A Reference Framework for Emergent Space Communication Architectures oriented on Galactic Geography

Javed I. Khan & Omar Y. Tahboub
Media Communications and Networking Research Laboratory
Kent State University
44242-0001
javed|otahboub@kent.edu

Abstract

An exuberant space age is emergent, which is likely to see many compact yet innovative explorations much beyond imagined in the past requiring a reusable and sharable space communication infrastructure. Currently proposed space communication architectures mainly suffer from three design drawbacks high cost, narrowed scale and lack of concise geographical organization. Therefore, there has been a renewed interest for developing a new generation of architectures addressing these design drawbacks. Recently, a set of architectures have been proposed by NASA, JPL, CCSDS and BBN contributing towards the architectural design of the next generation space networks. However, it is not pretty simple proposals to determine there completeness, cost-efficiency and their capability to address varied communication and challenges of space environments. In this paper we backward one step, we describe a holistic framework for space communication. We identify the major constraints of space environment imposed by the galactic geography. We also outline a sufficiently complete design space of the plausible range of communication modalities this age of space communication might require. These requirements are based on the path and link concurrency and non concurrency based classification including edge and core mobility, link intermittency, and schedulability. Moreover, we survey three leading architectures namely OMNI, CCSDS and SpaceVPN. We show their extent of completeness, strengths, weaknesses, and what communication modalities they support and what they do not. In was shown that OMNI architecture will have the potential to serve near space mission missions, while SpaceVPN will be the architecture of next space age serving large scale deep space missions.

I. Introduction

THE world is witnessing a renewed invigoration in space exploration. Not only many nations but also many commercial initiatives are entering into space exploration. An exuberant space age is emergent which is likely to see many compact yet innovative explorations much beyond imagined in the past requiring a reusable and sharable space communication infrastructure. However, this infrastructure needs to be nimble, cost efficient, and has to accommodate multiple parties and mission of varied sizes and kinds- unlike the space exploration of the past- dominated by mission centric and communication architectures used mostly by larger research establishments.

To date the proposed architectures for space communication suffer from three design drawbacks: high cost, narrowed scale and lack of concise geographical organization. Major space communication agencies and research labs have undergone design exploration for a new generation of space communication architectures. Seven newly proposed communication architectures along with space internet protocols have been proposed by NASA, JPL, CCSDS and BBN[1] These proposals made significant contributions towards characterizing architectural design of next the generation space networks, yet is not easy to see if those are complete, if insufficient- then where exactly are the deficiencies, if these are cost efficient or at all usable in the face of varied communication constraints and challenges of space.

In this paper we take a step back. We delineate a holistic framework for space communication. We frame the major constraints of space environment imposed by hierarchical structure of space- that we call it galactic geography. It seems a sufficient space communication framework can be defined by three zones types and their recursive enumerations. We also attempt at outlining a sufficiently complete design space of the plausible range of communication modalities this exuberant space age era of space communication might require, based on the path and link concurrency and non concurrency based classification- which includes edge & core mobility, link intermittency, and schedulability.

We then provide a survey of leading architectures- namely OMNI[2,3] , CCSDS[4] and SpaceVPN[7] based on this reference framework. In particular we show their extent of completeness, strengths, weaknesses, and what communication modalities they support and what they don't.

The rest of the paper is organized as follows, section II describes the reference framework, section III surveys the three space architectures, section VI provides the evaluation discussion of the architectures and section V concludes the paper.

II. A Reference Framework for Emergent Space Communication Architectures

We propose a reference framework for future emergent space communication architectures oriented on galactic geography.

A. Three-Zone Space Architecture Geography

This framework breaks the geography of space communication architectures into three galactic zones. The earth zone represents the all terrestrial network assets deployed for space communication purposes. Typically, the earth zone represents the terrestrial segment of the overall communication architecture. This zone mainly consists of high-speed network backbone that links the network assets deployed on earth to each other. As shown in Figure.1, users such as researchers gain access to various explorations deployed in space through secured internet connections to a number of MOCs. Space agencies, MOCs are further links to ground station and white sands via high speed VPNs.

