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Developing Architectures and Technologies for an Evolvable NASA Space Communication Infrastructure

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July 2004

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Space communications architecture concepts play a key role in the development and deployment of NASA's future exploration and science missions. Once a mission is deployed, the communication link to the user needs to provide maximum information delivery and flexibility to handle the expected large and complex data sets and to enable direct interaction with the spacecraft and experiments. In human and robotic missions, communication systems need to offer maximum reliability with robust two-way links for software uploads and virtual interactions. Identifying the capabilities to cost effectively meet the demanding space communication needs of 21st century missions, proper formulation of the requirements for these missions, and identifying the early technology developments that will be needed can only be resolved with architecture design. This paper will describe the development of evolvable space communication architecture models and the technologies needed to support Earth sensor web and collaborative observation formation missions; robotic scientific missions for detailed investigation of planets, moons, and small bodies in the solar system; human missions for exploration of the Moon, Mars, Ganymede, Callisto, and asteroids; human settlements in space, on the Moon, and on Mars; and great in-space observatories for observing other star systems and the universe. The resulting architectures will enable the reliable, multipoint, high data rate capabilities needed on demand to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of outposts in-space, on the Moon or on Mars.

I. Introduction

Space communications architectures and technologies in the 21st century must meet the growing needs of Earth sensor web and collaborative observation formation missions, robotic scientific missions for detailed investigation of planets, moons, and small bodies in the solar system; human missions for exploration of the Moon, Mars, Ganymede, Callisto, and asteroids; human settlements in space, on the Moon, and on Mars; and great in-space observatories for observing other star systems and the universe[1]. An advanced, integrated, communications infrastructure will enable the reliable, multipoint, high data rate capabilities needed on demand to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of in-space outposts, the Moon or Mars.

Past work in space communications was developed from several unrelated perspectives of the different enterprises with a view toward providing communication services for each new mission as it came along. Communications for Earth observing missions[2], for instance, were developed independently from what was needed for other missions, such as the human shuttle and ISS missions. NASA implemented the Tracking and Data Relay Satellite System (TDRSS) as a space network for general use by NASA's human missions and Earth observing missions. Unfortunately, the costs of using the TDRSS services (special on-board communication equipment, the TDRSS White Sands Complex, and dedicated ground networks) were considered too high for most Earth observing missions, so those missions used new and modified older ground stations for capturing their data. Communications for Mars and deep space missions also developed independently from the others and shared the use of the Deep

Space Network (DSN). Communications were again treated from a services perspective[3], and although the interfaces and protocols used for different missions were standardized, the standards could not support autonomous networking and data routing. More recently, the enterprises have been accumulating the capabilities that are felt to be necessary for future missions. However, the enterprise solutions identified for future communications remain services-centric, that is, the solutions are specific to each enterprise's missions and are not integrated into an overall NASA communication infrastructure solution, wherein the in-space nodes can communicate with each other as well as with users on Earth through the Internet. The commercial Iridium communication satellite constellation, although not as successful as originally anticipated, did prove that inter-spacecraft communications and networking was possible.

The approach taken in this paper is architecture-centric in that the work will lead to an integrated, inter-networked, space communications infrastructure developed from architectural elements and interfaces. Within this networked infrastructure, data will move from sensor to user under autonomous control of the nodes within the network. Human operations will become maintenance and network administrative functions. To obtain the requirements that follow, node-to-node link capability needs were captured from data provided by the enterprise mission planners and technologists. These capabilities include data rates, distance, and function needed over each general link from the Earth-side network and terminal to the in-space user node. Later work will extend into defining and standardizing the hardware and software interfaces to be implemented in each node and identifying the most appropriate technologies to implement for those nodes. It is expected that this architectural development work will need to continue as the infrastructure is first emplaced and then as it grows with time.

In this paper, we describe an integrated communications architecture that will support the Vision for Space Exploration articulated by President Bush on January 16, 2004[1]; we provide a summary of the communications needs and capabilities that the nodes in the resulting new infrastructure will satisfy; and we then identify the architectural tradeoffs and the technology gaps that must be resolved to achieve a workable new architecture. We discuss those elements of the communications infrastructure that enable and enhance robotic and human exploration of the Moon and Mars. We do not cover communication support for robotic missions to the outer planets.

II. Space Communication Architecting Process

The overall space communication architecture shown in Fig. 1 was developed based on NASA's needs and requirements collected through participative processes[4]. This paper takes a first look at the space communication architecture in an integrated fashion while addressing the needs of the NASA enterprises. The figure shows the scenario of a networked space communications infrastructure with connections to the regions of interest within the solar system[5]. The communication capabilities are provided by constellations of communications relay satellites; sensor web inter-spacecraft communications packages for relaying data between science observation satellites in high Earth orbits; high data rate, small, autonomous ground terminals; communications relay spacecraft placed in gravitationally balanced Lagrange orbits between the Earth and Moon and the Earth and sun; relay satellites around the Moon; and science and relay satellites placed in orbit around Mars, the outer planets and small bodies. The communication links shown in Fig. 1 are further described in the following sections.

A. Architecture Elements and Interfaces

The architecture is represented by four architectural elements[4]. Blue lines indicate high rate, inter-nodal links between backbone elements; red lines are links from access elements (i.e., robotic and human exploration spacecraft) to backbone elements; green lines are inter-spacecraft links; and yellow lines indicate short range between proximity elements. Collectively, links within and between these elements represent segments of the pathways needed to achieve the end-to-end data-passing capability envisioned for future NASA communications. The high rate backbone network elements are the intra-network structures of high rate communication nodes and inter-nodal links that utilize advanced communication technologies to increase data rate by orders of magnitude while reducing overall costs. The flexible access network elements are re-configurable communication systems at the edges of the backbone networks that enable in-space humans, robotic spacecraft, aircraft, or ground vehicles to communicate to the infrastructure edge-nodes. Inter-spacecraft cooperative network elements incorporate the technologies necessary to enable intercommunications between future NASA spacecraft flying in formation, in clusters, or in constellations. Proximity wireless network elements include: short range, low power, low cost communications packages for inter-communication between small sensor packages, and small wireless local area network (WLAN) packages to support high data rate, bidirectional communications for voice, video, data, and control between humans and robots over a distance of meters to a few kilometers.

