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Space Internet architectures and technologies for NASA enterprises

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SUMMARY

NASA's future space communication needs and requirements will be addressed through a space communications network that mirrors the terrestrial Internet in its capabilities and flexibility. NASA's needs and requirements for future data gathering and distribution by this Space Internet have been obtained from NASA's Earth Science Enterprise (ESE), the Human Exploration and Development in Space (HEDS), and the Space Science Enterprise (SSE).

To address NASA's future needs, we propose and describe an integrated communications infrastructure based on Internet technologies, the architectures within the infrastructure, and the elements that make up the architectures.

The architectures meet the requirements of the enterprises beyond 2010 with Internet compatible technologies and functionality. The elements of an architecture include the backbone, access, inter-spacecraft, and proximity communication parts. From the architectures, technologies have been identified which have the most impact and are critical for the implementation of the architectures. Published in 2002 by John Wiley & Sons, Ltd.

1. INTRODUCTION

NASA and its enterprises continually generate strategic, mission, and technology requirements plans [1]. The requirements identified from these plans for NASA's communications infrastructure beyond 2010 include handling real time data delivery at high data rates with large data sets; provisioning for secure data movement and operations; seamless interoperability between in-space entities; and enabling end-to-end interactivity between the user and the in-space instrument. The open standard interconnection (OSI) seven-layer model or its derivatives married with standards compliant networking interfaces and modern high data rate microwave and optical hardware are essential ingredients of a communications architecture that can accomplish the identified requirements [2–5]. Significant increases in the quantity of data handled and the simplification of delivering that data to its destination are advantages expected

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from this combination. By incorporating Internet or Internet-like technologies throughout its communications infrastructure, NASA can freely tap into the continuous improvements in data delivery and capability that other developers bring to the Internet [2,6,4].

NASA's communications infrastructure has grown out of the need to provide special services to each new mission as they were implemented. A vertically organized mission used infrastructure pieces that were designed to that single mission's requirements—resulting in communications assets only useful to that single mission. While it was possible to reuse some of the assets, such as the larger ground antennas, even these had to be modified to handle new mission requirements as they came along. Since this hardware was designed to operate at the lower frequencies (S- and X-band) and was not designed for flexibility, it has been increasingly difficult to bring the assets up to the capability of the commercial satellite systems that now operate at very high bit rates in the K-band.

NASA must consolidate its communications assets into a more horizontal infrastructure so that the capabilities can be used to the advantage of any kind of mission that may wish to 'plug-in' to it [8]. The infrastructure must be revised to meet general specifications rather than meet any specific mission's requirements. Missions would then be designed to interface to a general, highly capable, and standardized infrastructure [6,8,4,5]. Once the infrastructure has been 'flattened' and modified to provide high qualities of service to any mission type, further developmental activity will concentrate on continuous improvement of the capabilities of the infrastructure to the benefit of all missions.

We believe the architectural elements within the infrastructure will evolve to realize autonomy, flexibility, and reliability for the missions, for the networks, and for operations. This can only be achieved by including intelligent, interactive, and reconfigurable functions in the hardware and software layers throughout the infrastructure.

The NASA space communication technology programs have taken on the early development of the hardware and software technologies needed to make the initial changes to the infrastructure and enable it to surpass the present commercial communications capabilities. However, NASA is also aware of and will take advantage of the capabilities offered by the Internet and its technologies. One of the primary advantages of the Internet is that it is truly horizontal in its structure. That is, anyone can procure a computing device, connect to the Internet, and communicate through it because of the great flexibility and highly diverse set of open interoperability standards that the Internet conforms to and that are provided within each computing device.

The basic architectures discussed are those that are needed to support three of the NASA enterprises: the Earth Science Enterprise (ESE), the Human Exploration and Development in Space (HEDS), and the Space Science Enterprise (SSE). These architectures were inspected for similar aspects that were broken out as separate architectural elements.