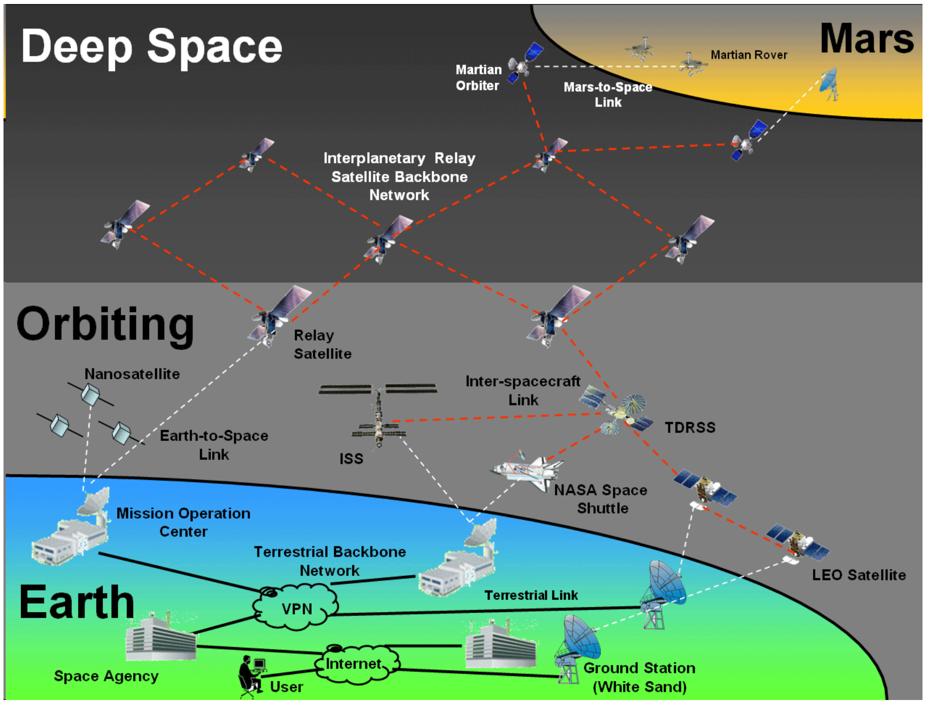

Figure.1: Three-zone galactic framework for space communication architectures

The orbiting zone forms the planetary spatial vicinity in which various spacecrafts orbit. This zone consists of various spacecrafts formations deployed different altitudes including low, medium and geostationary. As shown in the figure below, spacecrafts consists of LEO, MEO, GEO, Nanosatellites, space shuttles and International Space Station (ISS).

The deep space zone forms the interplanetary backbone network infrastructure that will enable interplanetary communication. This zone consists of multiple relay satellite formations and provides long hull interplanetary network infrastructure that will service the entire solar system. As shown, backbone relay satellite network interconnects between the orbital vicinities of earth and Mars.

his galactic geography is further broken into five-zonal hops described as shown in Figure 2. The home colony zonal hop represents the earth zone. The home orbital zonal hop represents the earth orbital vicinity. The space backbone zonal hop the represents interplanetary relay satellite networks. Similar to the home zonal hop, foreign orbital zonal hop also represents the orbiting range of spacecrafts deployed at different

planets like Mars. The foreign colony zonal hop is the network deployed at the surface of planet other than the earth. One feature distinguishes this zonal hop from its earth counterpart is the type of network assets deployed there, which include scientific equipments, rovers, and in-situ sensors**.**
From the three zone galactic framework, we outline three usage scenarios described as follows:

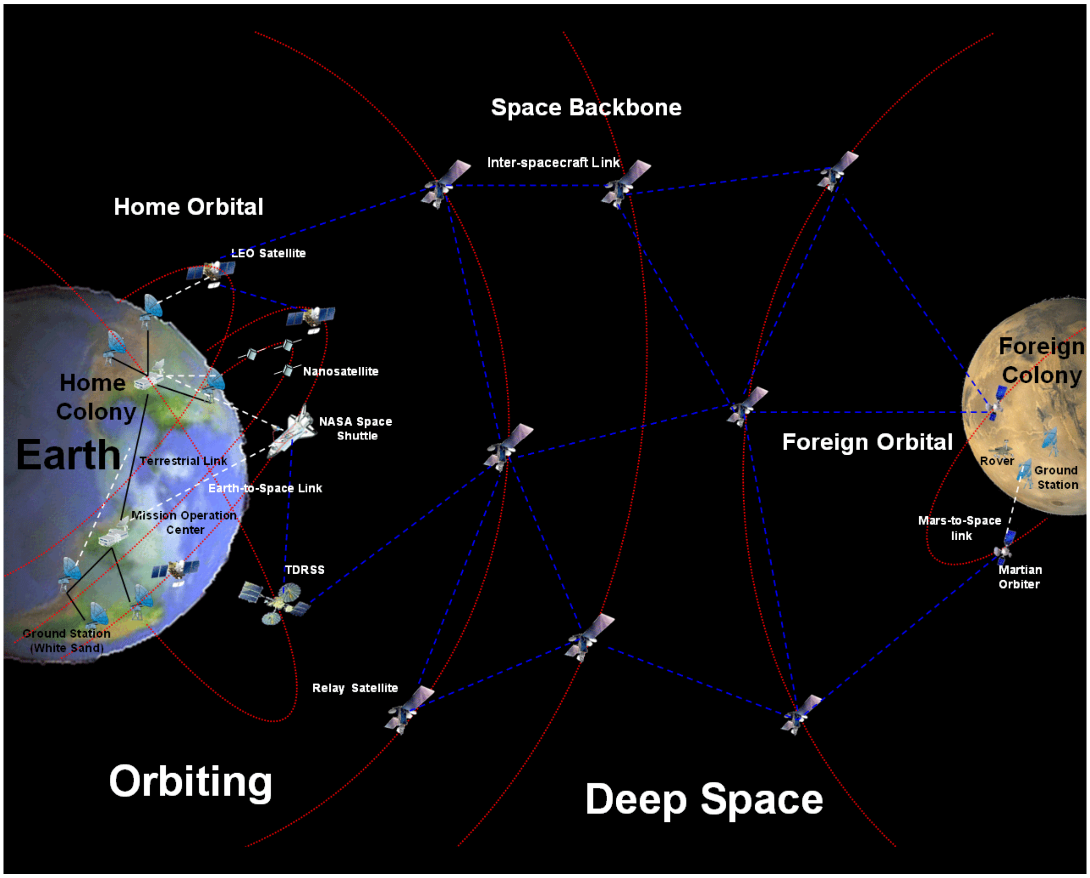

Figure 2: The five zonal hops if of the space communication architecture

1) **Remote Nanosatellite access:** This scenario involves only three zonal hops. At the earth zone, end-users like researchers and scientist can gain remote access to a scientific experiment being conducted onboard a Nanosatellite deployed in the earth orbital zone. End-users connect to a MOC via secured Internet connection, who is further connected to a number of ground stations through secured high-speed communication backbone. At the earth orbiting zone, the Nanosatellite formation is deployed and is linked to a number of ground stations deployed in the earth zone. The on-board system inside the each Nanosatellite forms the foreign colony. In this scenario, communication between end-users and Nanosatellite traverses three zonal hops: home colony, home orbital and foreign colony and visa versa.