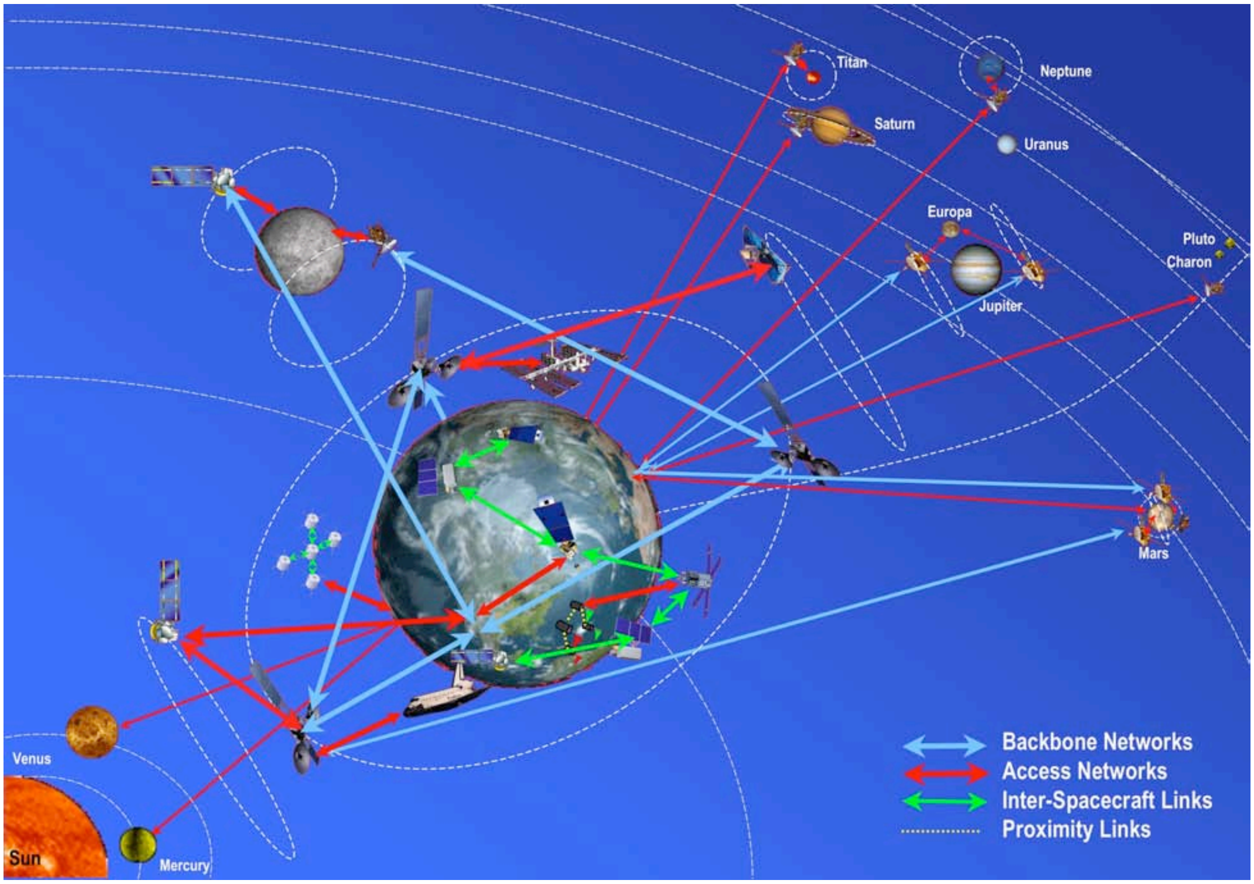

Figure 1: Integrated space communication architecture.

B. Layered/Integrated Communications Architecture

With integrated architectures, NASA will be able to achieve intelligent communications. The communication networking paths will utilize the lower five of the seven Open System Interconnection (OSI) model layers (Fig. 2) to achieve Internet protocol (IP) data routing capabilities[6]. Current approaches have only nominal interaction between these layers[7]. However, interactive control between the layers enables autonomous data routing on-board and between spacecraft by allowing control of antenna pointing, transmitter power, transmit data rates and media access methods that vary with distance, thus permitting a complete end-to-end data routing capability. It also enables spacecraft or users to demand access to the network as if they were making a cellular phone call. Common protocols and interfaces at these layers will enable inter-active links to be made and broken on demand of any node in the network, thus enabling complex and deeply networked communications channels between nodes in space and on Earth.

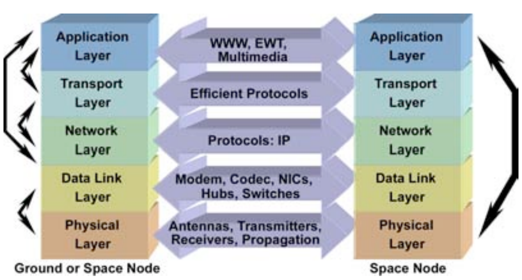

Figure 2:Internet protocol layers used in integrated communication architecture.

C. Communication Nodes – Descriptions and Options

As the next step, the individual communication nodes within each region of the evolutionary architecture model were identified[5]. These nodes included all entities (sensors, spacecraft, aircraft, robots, humans, etc.) that might communicate with each other inside or outside of the region. Then links for each pair of nodes that might reasonably be expected to inter-communicate were identified. This provided a view of all the links into and out of a particular node and a means to tabulate their physical and desired characteristics. These node-to-node links become the optional building blocks of the architectures. There are multiple paths by which data can move from one node to another. The existence of a path depends on whether a particular architectural element option is chosen for implementation into the infrastructure. Many node-to-node link options will likely drop out of consideration with further analysis.

