced, it can be concluded that Hi-DSN partially addresses the transportation layer design challenges.

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Design Challenge/Protocol Architecture	OSI-Based	CCSDS-based	GPM IP-based	Hi-DSN	NASA Enterprise	CANDOS	SpaceVPN
Handling high bit error rates							
Convolutional FEC		☑			☑	☑	
Reed-and-Solomon FEC	☑		☑		☑	☑	
Spatial Multiplexing				☑			☑
Time Multiplexing				☑			☑
Multi-orthogonal Code Multiplexing				☑			☑
Dynamic network topologies							
Addressing							
Routing Information Dissemination	☑		☑	☑		☑	☑
Routing in Space Networks	☑		☑	☑		☑	☑
Routing Quality of Service (QoS)							
Link Intermittency							
Support for Link Availability dissemination	☑		☑	☑		☑	☑
Optimal End-to-End Shortest Route Computation							
Optimal Flow Control							
Handling long propagation delay							
Existence of Backbone Space Network				☑	☑	☑	☑
Hierarchical Network Topological Structuring (constellation formation, cluster).				☑	☑	☑	☑
Resource Allocation							
Burst Scheduling.				☑			
Congestion Control.						☑	☑
Packet Scheduling.						☑	☑
High link asymmetry							

Security						
Application Firewalls.	☑ (Earth)	☑ (Earth)	☑ (Earth)	☑ (Earth)	☑ (Earth)	☑ (Earth)
Physical Layer Data Encryption.		☑ (Space/Deep)				
Data Link Layer Data Encryption.		☑ (Space/Deep)				
Network Layer Data Encryption.	☑ (Earth)	☑ (Space/Deep)	☑ (Earth)	☑ (Earth)	☑ (Earth)	
Virtual Private Networks VPN.	☑ (Earth)		☑ (Earth)	☑ (Earth)	☑ (Earth)	☑ (Earth)
Extreme Protocol Reliability						
Fault Tolerance.						
Self-Stabilization.						
Existence of Backup systems	☑	☑				
Command in the blind	☑	☑				

Table 9: Design evaluation summary of the next generation space network protocol architectures.

5. Conclusion and Future Work

This paper provided an in-depth critical design evaluation for the state-of-art next generation space protocol architectures. We first surveyed the design of the state-of-art next generation SNPAs proposed by [RHC 05] [HCp 05] [Bergamo 05] [BCDFHSW 02] [BH 02]. Second, we defined the five-tier space network infrastructure as future infrastructure on which next generation SNPAs will operate. Third, the defined space network infrastructure we defined, we identified eight major design challenges imposed by the design of the next generation SNPAs. This framework has categorized these design challenges according to their OSI reference model. Further, these design challenges are categorized according to the data link, network, and transport layers. Fourth, we critically evaluated the design of five leading protocols architectures [RHC 05] [HCp 05] [Bergamo 05] [BCDFHSW 02] [BH 02] through the design evaluation we defined.

Based on the critical evaluation conducted we arrived to two main observations. First, the design OMNI, IP-based and CCSDS-based SNPAs are mature at the data link layers and are still under research at the network and data link layers. However, the CCSDS has a mature security design at the data link layer level. Second, the data link layer design of the Hi-DSN and NASA enterprise SNPAs is mature, while the design of their network and transport layers are in the development. Although the previous space protocol architectures [RHC 05] [HCp 05] [Bergamo 05] [BCDFHSW 02] [BH 02] provided extensive description for the services and design issues of their underlying architectures, surprisingly none of them clearly addressed the crucial issues related to both of the network transport layers by means of space addressing, routing, and reliable end-to-end transport protocols.

Never the less, the network layer forms the central component in a protocol architecture on which the upper and lower protocol layers are based. Therefore, efficient space protocol architecture must provide protocols and mechanisms that implement space addressing and predictable mobile routing in dynamic space network topologies. Besides the network layer, space protocol architectures are also required to provide end-to-end transport protocols that enable reliable and real-time data delivery in space environments where extremely long propagation delays do exist. Hence, network and transport layer design issues are still considered unfulfilled space protocol design challenges.

Our future perspectives are focused on providing efficient space protocol architecture design that entirely addresses the design challenges identified by our design evaluation framework. Our future space protocol architecture will emphasize on providing a robust space network protocol layer that leverages the design challenges of the space network layer. This protocol architecture aims to provide novel schemes for space predictive mobile space routing depicted from the routing algorithms proposed in [MSAMZE 04] [SLG 01] [LDS 04].

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