2) **Mars observation**: This scenario also involves four zonal hops. At the earth zone researches and investigator at the different MOCs access Mars observing satellites deployed at the foreign orbital. As shown in Figure 1, MOCs are connected to ground stations via secured high-speed terrestrial network backbone linked to relay satellites deployed in the home orbital. At the earth orbital, the relay satellites deployed at the geostationary are linked to the interplanetary relay satellite formation at the space backbone zonal hop. At the space backbone zonal, relay satellite formation provide access to the orbiters deployed in the Martial (foreign) orbiting zonal hops. At the foreign zonal hop, orbiters collect

imagery of the Martian surface. Therefore the communication between MOCs and Martian orbiters passes through four zonal hops: home colony, home orbital, space backbone and foreign orbital.

3) **Martial sacrificial robot access:** Assume that the rover deployed at Martian surface collecting imagery data. Scientists at MOC in the earth zone intend to download the telemetry data from the Martian rover. Based on the previous scenario the communication between the MOCs and Martian rover deployed will pass through five hops: home colony, home orbital, space backbone, foreign orbital and foreign colony. According to the framework, the rover is deployed in the foreign colony accessible by the Martian orbiters deployed at the foreign orbital.

B. Features

1) Resource Allocation

Generally, space missions occupy three types of resources: launch, computation and communication. Mission launching resources include MOCs, launching facilities and ground stations such as white sands. Computation resources are given in the form of data and control (software and hardware) processing systems and scientific equipments deployed either onboard spacecrafts on colony surface. In addition, communication resources include two types of resources: quantitive and qualitative. Quantitative resources represent all network hardware deployed at three galactic zones, while the qualitative resources represent the QoS link metrics such as: bandwidth, delay, load and jitter.

One distinguishable aspect of space missions is the limitedness of these resources since they are allocated to sustain their needs. This aspect is more crucial at the orbital and deep space zones due to the energy consumption constraints. Moreover, yet another crucial issue related to resources sharing and to ensure fair allocation. Therefore, the architecture should support pre-planning resource allocation ahead of missions.

2) Addressing

Addressing is the principle end-to-end communication enabler mechanisms in communication networks. This mechanism also provides the capability of uniquely identifying, locating and managing specific entities linked within a communication network. Moreover, addressing also provides the means for determining the hierarchal organization of the entities belonging to a communication network. Similarly, space networks architectures apply this mechanism to enable end-to-end communication services among its assets. Space network addressing should consider the hierarchal organization of the network assets deployed at the three galactic zones. At the earth zone, terrestrial network assets universally apply IP addressing. At the orbiting and deep space zones IP is still employed by current architectures. Space network addressing should deliver two main features: transparency and scalability. Addressing transparency hides the details of galactic organization of the space network causing it to appear as a single and yet global network. Further, addressing scalability guarantees that the address space is adequately capable of uniquely identifying every single entity deployed in the space network.

3) Mobility

Generally, two types of mobility patterns exist in conventional communication networking: static (stationary) and dynamic. Mobility feature in space communication networks further introduces a third type of mobility pattern third called *semi-mobility*. Semi-mobility behavior is an intermediate behavior between stationary and dynamic. More specifically, semi-mobility is distinguished by its predictability unlike ad hoc nature of dynamic mobility. Under semi-mobility behavior, the relative coordinates of a network entity can be given precisely as a function of time. According to the galactic geography described, three types of mobility patterns exist. At the earth zone, network entities have both stationary and dynamic mobility behavior. At the orbiting zone, network entities are dominated by semi-dynamic dynamic behavior. At the deep space zone both, both semi- and dynamic mobility exist. The three types of mobility patterns and their existence at the zonal hop is given by Table 1.

It can be noted from that mobility patterns break network entities into two categories: end-systems and intermediate systems. One main characteristic that differentiates intermediate systems from end-systems is routing. Intermediate additionally provides routing and data forwarding services unlike end-systems, who only provide data transmission and reception services. Intermediate systems at home and foreign colony zonal hops can be either stationary or dynamic, while semi-dynamic at both orbiting and backbone zonal hops. Routing in terrestrial networks follows two mainstreams: static and ad hoc. In the former routers are stationary, while in the latter routers are dynamic.

Space Network Entity Type	Home Colony	Home Orbital	Space backbone	Foreign Orbital	Foreign Colony
End-Systems	Stationary/Dynamic	Semi-Dynamic	Semi-Dynamic/Dynamic	Semi-Dynamic	Semi-Dynamic
Intermediate-Systems	Stationary	Semi-Dynamicity	Semi-Dynamic	Semi-Dynamicity	stationary

Table 1: Mobility patterns in space communication architectures

Moreover, ad hoc routing relies on performing link state distribution, neighbor discovery, and route set up periodically assuming that the relative the entire network topology would remain intact for a sufficiently long period of time. In space networks, ad hoc routing techniques are obsolete due to the constant mobility of spacecrafts and hence it can be no longer assumed that the entire topology would remain intact for a long period of time. Therefore, enabling dynamic mobility pattern at the latter zonal hops forms crucial design issue future space architecture should consider.