The Earth vicinity communications nodal group encompasses the communications infrastructure needed to support robotic and human missions from the Earth surface to high Earth orbit (HEO). It includes: that part of the DoD's transformational communications architecture (TCA) (Armstrong, 2003) that NASA may implement and/or use; communication relay satellite networks that may optionally be placed in geosynchronous Earth orbits (GEO); or high inclination Molniya orbits, medium Earth orbit (MEO), and low Earth orbit (LEO) Earth observer satellite data and command paths. The Moon vicinity nodal group encompasses the surface and orbits of the Moon and the Earth-Moon system's Lagrange points. Elements of the physical communications infrastructure considered in this group include: communication relay satellites in Earth-Moon Lagrange orbit or Moon orbit, long-link Moon-to-Earth communications and wireless local area networks (WLANs) on the surface of the Moon. The Earth-Sun Lagrangian vicinity nodal group comprises those elements of the communications infrastructure that might be placed at the Earth-Sun Lagrange points L1, L2, L4, and/or L5 to provide high data rate backbone capabilities for Earth, Sun, galaxy, or universe observing missions and deep space science missions. The Mars vicinity nodal group encompasses communications infrastructure that might be implemented to support robotic and human missions at Mars. It includes: a relay satellite network for Mars that might optionally be placed in Mars synchronous orbit (MSO), Mars high orbit (MHO), and/or Mars low orbit (MLO); networks for Mars orbit, air, and surface robotic missions; and Mars human outpost communication networks. The deep space communications nodal group is the communications infrastructure that is dispersed among the outer planets and moons in support of robotic and later human missions. It includes outer planet mission communication systems and communication relay spacecraft that might be placed in Jupiter-Sun L1, L2 halo orbits.

III. Requirements

The high level mission communication data rate requirements in Table 1 and the required characteristics that follow motivate the need for a set of links between nodes of NASA's future space architecture. These capabilities are addressed by examining individual node-to-node links. The resulting architecture can then be used to identify and focus technology development needed to support the physical network of communications links. Once the new technologies are in place in the physical architecture, the required high-level capabilities will be fully realized.

Table 1: Infrastructure requirements.

Nodal Group	Node to Earth	Current	2010	2020+
Earth Vicinity	LEO Spacecraft (Direct Link)	150 Mbps	>1 Gbps gateway, 1 Gbps D/L	10 Gbps
	GEO Spacecraft (Direct Link)	150 Mbps	>1 Gbps	10 Gbps
	STS	50 Mbps	50 Mbps	50 Mbps
	ISS	48 Mbps	150 Mbps (2005)	300 Mbps
Moon	Earth-Moon L1, L2			0.2 up/1 down Gbps
	Moon			0.2 up/1 down Gbps
Earth-Sun L1, L2	GEO relay and Earth		20 Mbps	>100 Mbps
Mars	Mars Science	100 Kbps	5 Mbps	20 up/100 down Mbps
	Mars Exploration	–	10 Mbps	20 up/100 down Mbps
	Mars Proximity Link	–	–	1-100 Mbps
Outer Planets	Jupiter to Outer Heliosphere	10 Kbps	1 Mbps	>10 Mbps

A. NASA Enterprises Needs

NASA's communications infrastructure must support all varieties of science and human exploration in the future. The science to be supported ranges from observation of the Earth, Moon, Mars, and the outer planet systems to the universe. The science also includes that which is obtained during human exploration and inhabitation of space, the Moon, Mars, and outer planet moons. Most of the NASA science missions that are under study require high-bandwidth communications, including (in very short summary): hyperspectral imagery, synthetic aperture radar imagery, atmospheric measurements, and radar sounding of the Earth, planets, and moons; astronomical imagery from radio frequencies to gamma rays of other star systems, the galaxy, and universe; robotic measurements of planet/moon surface and atmospheric properties; and the search for life by many means.

B. Emerging Needs for the Space Exploration Initiative

Future robotic missions will need to operate autonomously by sensing the area around them so they can make decisions about where to go, what samples to measure, what data to report, and how to request and connect to the space communication network. Other robotic entities must be intimately connected to human operators via wireless systems that enable real-time, or delayed-time video and control for close coordination such as in assembling large space structures. The goal of the new infrastructure design is to become a space Internet that is as autonomous as possible in operation and one in which connections are made and broken as needed by the requesting entity. This kind of communications infrastructure is needed to enable access on the demand of any mission entity, including spacecraft, surface robot, in-space exploring human, and Earth user, while using as few human operators as possible to provide the capabilities. This Internet architecture also serves the needs of the public by allowing direct viewing of mission activities and enabling safe (protected against unauthorized operations) public participation in those activities.

IV. Architecture and Technology Framework for Evolvable Space Infrastructure

Rather than change in the independent, mission-specific way that the present NASA communications infrastructure grew to support the exploratory missions of the past, the infrastructure of the future will grow in an integrated fashion and evolve to support >100Mbps data rates for robotic missions to the Moon by 2010 and human missions to the Moon by 2015. Likewise, communications networks will reach 100Mbps to support robotic missions to Mars by 2015 and human missions beyond 2020. The characteristics required by the evolving infrastructure are shown in Table 2.

Table 2: Required characteristics of the infrastructure.