Figure 1 displays the extent of the infrastructure as it is today. To communicate with his/her instrument on a spacecraft, a scientist must first co-ordinate activities with a science operations team who, in turn co-ordinates with a mission operations team. The mission operations team co-ordinates the scheduling of the space network (SN), ground network (GN), or deep space network (DSN) assets, whichever are to be used, so as to achieve connection with the user's spacecraft for up-link of commands or down-link of data. The output of the series of activities is a highly controlled set of command directives that are sent to the instrument. The instrument later produces a data stream that is sent back through the system, decoded, and captured first by mission operations and then passed on to science operations for sorting into data files and saved

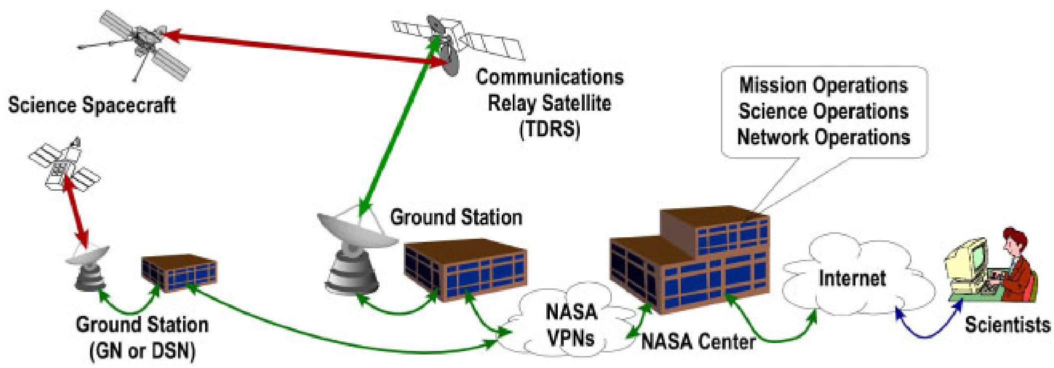

Figure 1. Present NASA communications architecture.

in data storage. This infrastructure requires a considerable amount of operations support and does not enable the real time interactive operation feedback loop of instrument output followed by timely user response. It does not allow the scientist easy access to the instrument's controls as is the case with laboratory or even remote controlled field instruments on Earth.

NASA is now striving for an architecture that provides transparent end-to-end connectivity (see Figure 2) between the scientists, the mission spacecraft, and instruments. Transparency here implies the user need not know nor be skilled in special procedures to interact with a mission instrument or spacecraft. All procedural issues are handled autonomously by software at the user's computing device, within the communications infrastructure's control systems, and on-board the spacecraft itself—much like data are moved and handled autonomously by the Internet. From the instrument and spacecraft perspective, transparency implies that the communications interfaces are standardized and that the spacecraft can request service and obtain it from any of the communications assets that are listening.

This new architecture is based on Internet technologies. Mission operations, science operations, hardware and spacecraft vendors, and the public (providing they are authorized), are afforded the same high rate connectivity to NASA's exploration, science, and hardware. This architecture enables the scientists and all operations personnel to break free of the serial task-passing mode described above for operating present mission spacecraft and instruments.

The general infrastructure for this space Internet [2,6] is discussed below and includes the architectural elements shown in Figure 2:

- Backbone network (BN)—SN, GN, NASA's Intranets and virtual private networks (VPNs), the Internet, and any commercial or foreign communications system that may be employed;
- Access network (AN)—the radio and/or optical communication interfaces between the backbones and the mission spacecraft and/or vehicles, and the local area networks (LANs) on-board the spacecraft and/or vehicles;
- Inter-spacecraft network (IN)—the radio and/or optical communication interfaces between spacecraft flying in a constellation, formation, or cluster;
- Proximity network (PN, not shown in the figure)—the radio and/or optical communication interfaces between vehicles (rovers, airplanes, aerobots), landers, and sensors spread out in an *ad hoc* network.