4) 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 zonal hop, where communication links have shorter life compared to the links setup at the home and orbiting colonies. This is due to the fact that orbiting spacecrafts are not always geosynchronous; hence would not be capable of maintaining continuous links. In other words, links are active only for a limited period of time due to the constant node mobility. One common feature home and orbiting colonies have is the high node density; hence long-lasting communication links. For instance most of terrestrial links at the home colony zonal-hop are permanent due to its static dynamicity nature. The concept of link intermittency is elaborated for a time-varying connected graph in Figure 3.

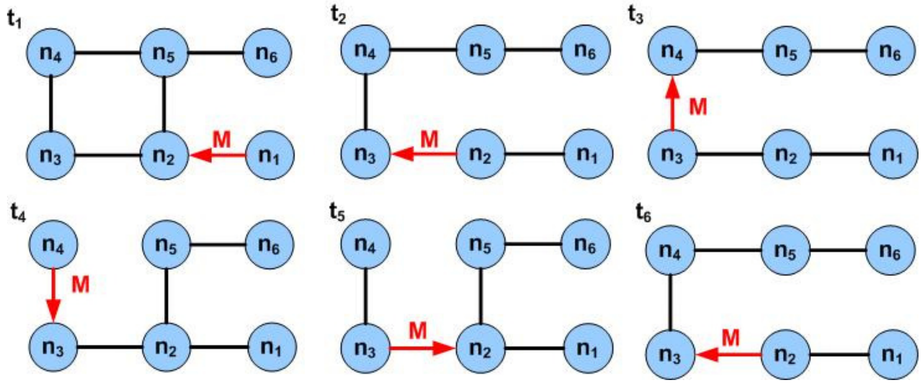

Figure 3: Link Intermittency

The entire set of edges is intact in initial graph at time t_1, n_1 intends to send a message M to n_6 through the path (n_1, n_2, n_5, n_6). At t_2, the message is received by n_2, the link (n_2, n_5) goes down, and n_2 reroutes M to n_3 through the path (n_2, n_3, n_4, n_5, n_6). At t_3, M is received by n_3 and forwarded to n_4.At t_4, M is received by n_4, the link (n_4, n_5) while the link (n_2, n_5) returns up. Therefore n_4 reroutes M to n_3 through the path (n_3, n_2, n_5, n_6). At t_5, M is received by n_3 and forwarded to n_2. At t_6, M is received by n2, the link (n_2, n_5) goes down again, and n_2 reroutes M to n_3 through the path (n_2, n_3, n_4, n_5, n_6). The links (n_2, n_5) and (n_2, n_5) will interchangeably keep going up and down keeping M to be rerouted back and forth between n_2 and n_4 causing and message trap.

Such message trapping scenarios would occur at the orbiting and deep space zone. Furthermore, the capability of such communication architecture of handling link intermittency should be demonstrated in terms of its message trapping prevention and avoidance mechanisms.

5) Extreme Protocol Reliability

Generally, the spending budgets allocated for space missions tend to be in the scale of Billions of dollars. The fact behind this aspect is attributed to high expense of spacecrafts, launching facilities, scientific equipment and personnel. Moreover, deploying a space mission at the orbiting or deep space zone would involve a series of activities that include launching a spacecraft, deploying scientific equipment deployment and commanding and controlling its operations. It universally agreed that spacecrafts are the most expensive transportation systems costing hundreds millions of dollars [REF]. The high cost space mission entities impose the demand for extremely reliable communication protocols performing the command and control activities. For instance losing a spacecraft due to miss-control be a multi-hundred million dollars fault; hence intolerable.

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.

6) Security

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.

7) Long propagation delays

This constraint is related to the capability of supporting connectivity under a wide range of propagation delays and relative velocity. By referring to the space network infrastructure shown at Fig. 1, it can be noticed that the inter-zonal hop distances (listed in Table 2) are remarkably long.

Inter-zonal hop range	Distance (Km)
Home colony - Home orbital	250-2000[9]
Home orbital - Space Backbone Network	1-2800[9]
Space Backbone Network- Foreign orbital	1-100,000[6]
Foreign orbital - Foreign colony orbital	800[8]

Table 2: The inter-zonal hops distances

For a spacecraft in low-altitude orbits, the inter-spacecraft distances may range from 1 meter to 100,000 kilometers For instance, the average distance between the Earth and the Moon is 84,399 kilometers, whereas the average distance between the Earth and Mars is approximately 200 million kilometers. These wide distances form a major impact on the space network performance. The propagation delay would become a factor impacting the choice of medium access technique. Extremely long propagation delay has two direct implications: longer response time and sharp link bandwidth degradation.

8) High link asymmetry

This feature is commonly observed through the space network assets deployed at the orbiting and deep space zones, where spacecrafts mostly have much greater downlink than uplink bandwidth. This true underlying reason behind this asymmetry is driven in part by physics, and more specifically the legacy equipments. Future space missions will enable sending (uploading) real-time multi-media data to spacecrafts deployed in the orbiting and deep space zones placing high demands for high bandwidth bi-directional space-links(this include earth to spacecraft and inter-spacecraft links).