Required Characteristic	Rationale
Be available 24/7.	Basic requirement of human missions and most missions requiring low latency data return.
Integrated Architectures	Use of standard interfaces (hardware, wireless, and protocols) across the infrastructure increases data routing options and reduces costs of implementation.
Low cost, modular and efficient.	This can be achieved by adapting commercial technology standards to use in space.
Handle multipoint connections to multiple nodes simultaneously.	Essential for broadcasting data to many spacecraft simultaneously; for inter-spacecraft coordination of timing, maneuvers, and collaborative science data gathering; and for enabling autonomous end-to-end routing of data.
Highly reliable connections	Connections must be reliable to meet the very high data rates or the required characteristics will not be met.
Long life expectancy.	High cost of development and space flight dictates lifetimes of greater than 20 years.
Highly reconfigurable	To accommodate upgrades and enable growth in capabilities over time.
Be secure.	Cannot allow intruders to take control of the systems nor allow sampling of private data.
Connect End-to-end	Enabling data to move on demand from user to spacecraft instrument or back greatly reduces operations support costs.
Handle multiple robotic and human missions simultaneously.	Essential for providing communication routes for many spacecraft simultaneously so that many data streams can be routed from end-to-end autonomously.
Multiple quality of service levels	QoS diversity is required to handle voice, video, science data and control data simultaneously.
Minimum latency within the networks.	Required for maintaining the tightest possible control loops that are necessary in most human-operated remote missions. It also helps for keeping human-human communications as close to real-time as possible.
Provide navigation capabilities within telemetry signals.	Needed for missions that must coordinate their activities and for flying in formations.
Operate in extreme environments	In-space hardware must survive solar flares and cold temperatures. Planetary/moon hardware faces large temperature swings (Moon, Mars), high radiation (Europa), high temperature (Mercury).

NASA's communication infrastructure will become an autonomously operated system of networks on the ground and in-space. It will be possible for an in-space human or robotic spacecraft, rover, or ground-based user to demand and receive access to an arm of the network from nearly anywhere on or around the Earth, the Moon, or the Solar System. An integrated architecture that implements an infrastructure with the desired characteristics is made up of several regions of interest where groups of communication nodes represented by science and human missions will likely need access to modern networked, high data rate communications for conveying images, science data, voice, video, and control data among themselves and with Earth. The nodal regions of interest include the Earth vicinity from its surface to high Earth orbits, the Moon vicinity from lunar surface to the near and far Earth-Moon Lagrangian halo orbits (EM_{L1} and EM_{L2}), the Earth-Sun Lagrangian orbits (ES_{L1}, ES_{L2}, ES_{L4}, ES_{L5})[8], Mars vicinity from its surface to the Mars synchronous orbit, Jupiter vicinity from its atmosphere to its Jupiter-Sun Lagrangian orbits (JS_{L1}, JS_{L2}), and the neighborhoods of the rest of the planets, moons and objects in the Solar System. In this paper we cover only the Earth-Sun Lagrangian orbits at ES_{L4} and ES_{L5} insofar as they may be used in support of missions to Mars. We do not cover the nodal regions beyond Mars. The architectural scenario described in the following sections implements the evolutionary space communications architecture, its architectural elements and interfaces, the science it supports, and its concept of operations.

A. Earth Vicinity Communications Infrastructure

The Earth vicinity communications infrastructure for observation and exploration missions is diagrammed in Fig. 3 and includes the LEO, MEO, GEO, HEO relay satellites that may be implemented.

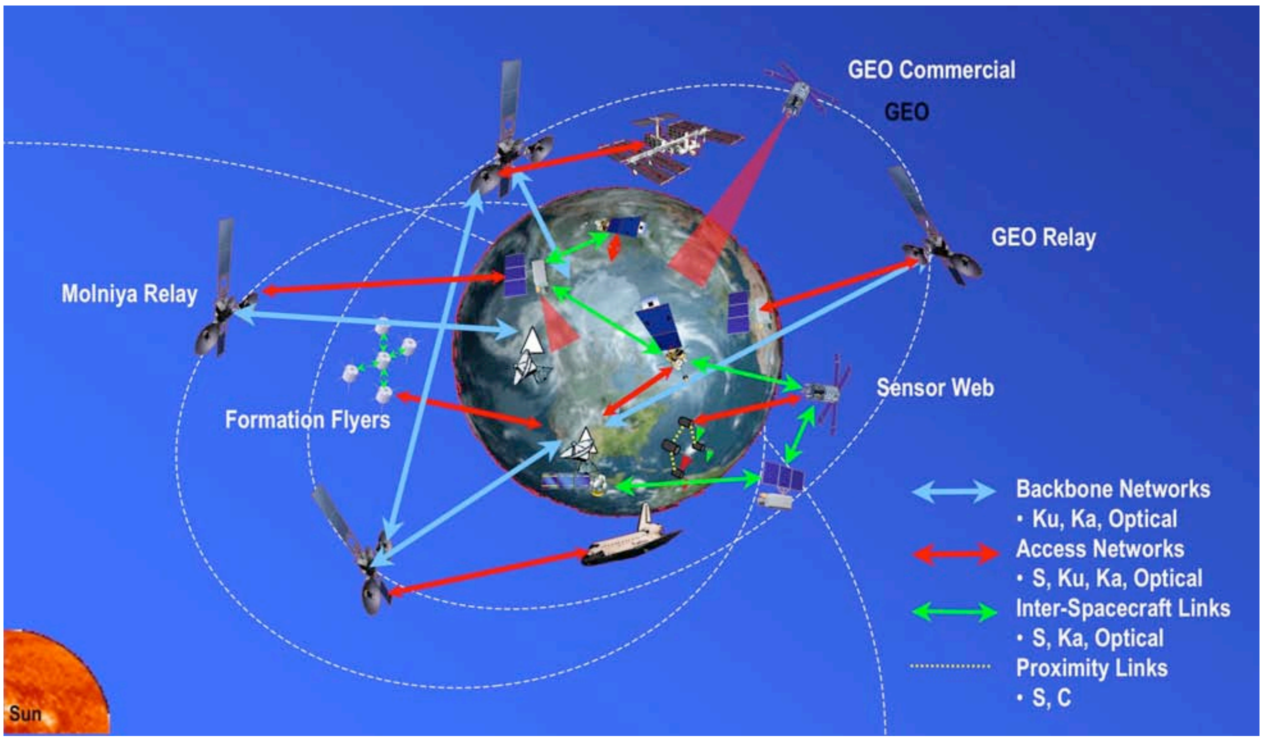

Figure 3: Earth vicinity communication links.