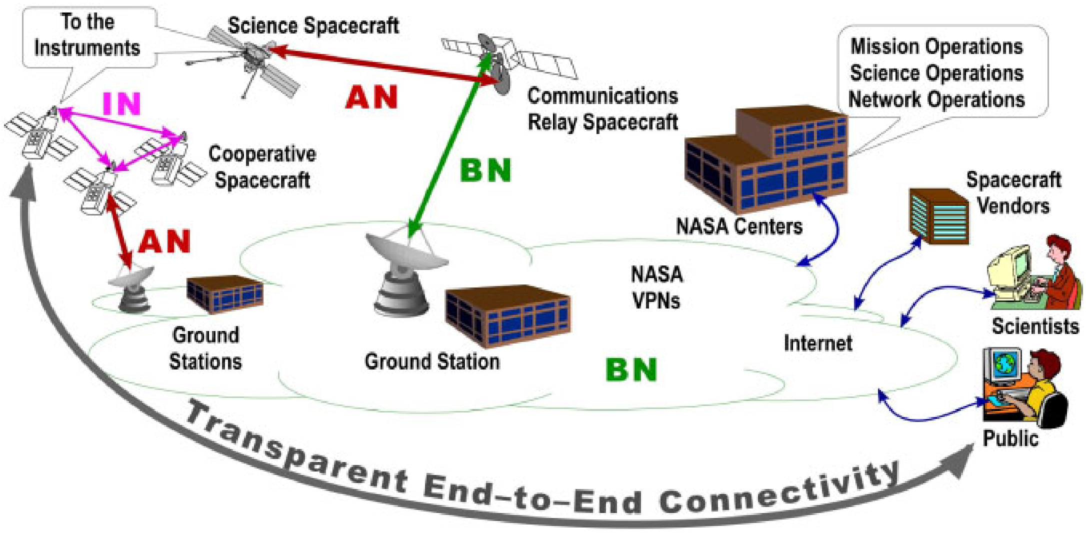

Figure 2. NASA's future space Internet communications architecture.

2. ENTERPRISE REQUIREMENTS

2.1. Earth Science Enterprise (ESE)

The technologies for the Earth Science Enterprise (ESE) missions enable very high rate data transfers between the ground and low earth orbit (LEO), the Moon, and the vicinity of Earth's orbit around the sun. The new technology initiatives in high bandwidth microwave and optical links and in the space Internet enable direct data distribution to the scientist and public, high rate image processing and delivery, and the gathering of specialized products for environmental monitoring and forecasting. Lightning and rain correlations, storm, fire, and plume gas tracking, crop and ocean health and pollution monitoring, etc. are all improved with near real time finished data product availability to any interested person on the Internet.

Missions use the access and backbone networks to pass high rate data, low rate telemetry, and commands between the spacecraft and ground. Missions supported by ESE networks include the Earth Observing System (EOS), NOAA weather satellites, Landsats, and others.

With the future communications architecture a mission could use, at its convenience, the SN, or a commercial communications satellite system, or the GN as they would all present similar wireless interfaces and protocols as the access links for the user spacecraft. NASA is developing the standard interface technologies for the access and backbone networks that are needed to enable a spacecraft to connect through any network system. Whether or not a mission needs the flexibility to connect to any backbone is then left up to the mission development team. The plan is to have the capability in-place.

The technologies for inter-spacecraft networks will apply to any co-operative multi-spacecraft missions that are implemented. Missions of this type being considered include: Leonardo, a loose formation flying cluster of 6–12 spacecraft that are each measuring and correlating between themselves the light reflected back through the top of the atmosphere; and sensor webs made up of disparate mission spacecraft (such as Earth Observing and Landsat spacecraft) flying in collaborative formation and exchanging data to co-ordinate and synchronize measurements over areas of common interest to all the missions.

ESE will also benefit from work on low power proximity networks. Ground, sea, air, and space sensors that measure Earth's parameters will communicate with each other and with data gathering spacecraft using these proximity technologies.

2.2. *Human Exploration and Development in Space (HEDS)*

The HEDS enterprise will benefit from the very high data rate transfer capabilities of the future networks. These technologies provide clear examples of the advantages of developing for the general benefit of the NASA enterprises rather than for specific mission requirements—all missions get a better overall system. General technologies that benefit HEDS include Ka/Q/V-band and optical technologies, utilization of commercial satellites, and improved utilization of government communication satellites. Other features of general utility are direct data distribution to the scientist and public, and IP-based communications for shuttle and the International Space Station (ISS) which will handle voice, video, data, and emerging commercial and military broadband services.