III. Emergent Space Communication Architectures

In the early of nineties, when an emergent space exploration took place, national space industries realized the importance of standardized communication protocols that provide integrated mission access, command and control services. The **CCSDS** was among the pioneering organizations that aimed to standardize space network protocols. The CCSDS has accomplished that through providing protocol recommendations covering four categories. The first category includes telemetry, tracking, and command, and second includes information interchange processes, the third includes cross-support potations, and the fourth includes radio-metric and orbit data.

Furthermore, these recommendations are motivated to serve the growing demand for interplanetary communication for current and future space missions. 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 envisions the entire Internet on a planet as single network, and the interconnection among these disconnected planetary Internets constitutes the IPN . Therefore, the major goal of IPN is to expand the use of standard Internet protocols to serve in space and deep space missions. Since the beginning of this millennium, **Consultative Committee for Space Data Systems** CCSDS[4] 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.

The **Operating Missions as Nodes on the Internet** (OMNI)[2] architecture proposed by NASA/GSFC to provide a simple and cost-effective communication infrastructure for NASA future missions. This architecture aims to integrate terrestrial networks to space networks to enable mission operations that organize network assets as Internet nodes. Moreover, such organization facilitates access to on-board spacecraft equipments though standard remote access protocols. One design breakthrough this architecture attempted to achieve is the adoption of standard Internet technologies which in effect broadens the use of COTS hardware. Furthermore, the use of COTS technologies will play a key role in reducing the development time and costs of future space mission development.

While the OMNI project was focusing on the adoption of COTS in future space missions, NASA's attention was also focused towards high-throughput space missions in the near future. Therefore, NASA has contracted the design and development of space communication architecture to BBN technologies. This architecture is intended for supporting wide range of space missions and spacecraft configurations. This architecture is named **High Throughput Distributed Spacecraft Network Hi-DSN**[5], which integrates both space and terrestrial networks to provide infrastructure for an ad hoc space communication. Hi-DSN architecture is planned to serve the communication demands between among ground base-stations, planet rovers and low-flying probes. In addition, it will be relevant environment for integrating various space missions enabling resource sharing that include network assets and mission data.

As an extension for Hi-DSN, **SpaceVPN**[7] was proposed. SpaceVPN is intended to provide the architectural specifications for the earth zone focusing on enabling both secured real-time access to both onboard spacecraft resources. According the context of SpaceVPN, the spacecraft resources include science data, instruments and sensors.

IV. Design Evaluation

In this section, we utilize our reference framework for evaluating the design of four of the leading space communication architectures. These architectures include: OMNI (Operating Mission as Node Internet project), CCSDS (Convulsive Committee for Space Data Systems), Hi-DSN and SpaceVPN.

The evaluation criteria are based on the set of standard services provided along with set of environmental constraints addressed by each of the architectures.

A. The CCSDS Architecture

The space communication architecture of CCSDS consists of three zones: earth, orbiting and deep space. The first and the second segments are similar to the ones that belong to OMIN architecture in terms of the purpose and the contents. The deep space zone consists of "store-and-forward" relay satellites, communication, science spacecrafts (orbiters) and planetary colony networks (in-situ Internet). The services supported by the OMNI are summarized by the following listing.

1) **Resource Allocation:** This service is fully supported in the earth zone since it is based terrestrial network technologies. At the orbital and deep space zones, resource allocation can be performed statically from the earth zone. However, the CCSDS architecture does not specify the support for resource allocation at any of the zones.
2) **Addressing:** Conventional IP addressing is used at the earth zone, while SCPS-NP (CCSDS Space Communication Protocol Specification-Network Protocol) is used at the orbital and deep space zones.
3) **Mobility:** Stationary and dynamic mobility patterns are supported at the earth zone. At the orbiting and deep space zones, the architecture supports semi-dynamic mobility pattern. However, no concise recommendation determines the type of mobility pattern supported at latter galactic zones.
4) **Support for Link Intermittency:** This service is supported by at the orbiting zone statically. The deterministic nature of the topological dynamicity at the orbital zone enables the prediction of link state ahead of transmission. This would enable space network administers to determine the optimal paths under periodical link outages (intermittency).
5) **Extreme Protocol Reliability:** The context of reliability is related to the design physical layer. Extreme reliability is supported at both galactic zones. At the earth zone, all terrestrial networks demonstrate a high degree of reliability and fault tolerance. Moreover, the hardware design space link transmitters are designed with the considerations of providing maximum reliability in terms of fault tolerance, error detection and correction.
6) **Security:** This service is supported by both zones. At the earth zones users, investigators and scientists access mission command and operation centers through secured VPNs implementing the highest data encryption standards along with authentication procedures. This service is supported by the three zones. Communication links between ground stations and spacecrafts, and among spacecrafts at the orbiting and deep zones employ standardized security protocols.
7) **Handling long propagation delays:** This constraint forms a crucial challenge at the orbiting and deep space zones, and more specifically at splicing area between the home colony and home orbiting, and between foreign orbiting and foreign colony. The bandwidth link delays provided by the space links between ground stations and spacecrafts, and between spacecrafts are sustainable enough to handle the effect of long propagation delays.
8) **High Link Asymmetry**: This constraint s related to two types of links: ground-station to spacecrafts and inter-spacecraft. However, this architecture does not address this constraint in spite of its applicability.