A listing of all of the optional node-to-node links that were considered, their data rates, link distances, likely technologies, and types of service is given in Table 3. The node-to-node links considered in the table include:

1) from TDRSS (or similar) geosynchronous space network links to Earth observing satellites and human missions;
2) from Medium Earth Orbit (MEO) relay networks links to Earth observing satellites and human missions;
3) from High Earth Orbit (HEO) including Molniya orbit relay networks to Earth observing satellites and human missions;
4) from Earth orbiting missions to HEO, GEO, or MEO networks;
5) from Low Earth Orbit (LEO) satellite to ground terminals;
6) between LEO satellites configured into a Sensor Web;
7) between ISS or Shuttle and HEO, GEO, or MEO networks; and
8) between ground terminals and ISS or Shuttle.

Table 3: Characteristics and requirements of node-to-node link options that were considered for Earth vicinity communications.

Node-to Node Link	Data Rate (Mbps)	Distance	Technology	Service
1) Space network (similar to TDRSS) element link to:				
NASA LEO satellite	1,200	35,000 km	Optical	Demand access data IP network services
NASA LEO satellite low rate	10	35,000 km	X-band	Multiple access on-demand to move data, emergency, TT&C
Human spacecraft	1,200	35,000 km	Optical	Bidirectional voice, video, data access data services
Space network element (crosslink)	10,000	35,000 km	Optical	Bidirectional backbone data
Lunar missions	1,000	0.25 Mkm	Optical	Bidirectional voice, HDTV, data
Earth-Sun L1, L2	300	1.5 Mkm	Optical	Backbone and Science data
Mars missions	100	2.5 AU	Optical	Bidirectional voice, HDTV, data
2) MEO relay link to:				
NASA LEO satellite	1,000	4,000 km	Optical	Demand access data IP network services
NASA LEO satellite low rate	10	4,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
Human spacecraft	1,000	4,000 km	Optical	Bidirectional voice, video, data access data services
MEO network element (crosslink)	10,000	4,000 km	Optical	Bidirectional backbone data
3) HEO and Molniya relay link to:				
NASA LEO satellite	500	100,000 km	Optical	Demand access data IP network services
NASA LEO satellite low rate	5	100,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
Human spacecraft	500	100,000 km	Optical	Bidirectional voice video, data access data services
4) Earth satellite link to:				
NASA HEO satellite	500	100,000 km	Optical	Demand access data IP network services
NASA HEO satellite low rate	5	100,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
NASA GEO satellite	1,200	35,000 km	Optical	Demand access data IP network services
NASA GEO satellite low rate	10	35,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
NASA MEO satellite	1,000	4,000 km	Optical	Demand access data IP network services
NASA MEO satellite low rate	10	4,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
5) Ground terminal link to:				
NASA LEO satellite	>1,000	2,000 km	Ka-band	Access data services
6) LEO satellite link to:				
NASA LEO satellite	1,000	4,000	Ka-band	Share and route data
7) ISS or Shuttle link to:				
NASA HEO satellite	500	100,000 km	Optical	Demand access data IP network services
NASA HEO satellite low rate	5	100,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
NASA GEO satellite	1,200	35,000 km	Optical	Demand access data IP network services
NASA GEO satellite low rate	10	35,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
NASA MEO satellite	1,000	4,000 km	Optical	Demand access data IP network services
NASA MEO satellite low rate	10	4,000 km	Ka-, X-band	Multiple access on-demand to move data, emergency, TT&C
8) Ground terminal link to:				
ISS or Shuttle	>1,000	2,000 km	Ka-band	Access data services

B. Lunar Communication Infrastructure

The Moon vicinity communications infrastructure for robotic and human missions diagrammed in Fig. 4 includes Earth-Moon Lagrangian halo orbit relay satellites at EM_{L1} and EM_{L2}, lunar orbit relay satellites, and lunar surface wireless local area networks (WLANs) that may be implemented.

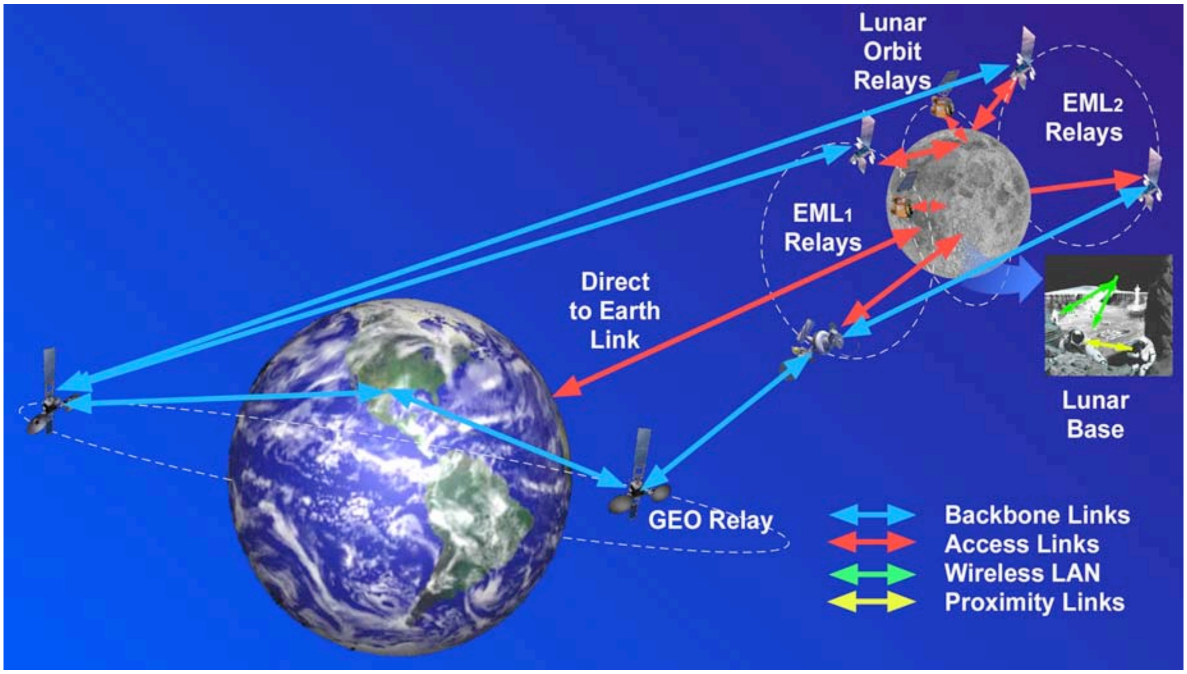

Figure 4: Moon vicinity and Earth-Moon communication links.