Self forming and dissolving *ad hoc* proximity networks may be necessary for the co-ordination and safety of work in the external ISS vicinity. These *ad hoc* networks are an important part of several mission concepts under study in the other enterprises. It's likely that common solutions can be found that would be inherently superior to re-inventing these networks for individual missions. Solutions already emerging from the commercial sector are the IEEE 802.11 and the European originated Bluetooth specifications as well as the open and the proprietary specifications for the cell phone environment. IEEE 802.11 and Bluetooth are tailored for communication between multiple computers in a slow mobile environment. Bluetooth generally operates below 1 Mbps but IEEE 802.11 can operate at respectable speeds ranging from 2 to over 50 Mbps. At these speeds, members in an *ad hoc* group around the vicinity of the ISS can easily pass voice and video between them to enhance safety and improve in-space work effectiveness. These specifications handle communications in an *ad hoc* group by autonomously picking up new members and dropping off those that pass out of the range of the group. Secure communications utilizing these ad hoc systems is important to prevent unauthorized access. Security is incorporated into the space networking protocols and will continue to be an important aspect of space networking.

2.3. *Space Science Enterprise (SSE)*

Technologies for the SSE are derivations from the technologies being developed for the other enterprises. Deep space missions and missions to Mars will also take advantage of the high bandwidth microwave and optical links being developed for general use. The Mars Network will eventually employ surface-to-orbiter access links and surface-to-surface proximity networks, as well as the K-band and optical link technologies that are also being developed for ESE and HEDS.

The Earth-side networks for SSE include the GN and the deep space network (DSN). The GN is used to communicate with the in-space observatory missions of the Astronomical Search for the Origins and Structure and Evolution of the Universe theme programs and with the Earth-orbiting and solar observing missions posed by the Sun–Earth Connection theme program. The DSN is used to communicate with spacecraft normally beyond 1 AU, such as the Mars Exploration Program missions and the missions to the inner and outer planets and small bodies.

In-space observatory missions being considered for implementation include the Terrestrial Planet Finder (TPF) and the Micro-Arcsecond X-ray Imaging Mission (MAXIM). TPF is a mission of five formation-flying spacecraft acting as an interferometer that can cancel the halo of light around a star and make visible Earth-sized planets residing within the halo. MAXIM is a 36 spacecraft, formation-flying mission that forms a high resolution X-ray telescope for viewing the event horizon of a black hole. Future observatory missions will likely be placed in the vicinity of Earth—from LEO out to the libration points at L1, L2, L4 and L5 (see Figure 3). The access networks for these observatories will utilize Ka-band communications and become IP compliant such that data from the observatories will be available to scientists and the public in near real time. The networks will enable each using scientist, in turn, to have full control of an observatory via the Internet.

Earth orbiting missions include atmospheric chemistry, physics, earth plasma, and solar wind interaction experiments such as the Geospace Electrodynamic Connections (GEC), Magnetospheric Constellation (MC), and Magnetospheric Multiscale (MMS) missions. Five spacecraft flying in loose formation comprise the GEC mission for observing the electrodynamic coupling of the magnetosphere, ionosphere, and the atmosphere. The MC mission utilizes 40 or more spacecraft flying in 'petal orbits' around Earth to measure magnetic field variation to map the build-up and decay of trapped particles in the radiation belts due to solar storms. The five spacecraft of MMS fly in a loose tetrahedral formation that dwells at apogees at the key boundary regions of the Earth's magnetosphere to synchronously measure differences across the boundary layers. These missions are just a few of those being investigated for future implementation. These and other missions are described online at the enterprise sites, see Reference [1] for links to those sites.

Ground stations located at Goldstone, California, Canberra, Australia, and Madrid, Spain comprises the Earth-side of the DSN. The larger antennas, 34 and 70 m, form part of the backbone network to Mars and the access network for other deep space mission spacecraft. Ka-band upgrades continue to be made to the DSN. Optical communications from telescopes atop mountains may also be added as a DSN capability.