B. The OMNI Architecture

The OMNI communication architecture consists of two segments that correspond to earth and orbiting galactic zones. The earth zone is the network backbone connecting three types of network assets: space missions and control centers, ground base-stations and users. The features supported by the OMNI are summarized by the following listing.

1) **Resource Allocation:** This service is fully supported in the earth zone, since it is based on standard terrestrial network technologies. At the orbital zone, resource allocation can be performed statically if it is preformed a head of the mission. However, the OMNI architecture does not provides the architectural specs for supporting any sort of resource allocation at any of the three zones.
2) **Addressing:** IP addressing is used at both the earth and orbiting zones. Moreover, IP addressing is used on-board spacecraft networks.
3) **Mobility:** The mobility patterns supported at the earth zone includes: stationary and dynamic. At the orbiting zone, semi-dynamic mobility patter is supported
4) **Support for Link Intermittency:** The deterministic nature of the topological dynamicity at the orbital zone enables the prediction of link state ahead of transmission. This would enable space network administers to determine the optimal paths under periodical link outages (intermittency).
5) **Extreme Protocol Reliability:** The context of reliability is related to the design physical layer. Extreme reliability is supported at both galactic zones. At the earth zone, all terrestrial networks demonstrate a high degree of reliability and fault tolerance. Moreover, the hardware design space link transmitters are designed with the considerations of providing maximum reliability in terms of fault tolerance, error detection and correction.

6) **Security:** This service is supported by the three zones. At the earth zones users, investigators and scientists access mission command and operation centers through secured VPNs implementing the highest data encryption standards along with authentication procedures. Communication links between ground stations and spacecrafts and among spacecrafts at the orbiting and deep zones employ standardized security protocols.
7) **Handling long propagation delays:** This constraint forms a crucial challenge at the orbiting zone, and more specifically at splicing area between the home colony and home orbiting, and between foreign orbiting and foreign colony. The bandwidth link delays provided by the space links between ground stations and spacecrafts, and between spacecrafts are sustainable enough to handle the effect of long propagation delays.
8) **High Link Asymmetry**: OMNI supports link asymmetry at the orbital zone, especially at the home orbital zonal hop.

C. The SpaceVPN Architecture

Similar to the CCSDS architecture, SpaceVPN is also three-zone architecture. The first zone is the earth which consists of the assets deployed on earth such as base-stations and mission operation centers. The second zone is the orbiting zone that consists of the spacecraft networks deployed within the vicinity of the Earth and the Moon. The third tier zone is the deep space network, which consists of the interplanetary relay satellites responsible of relaying command data among different planets in the solar system. The services supported by the SpaceVPN are summarized by the following listing**.**

1) **Resource Allocation:** This service is fully supported in the earth zone. At the orbital and deep space zones, resource allocation can be performed statically from the earth zone. However, the SpaceVPN architectures does not
2) **Addressing:** Conventional IP addressing is used at the earth zone. At the orbiting and deep space zone SpaceVPN also employs IP (IPSec) addressing.
3) **Mobility:** SpaceVPN supports both stationary and dynamic mobility patterns at the earth zone. Moreover, this architecture supports both semi- and dynamic mobility patterns at the orbiting and deep space zones. Surprisingly, SpaceVPN will support such dynamic mobility at the orbiting and deep space zones through the proposal of ad hoc multi-hop satellite network infrastructure to be deployed at the orbiting and deep space zones.
4) **Support for Link Intermittency:** This service is supported by at the orbiting zone statically. The deterministic nature of the topological dynamicity at the orbital zone enables the prediction of link state ahead of transmission. This would enable space network administers to determine the optimal paths under periodical link outages (intermittency).
5) **Extreme Protocol Reliability:** The context of reliability is related to the design physical layer. Extreme reliability is supported at both galactic zones. At the earth zone, all terrestrial networks demonstrate a high degree of reliability and fault tolerance. Moreover, the hardware design space link transmitters are designed with the considerations of providing maximum reliability in terms of fault tolerance, error detection and correction.
6) **Security:** SpaceVPN supports security at the earth zone. However, it does not specify security services at the orbital and the deep space zones.
7) **Handling long propagation delays:** This constraint forms a crucial challenge at the orbiting and deep space zones, and more specifically at splicing area between the home colony and home orbiting, and between foreign orbiting and foreign colony. The bandwidth link delays provided by the space links between ground stations and spacecrafts, and between spacecrafts are sustainable enough to handle the effect of long propagation delays.
8) **High Link Asymmetry**: This constraint s related to two types of links: ground-station to spacecrafts and inter-spacecraft. The design of the MAC layer provides QoS-oriented bandwidth allocation mechanisms to handle this constraint.

D. Discussion

The features supported by the three architectures are summarized by Table 10, for comparison purposes we added a hypothetical architecture namely Ideal, which supports all the features of space communication environments.