Table 4 is a list of the optional Earth to Lunar vicinity node-to-node communication links and the links between entities on the Lunar surface or in Lunar orbit that were considered for supporting robotic and human missions to the Moon. The options that were considered are grouped in the table as follows:

1) Large Satellites in Medium Moon Orbit (LSMMO) - A constellation of 8 communications relays are placed in two orbital planes (3 active and 1 spare in each plane) that are 90 degrees out of phase, one polar and one equatorial orbit at >2000 km altitude to provide nearly 24/7 coverage between Earth and missions anywhere on the lunar surface and between entities on that surface. Data from lunar surface to lunar surface are also routed around the constellation. Each satellite has a link to Earth, to the lunar surface, and a satellite-to-satellite crosslink package.
2) Communication relay spacecraft placed in Earth-Moon L1 (EM_{L1}) halo orbit - Two spacecraft on opposite sides of the EM_{L1}halo orbit can provide nearly 100% 24/7 coverage of most of the Earth-facing side of the Moon. A large halo orbit diameter with three or four relay spacecraft would provide 24/7 coverage of the rim of the Moon. Communication between near side Moon surface entities via an EM_{L1} relay has moderate latency of $\approx$ 0.4 s.
3) Communication relay spacecraft placed in Earth-Moon L2 (EM_{L2}) halo orbit - Two spacecraft on opposite sides of the EM_{L2} halo orbit can provide nearly 100% 24/7 coverage of most of the far side of the Moon. A large halo orbit diameter with three or four relay spacecraft would provide 24/7 coverage of the rim of the Moon from the far side. Communication between far side Moon surface entities via an EM_{L2} relay has moderate latency of $\approx$ 0.4 s. Communication from the far side Moon surface to an L2 satellite to an L1 satellite and then to the near side Moon surface has latency of $\approx$ 1s.
4) Small Satellites in Low Moon Orbit (SSLMO) - A constellation of 35 small communications relays are placed in 5 equally spaced low orbit orbit planes with 6 active and 1 spare satellite in each plane to provide nearly 24/7 coverage between Earth and missions anywhere on the lunar surface and between entities on that surface. Data from lunar surface to lunar surface are also routed around the constellation. Each satellite has 2 to 4 communication packages for communication to the lunar surface and for inter-satellite crosslinks.

Table 4: Characteristics and requirements of node-to-node link options that were considered for Earth to Moon and Moon vicinity communications.

Node-to Node Link	Data Rate (Mbps)	Distance	Technology	Service
1) LSMMO relay spacecraft constellation				
Earth ground	>300	384,000 km	Ka-, X-bands	Backbone data services
Earth orbit relay	1,000	384,000 km	Optical	Backbone data services
LSMMO relay spacecraft (crosslink)	1,000	6,500 km	Optical, Ka	Backbone data services
Moon low rate	10	2,700 km	Ka-, X-bands	Emergency, TT&C
Moon science orbiter	100	2,700 km	Ka-, X-bands	Science files
Moon human outpost	1,000	2,700 km	Optical, Ka	Bidirectional voice, HDTV, data
2) Earth-Moon L1 (EML_1) communication relay spacecraft				
Earth ground	>300	323,000 km	Ka-, X-bands	Backbone data services
Earth orbit relay	1,000	323,000 km	Optical	Backbone data services
Earth-Moon L1 Gateway	1,000	10,000 km	Optical, Ka	Access data services
Moon relays, high rate	1,000	61,000 km	Optical, Ka	Backbone data services
Moon low rate	10	61,000 km	Ka-, X-bands	Emergency, TT&C
Moon science orbiter	100	61,000 km	Ka-, X-bands	Science files
Moon human outpost	1,000	61,000 km	Optical, Ka	Bidirectional voice, HDTV, data
3) Earth-Moon L2 (EML_2) communication relay spacecraft				
Earth ground	>300	445,000 km	Ka-, X-bands	Backbone data services
Earth orbit relay	1,000	445,000 km	Optical	Backbone data services
Moon relays, high rate	1,000	61,000 km	Optical, Ka	Backbone data services
Moon low rate	10	61,000 km	Ka-, X-bands	Emergency, TT&C
Moon science orbiter	100	61,000 km	Ka-, X-bands	Science files
Moon human outpost	1,000	61,000 km	Optical, Ka	Bidirectional voice, HDTV, data
4) Small Satellite, Low Moon Orbit (SSLMO) relay spacecraft constellation				
SSLMO relay spacecraft (crosslink)	1,000	2,100 km	Ka	Backbone data services
Moon low rate	10	650 km	Ka-, X-bands	Emergency, TT&C
Moon science orbiter	100	650 km	Ka-, X-bands	Science files
Moon human outpost	1,000	650 km	Ka	Bidirectional voice, HDTV, data
5) Small Satellite, Low Moon Orbit (SSLMO) Lunar surface terminal relays				
Earth ground	>300	384,000 km	Ka	Backbone data services
Earth orbit relay	1,000	384,000 km	Optical	Backbone data services
SSLMO relay spacecraft (crosslink)	1,000	650 km	Ka	Backbone data services
6) Human lunar outpost sends and receives voice, video, and data using direct to Earth links				
SSLMO relay	1,000	650 km	Ka	Bidirectional voice, HDTV, data
LSMMO relay	1,000	2,700 km	Optical, Ka	Bidirectional voice, HDTV, data
Earth-Moon L1 relay	1,000	323,110 km	Optical, Ka	Bidirectional, multipoint, voice, video, remote control, science data, emergency
Earth orbit relays	1,000	384,400 km	Optical, Ka	Bidirectional, multipoint, voice, video, remote control, science data, emergency
Earth terminal	200	384,400 km	Ka-, X-bands	Science data, emergency, TT&C
7) Lunar outpost wireless local area network (WLAN)				
Other lunar surface entity at close range	>100	100 m	Ka-, X-, C-bands	Bidirectional, multipoint, voice, video, remote control, data, emergency
Other lunar surface entity at long surface distance	>50	50 km	Ka-, X-, C-bands	Bidirectional, multipoint, voice, video, remote control, data, emergency