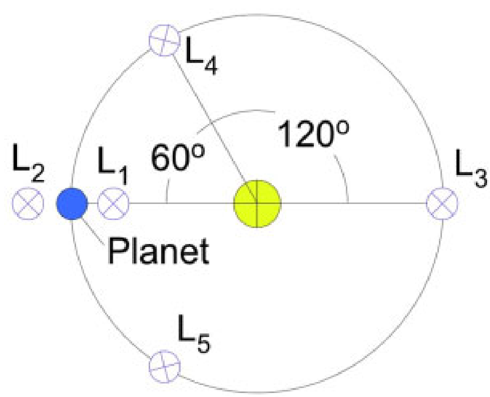

Figure 3. Stable Lagrange points associated with a planet.

Deep space communications delay times become too long for real time human interaction with a mission during critical and emergency operations. Because of this, mission spacecraft must perform critical and emergency procedures autonomously. A beacon mode system has been posed for modification of the DSN sites [7] to assist these autonomous operations and to reduce the overall cost of operations. This beacon system could be implemented with smaller diameter antennas that operate at very low bit rates. Some antennas would serve as lighthouse beacons that send timing and ranging return signals to spacecraft. A spacecraft receiving this beacon signal could then synchronize its clock with earth-time and could determine its distance from earth by timing the return of a signal it has sent to a receiving beacon and that was sent back by the lighthouse beacon. The spacecraft could also use one-way Doppler to determine its velocity relative to earth.

Once this beacon system is in place, a spacecraft would use it for sending low rate data back to earth to indicate the state of its health and to request communications service from the DSN. The beacon system will save costs by utilizing smaller antenna assets for the task of monitoring many spacecraft during the quieter phases of their missions and by enabling spacecraft to autonomously demand access to the larger assets only when needed for emergency or for support of mission critical data reception.

The present thoughts for a backbone network between Earth and Mars are to place three communications spacecraft in high altitude, high inclination ($\approx 60^{\circ}$) orbits about Mars. These spacecraft will usually be able to see each other and will cover fixed places on the surface for reasonably long periods of time. Most places on the surface will be in view of an orbiter most of the time. This simple constellation can support many surface and balloon activities at a time. The spacecraft would incorporate store-and-forward servers to temporarily hold data for transfer to another surface element or to the Earth. The spacecraft may also include inter-spacecraft communications links to pass data around Mars from one surface site to another or to the Earth.

In the more distant future, a solar system communication network could be implemented. It is assumed that in 20 years or so, most of the large flexible structure technologies would be in place so that large but lightweight communications systems could be placed in space at reasonable cost. In this concept, large antenna structures could be tethered together with a control spacecraft and a large solar array or nuclear power generator. The power source could provide power to all the units through wires in the tethers or by microwave beam. A control unit for this 'relay station' would act as a router for sending data received from earth through the appropriate relay antenna to a mission's spacecraft and for handling the mission's data return route. All units would handle their own pointing while the central control unit ensures that the units do not collide.

These relay stations could be placed at various Lagrangian libration points such as the L3, L4 and L5 points for the Earth, Mars, and Jupiter. Such relay stations could vastly improve the communications data rates to distant locations in the solar system.

3. ARCHITECTURE ELEMENTS

3.1. Backbone Network (BN)

The networks that comprise the backbone, indicated in Figure 4, include NASA's ground network (GN) and space network (SN—the tracking and data relay satellite system, TDRSS) [7]