Feature	Geographic Zone	Ideal Earth	CCSDS	OMNI	SpaceVPN	Ideal Space
Resource Allocation	Earth Zone	☑	☑	☑	☑	☑
	Orbiting Zone					☑
	Deep Space Zone					☑
Addressing	Earth Zone	☑	☑	☑	☑	☑
	Orbiting Zone		☑	☑	☑	☑
	Deep Space Zone		☑		☑	☑
Mobility	Earth Zone	☑	☑	☑	☑	☑
	Orbiting Zone		☑	☑	☑	☑
	Deep Space Zone				☑	☑
Support for Link Intermittency	Earth Zone					
	Orbiting Zone				☑	☑
	Deep Space Zone				☑	☑
Extreme Protocol Reliability	Earth Zone	☑	☑	☑	☑	☑
	Orbiting Zone			☑		☑
	Deep Space Zone					☑
Security	Earth Zone	☑	☑	☑	☑	☑
	Orbiting Zone		☑	☑	☑	☑
	Deep Space Zone					☑
Handling Long Propagation Delays	Earth Zone					
	Orbiting Zone		☑	☑	☑	☑
	Deep Space Zone				☑	☑
High Link Asymmetry	Earth Zone					
	Orbiting Zone				☑	☑
	Deep Space Zone				☑	☑

Table 3: Summary of the features supported by OMNI, CCSDS and SpaceVPN architectures

From features supported by the three architectures versus the Ideal architecture, the following points are made:

1) **Galactic geography:** Architectures of future emergent space missions should provide coverage to three geographic zones. CCSDS and SpaceVPN are three-zone architectures, while OMNI is two-zone architecture.
2) **Support for link intermittency**: Future space architectures aim to provide continuous access to space missions deployed at the orbiting and deep space zones. Unlike terrestrial links space links suffer from a limited life time due to constantan mobility of spacecrafts. This environmental feature forms an obstacle front achieving this goal. Therefore, the necessity imposes the organization of network assets in space to be efficient enough to guarantee such constant access to these assets. This issue is crucial at the deep space zone where the network density of network is low unlike the orbiting zone whose network density is sufficiently enough to overcome this issue. The OMNI future missions will be tolerant with ink intermittency; because their applications will support the notion of session resumption. Moreover, CCSDS proposed the existence interplanetary backbone network that facilitates such access, but does not address link intermittency directly. The design of the SpaceVPN –more specifically Hi-DSN addresses link intermittency through the topological organization of the network assets at the orbiting and deep space zones and the design of its physical layer. However, the completeness of their mechanisms does not demonstrate message trapping prevention scenarios.
3) **Addressing**: Future space architectures should provide transparent and yet scalable addressing scheme. It is shown that the three architectures apply conventional IP addressing at the earth layer. At the orbiting zone, OMNI and SpaceVPN still apply IP addressing, while CCSDS employs a SCPS-NP-

based addressing. At the deep space zone, IP-based addressing is used by SpaceVPN, while SCPS-NP-based addressing is used by CCSDS.

4) **Mobility**: Future space architectures should support stationary, semi- and dynamic mobility patterns at the three galactic zones. More particularly, these architectures will support varied-scale missions using various spacecraft configurations demonstrating different mobility patterns. Therefore, the necessity imposes on future space routing protocols to support dynamic router mobility. Further, these routing protocols should exploit a high degree of autonomy, which efficiently delivers route QoS such as packet arrival schedulability. The OMNI architecture supports semi-dynamicity behavior at the orbiting zone, through the support of Mobile IP (MIP). SpaceVPN introduces self-configurable satellite network infrastructure that aim deliver two special features: dynamic mobility and autonomy. SpaceVPN leverages the predictability of spacecraft orbital information to efficiently establish and maintain multi-hop routes. Moreover, the autonomy is provided through the ad hoc routing capabilities that enables automated neighbor discovery.
5) **Resource Allocation:** Due to the sharable and the limitedness of the communication resources at the orbiting and deep space zones, the design of the space communication architecture should efficiently ensure fair access to the space network assets. It is shown that none of the three architectures describe an architectural design that addresses resource allocation at these two galactic zones.
6) **Extreme Protocol Reliability:** The level of reliability provided by space communication architecture should guarantee proper operation of network assets deployed at the three galactic zones under various failure models. It can be noted that the three architectures assumes such reliability at the earth zone, since it is based on terrestrial technologies that delivers a high degree of reliability. On the other hand, none of these architectures exploit this feature at neither orbiting nor deep space zones.
7) **Security:** Future communication architectures will enable multi-national missions. More specifically, space missions will be administered by different parties from different nations. Future space missions will utilize shared communication architectures imposing the need for secured access policies to these missions. Due to shared nature, space network topology and routing information may remain exposed vulnerable to access attacks and eavesdropping. Moreover, conventional access security mechanisms like authentication and encryption work properly at the three galactic zones if proper policies are proposed. The three architectures support security at the earth zone and orbiting zones, assuming that the earth zone is the only gateway to orbiting and deep space zones. Therefore, securing access at the gateway would indirectly secure access to the rest of the architecture. However, none of these architectures considers any access policies to the exposed network information.
8) **Handling long propagation delays:** Future communication architectures aim to enable real-time access to space missions. More particularly, real-time access to on-board computers and scientific equipments deployed in orbiting and deep space zones. Long propagation delay feature forms a major obstacle front achieving this goal. Therefore, the necessity imposes the deployment of distributed multi-hop spacecraft networks at the orbiting and deep space zones. Moreover, there is also a necessary to deploy an efficient network infrastructure at the earth zone. The OMNI architecture assumes the existence of a high speed terrestrial communications architecture namely NASCOM at the earth zone. Due to fact that this architecture is two-zone, future missions would deployed at the home-orbital zonal hop utilizing the pre-existing LEO and GEO satellite networks. At this level, propagation delay does not form such an obstacle unlike missions deployed at the deep space zone. One the other hand, CCSDS proposed the existence of an interplanetary network backbone which contributes towards reducing the effect of propagation delay at the deep space zone. Furthermore, SpaceVPN proposed the existence of a distributed ad hoc inter-spacecraft network infrastructure to be deployed at the orbiting and the deep space zones.
9) **High link asymmetry**: Future space missions will also enable two-way communication with network assets deployed at the orbiting and deep space zones. In the current-state missions space uplink is only used for command and control, where the downlink is mostly used from telemetry data. Future missions will require space uplinks to no longer transmit command and control signal extending its functionality to transmit large volumes of data to scientific equipments deployed at various foreign colonies in the deep space zone. The nature of future missions operated by OMNI is planned to similar to the current-state ones. On the other hand, the design SpaceVPN physical network considers the support for higher space uplink data rates.