5) Lunar surface terminal relays SSLMO communication relays - Since the satellites were assumed to be small and inexpensive, it was not expected that they would have high data rate capabilities to Earth. Consequently two high data rate lunar surface terminals were assumed to be emplaced on the near-side of the Moon with high data rate capabilities with Earth. The SSLMO satellites would then route data from a surface entity, around the Moon, and down to a lunar surface terminal that routes the data to Earth.

6) Human lunar outpost communication links - Links are to Earth via SSLMO relays, LSMMO relays, EML1 relays, relays in Earth orbit, or direct-to-Earth terminals for sending and receiving voice, video, and data. There is a two-way latency of 2.5 s in signal turnaround with earth.
7) Lunar outpost wireless local area networks (WLAN) - Characteristics of surface communication networks between robots and humans include omnidirectional, local communications over short ranges (≈100m) and directional, (antenna pointed) communications over longer local distances (≈50 km) capable of handling voice, video, control, and data passing between multiple local entities.

C. Earth-Mars and Mars Vicinity Communications

The Mars vicinity communications infrastructure for robotic and human missions is diagrammed in Fig. 5 along with the deep space communications. It includes Mars communication relay satellites, science spacecraft, atmospheric craft, surface rovers, landers, sensor, and human outposts that may be implemented at Mars.

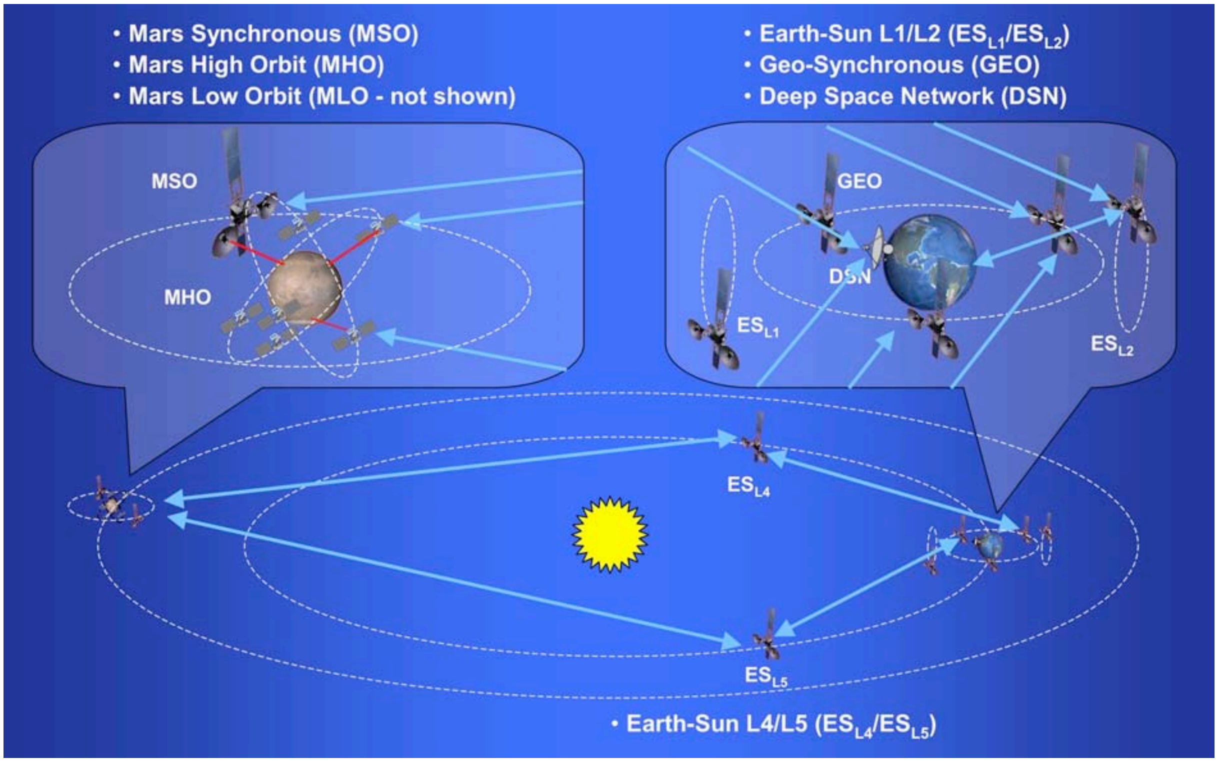

Figure 5: Mars vicinity and Earth-Mars communication links.

The node-to-node links between Earth and Mars and at Mars are identified in Table 5 as follows:

1) Earth-Mars communication using relay spacecraft placed at Earth-Sun L4 (ESL_4, Earth-leading orbit) and/or Earth-Sun L5 (ESL_5, trailing orbit) - A relay at either of these locations enables communication around the Sun during times of solar conjunction (when the Sun blocks the Earth view of Mars). Relay stations at both L4 and L5 add redundancy to the communication paths around the Sun.
2) Earth-Mars communication using Mars Synchronous Orbit (MSO) communications relay satellite - A relay satellite placed in MSO can provide 24/7 coverage between Earth and one side of Mars. Three MSO satellites would be needed to provide full coverage between the Earth and Mars.
3) Earth-Mars communication using Mars High Orbit (MHO) communications relay satellite network - Four to six communication relay satellites with crosslinks placed in MHO can provide 24/7 coverage of the entire planet.
4) Earth-Mars communication - Mars Low Orbit (MLO) science satellite with add-on relay network functions are already being deployed around Mars. These satellites are capable of low data rate communications (<1Mbps).
5) Mars vicinity communications - Data are sent and commands received from Mars orbit, atmosphere, or surface human or robotic entity using relays in MSO, MHO, and MLO. Direct to Earth communications are also considered.