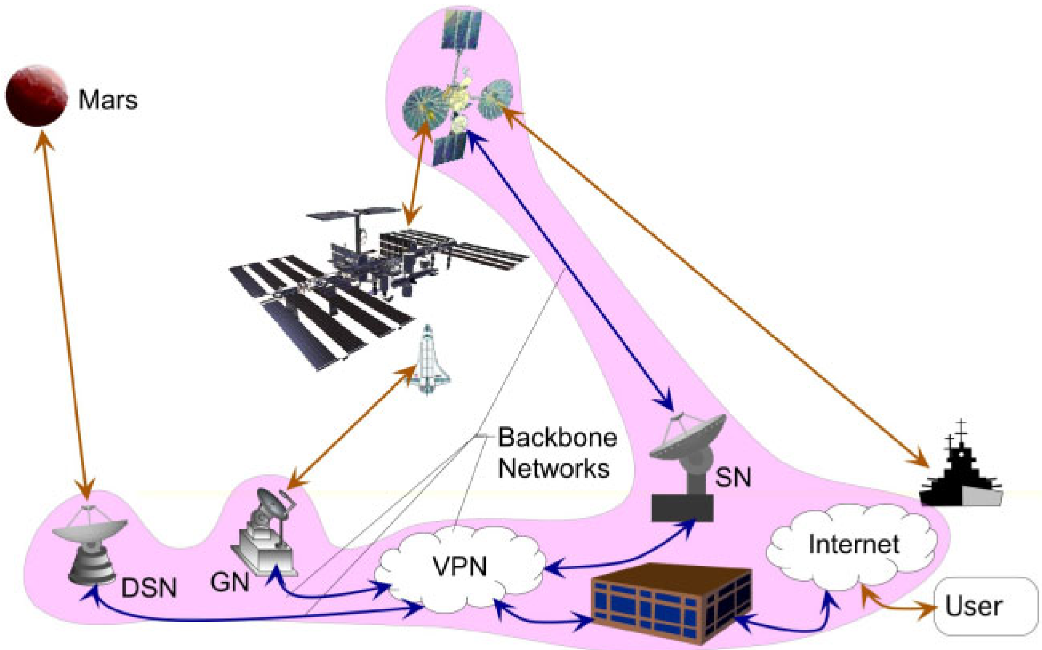

Figure 4. Backbone network elements.

and any commercial satellite systems that might be employed to provide communications services to NASA spacecraft. The backbone network also includes the VPNs that tie NASA's assets together. Information available through the backbone network includes data and tasking directives from: other spacecraft, vehicles, sensor networks, operations centres, archival databases, and users. The networks further enable pathways to foreign and domestic resources available on the Internet. These information access pathways can significantly improve a mission's science by enabling co-ordination of activities and by providing data to a spacecraft to facilitate on-board processing.

The data path through a backbone network is shown in Figure 5. The protocols levels that are used to handle the data that passes through the networks are shown on the left. The actual protocols to be used through the various network elements are under investigation. Protocols being considered at the data layer include asynchronous transfer mode (ATM), digital video broadcasting (DVB), high-level data link control (HDLC), and CCSDS transfer frame. At the network layer, IP is the main consideration for near Earth missions because it is compatible with ground networks. At the long distances to the inner and outer solar system, the SCPS network protocol (SCPS-NP) may be used because it is more compact than IP. Protocols presently being studied at the transport layer include transport control protocol (TCP) for Earth-orbit missions and user datagram protocol (UDP) and SCPS transport protocol (SCPS-TP) at the longer distances. At the application layer, file transfer protocol (FTP), CCSDS file delivery protocol (CFDP), simple mail transport protocol (SMTP), multicast dissemination protocol (MDP), network time protocol (NTP), and others are being studied for use in the space networks. In

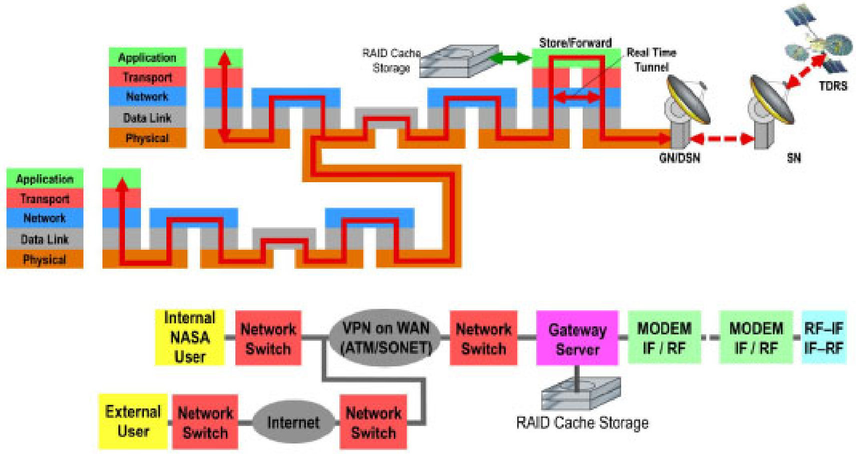

Figure 5. Backbone network model for GN, DSN, and SN.

Figure 5, the unlabelled protocol levels are shown to give a sense of where protocol conversions are likely to occur in the networks.