E. Evaluation

From the discussion made in the previous section, three observations are made. First, the OMNI architecture seems to be sustainable for the communication needs of space missions deployed at the earth orbital zone. It was shown that communication future OMNI-operated missions are soft compared to CCSDS- and SpaceVPN-operated missions. Through the features supported by the OMNI architecture demonstrates degree of completeness for future missions deployed exclusively at the orbiting zone. Second, the scope of CCSDS- and SpaceVPN-operated missions is focused towards deep space, which is more likely to take place in the near future. CCSDS proposal of the interplanetary backbone network would have a significant contribution towards deep space missions. However, CCSDS does not directly address most of the space environment features. Therefore, the completeness CCSDS architecture is restricted only at the level standards recommendations characterizing idealizing the space architecture of the future. Third, SpaceVPN can be considered that practical accomplishment of CCSDS ideal perspectives of future space architectures supported deep space missions. The design of SpaceVPN will provide key solutions to a number of crucial space environment features end-to-end communication, link intermittency, long propagation delays and link asymmetry. However, one design issue SpaceVPN might in the near future consider is provisions of concise security mechanisms at the orbiting and deep space zone. Therefore, SpaceVPN demonstrates a pretty high degree of completeness through its architectural design making it the space architecture of the next space age.

V. Conclusion and Future Work

An exuberant space age is about to commence. In this age it is likely to see many compact yet innovative explorations much beyond imagination. One remarkable aspect of this new age is the existence of a reusable and yet sharable space communication infrastructure. Current-state space communication architectures mainly suffer from three design drawbacks high cost, narrowed scale and lack of concise geographical organization. Therefore, there has been a renewed interest for developing a new generation of architectures addressing these design drawbacks. In this paper we take one step back, we describe the architectural design of future space communication architectures supporting emergent space missions. We first describe a holistic framework for space communication. We identify the major constraints of space environment imposed by the galactic geography. We also outline a sufficiently complete design space of the plausible range of communication modalities this age of space communication might require. Second, we survey three leading architectures namely OMNI, CCSDS and SpaceVPN. Third, we analytically evaluated the design of these architectures using the reference framework described. On the basis of the design evaluated carried out, it is concluded that the CCSDS architecture will only remain a resource of protocols standards for future space communication architectures to adopt. Moreover, the OMNI architecture will ideally service space missions deployed at the orbiting –home orbital zonal hop-. Finally, SpaceVPN provides a strong indication to be the communication architecture of the next space age.

VI. References

[1] Omar Y. Tahboub, and Javed I. Khan, **“A Critical Design Evaluation of the Next Generation Space Network Architectures”**, technical report TR-2007-09-01, Medianet Lab, July, 2007.

[2] Rash J., Hogie K., and Casasanta R., **“Internet technology for future space missions”**, Computer Networks, Volume 47, Issue 5, Elsevier, 2005.

[3] Hogie K., Criscuolo E., and Parise R., **“Using Standard Internet Protocols and applications in space”**, Computer Networks, Volume 47, Issue 5, Elsevier, 2005.

[4] Burleigh S, Cerf V, Durst R, Fall K, Hooke A, Scott K, Weiss H, “**The Interplanetary Internet: a communications infrastructure for Mars exploration”**, 53 International Astronautical Congress The World Space Congress, 2002.

[5] Bergamo M. AS., **“High-Throughput Distributed Spacecraft Network: architecture and multiple access technologies”**, Computer Networks, Volume 47, Issue 5, Elsevier, 2005.

[6] Bhasin, K., and Hayden, J. L., **"Space Internet Architectures and Technologies for NASA Enterprises,"** Int. J. Satell. Commun. 2002; 20, 311-332.

[7] Lapsly, D., Bergamo, M., **"An integrated approach to the development of wireless network protocols"**, International Conference on Mobile Computing and Networking, Proceedings of the 1st international workshop on Wireless network testbeds, experimental evaluation & characterization, Los Angeles, CA, USA, p.10-17, 2006.

[8] Bell, D.J.; Cesarone, R.; Ely, T.; Edwards, C.; Townes, S., **"Mars network: a Mars orbiting communications and navigation satellite constellation"**, IEEE Aerospace Conference Proceedings, Volume 7, Issue , 2000 Page(s):75 - 88 vol.7.

[9] Christopher R., **"Overview of LEO Satellite Systems"**, 1999 second annual International Symposium on Advanced Radio Technologies, Sept. 8-10, 1999.