6) Mars outpost wireless local area network (WLAN) - Characteristics of surface communication networks between robots and humans include omnidirectional, local communications over short ranges (≈100 m) and directional, (antenna pointed) communications over longer local distances (≈50 km) capable of handling voice, video, control, and data passing between multiple local entities.

Table 5: Characteristics and requirements of node-to-node link options that were considered for Earth to Mars and Mars vicinity communications.

Node-to Node Link	Data Rate (Mbps)	Distance	Technology	Service
1) Earth-Sun L3, L4 Relay Link to:				
Earth ground	>100	1 AU	Optical	Backbone data services
Earth orbit relay	>100	1 AU	Optical	Backbone data services
Mars relays, high rate	100	2.5 AU	Optical	Backbone data services
Mars low rate	1	2.5 AU	Ka-, X-bands	Emergency, TT&C
Mars science S/C	10	2.5 AU	Optical, Ka	Science files
Mars human outpost	100	2.5 AU	Optical, Ka	Bidirectional voice, HDTV, data
2) MSO Relay Link to:				
Earth ground	>1	2.5 AU	Ka-, X-band	Emergency, TT&C
Earth L1, L2, L4, L5, GEO orbit relay	>100	2.5 AU	Optical	Bidirectional Backbone data
Mars low rate	1	10,000 km	Ka-, X-bands	Emergency, TT&C
Mars science orbiters	100	10,000 km	Optical, Ka	Multiple science S/C files
Mars surface robots	10	10,000 km	Ka	Multiple science S/C files
Mars human outpost	100	10,000 km	Optical, Ka	Bidirectional voice, HDTV, data
3) MHO Relay Link to:				
Earth ground	>1	2.5 AU	Ka-, X-band	Emergency, TT&C
Earth L1, L2, L4, L5, GEO orbit relay	>100	2.5 AU	Optical	Bidirectional Backbone data
Mars low rate	1	4,000 km	Ka-, X-bands	Emergency, TT&C
Mars science orbiters	100	4,000 km	Optical, Ka	Multiple science S/C files
Mars surface robots	10	4,000 km	Ka	Multiple science S/C files
Mars human outpost	100	4,000 km	Optical, Ka	Bidirectional voice, HDTV, data
4) MLO Relay Package Onboard Science Spacecraft Link to:				
Earth ground	>1	2.5 AU	Ka-, X-band	Emergency, TT&C
Earth L1, L2, L4, L5, GEO orbit relay	>10	2.5 AU	Ka-band	Bidirectional Backbone data
Mars low rate	1	400 km	Ka-, X-bands	Emergency, TT&C
Mars science orbiters	10	400 km	Ka-, X-bands	Multiple science S/C files
Mars surface robots	10	400 km	Ka, X-band	Multiple science S/C files
Mars human outpost	10	400 km	Ka-band	Bidirectional voice, HDTV, data
5) Mars orbit, atmosphere, or surface human or robotic entity link to:				
MSO low rate	1	10,000 km	Ka-, X-bands	Emergency, TT&C
MSO high rate	100	10,000 km	Optical, Ka	Multiple science S/C files
MHO low rate	1	4,000 km	Ka-, X-bands	Emergency, TT&C
MHO high rate	100	4,000 km	Optical, Ka	Multiple science S/C files
MLO low rate	1	1000 km	Ka-, X-bands	Emergency, TT&C
MLO high rate	10	1000 km	Ka	Multiple science S/C files
Earth terminal	0.1	2.5 AU	Ka-, X-bands	Emergency, TT&C
Earth orbit relays	10	2.5 AU	Ka	Multiple science S/C files
6) Mars outpost wireless local area network (WLAN) link to:				
Mars surface/atmosphere entity	>100	100 m	Ka-, X-, C-bands	Bidirectional, multipoint, voice, video, remote control, data, emergency.
Mars surface/atmosphere entity	>50	50 km	Ka-, X-, C-bands	Bidirectional, multipoint, voice, video, remote control, data, emergency.

V. Conclusions

In this paper, we have described a space communication architecture that can meet the challenging requirements for human and robotic exploration missions to the Moon and that can evolve to enable and enhance human and robotic exploration missions to Mars. The systematic identification of the communications architectural elements and of the optional ways they can be implemented serves as valuable tool for indicating to the mission planner and scientist the possible communication capabilities that can be realized by the alternative configurations. It serves well for constructing strawman architectures for evaluating which options have the highest payback potential. Extensive system cost and risk analysis and trades will be the next logical step to refine the architecture for implementation.

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13. ABSTRACT ***(Maximum 200 words)***

Space communications architecture concepts play a key role in the development and deployment of NASA's future exploration and science missions. Once a mission is deployed, the communication link to the user needs to provide maximum information delivery and flexibility to handle the expected large and complex data sets and to enable direct interaction with the spacecraft and experiments. In human and robotic missions, communication systems need to offer maximum reliability with robust two-way links for software uploads and virtual interactions. Identifying the capabilities to cost effectively meet the demanding space communication needs of 21st century missions, proper formulation of the requirements for these missions, and identifying the early technology developments that will be needed can only be resolved with architecture design. This paper will describe the development of evolvable space communication architecture models and the technologies needed to support Earth sensor web and collaborative observation formation missions; robotic scientific missions for detailed investigation of planets, moons, and small bodies in the solar system; human missions for exploration of the Moon, Mars, Ganymede, Callisto, and asteroids; human settlements in space, on the Moon, and on Mars; and great in-space observatories for observing other star systems and the universe. The resulting architectures will enable the reliable, multipoint, high data rate capabilities needed on demand to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of outposts in-space, on the Moon or on Mars.

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