Notionally, the user connects to the backbone via NASA's Intranet by dial-in connection or local Ethernet, as implied by the internal users in the figure, or through a secured route from the external user over the public Internet. The middle two network switches in the figure are at a NASA centre on the NASA Intranet. The Intranet is connected to a ground station via the rightmost network switch and through a VPN allocated on a wide area network (WAN) provided by a private company. Physical layer technologies that may be used on WANs include asynchronous transfer mode (ATM), synchronous optical network (SONET), and frame relay. The ground station's LAN is most likely Ethernet or ATM. When the backbone is directly connected to a user spacecraft, the data can be directly passed on through to the user in real time, assuming the user is online or has an online autonomous system for capturing data. If the spacecraft is communicating with a NASA backbone network but the user is not connected to the backbone (e.g. when the WAN connection is down), tasking or science/telemetry data (depending on which entity is connected) is temporarily stored on a gateway server's fast redundant array of inexpensive disks (RAID) to be passed on later when a connection is established. User spacecraft connect to the backbone via modulated microwave or optical signals. The present interfaces are the antennas of the ground network (GN—NASA sites, foreign sites, and corporate sites), the tracking and data relay satellites (TDRSs) of NASA's space network (SN), and the antennas of the deep space network (DSN).

Of the new communications technologies being pursued by NASA, many will enable significant improvements to the backbone network. Table I identifies the type of technology and the title of each development in the left column. The pertinent parameters, today's state of the art (SoA) for those parameters, the near term (3–10 years) target values of the developments, and the projected values for the parameters in the future (beyond 10 years) are all also shown in the table. New BN implementations will be based on the results of the architecture and software studies. The new software tools identified in the table will be used to test network protocols and

Table I. Backbone network technologies.

Technology	Parameters	State-of-the-art	Near term	Future
Study-backbone networks Backbone network	Freq regimes: Links:	S-, X-, Ku-Band Direct & bent pipe relay (SN)	Ka-, W-band Direct & bent pipe	Optical Smart relays (light weight)
Communication architectures	Inter-operability:	None	Common frequencies and protocols	IP compatible
Software tools Internet over broadband hybrid networks and high data rate satellite networks	Protocol design:	TCP/IP & TCP/IP over ATM multicast with FEC and smart nodes	Efficient HDR connection to ground, caching, multicasting, mirroring	Multicast caches, prefetching, resource allocation
	Network design tools:	Tools to model large HDR sat. systems, traffic models, bandwidth allocation for multimedia, OPNET modeling of TDRSS-like systems	Broadband tools for QoS, Commercial broadband to ISS	
Software tools Modeling, simulation, and performance evaluation of hybrid networks	Design tools:	Internet over satellite simulation, traffic models, ISS comm. Scenarios, CORBA, JAVA, UML to networks	Algorithms and S/W for large hybrid networks, architecture trade-off analysis tools	Payload, traffic modeling, and dimensioning estimation
Software IP infrastructure for distributed space systems	Down time occurrences:	Unreliable, multiple failures due to protocol design	Fully reliable in normal environments	Fully reliable in adverse environments
Microwave Ferroelectric reflectarray	Frequency: Phase shift loss:	Ka-band 6 dB in	Ka-band <3 dB	Ka-band 1 dB
Microwave	Frequency:	Ka-band	3 Ka-band & 1 X-band Ant	Ka-band
MEMS actuator-based reconfigurable antenna	Switching: Insertion loss:	10 μm/sw	5 μm/sw 3dB	1 μm/sw

Microwave Hi-efficiency Ka-band MHEMT MMIC	Frequency:	Ka-band	25 – 27 + 32 GHz	
	Tx power:	0.1–4 W	0.1–4 W, SOA	
	Efficiency:	30%	45–50%	
Microwave Constant efficiency traveling wave tube high power transmitting sources	Frequency	8–32 GHz	32 GHz	To 100 GHz
	Power	30 W	30–100 W	To 200 W
	Efficiency	30%	50%	To 70%
Microwave Multibeam antennas reconfigurable antennae	Frequency:	Ka-band	Ka-band	Ka-band
	Bandwidth:	2% of centre frequency	7–10% of centre frequency	
Optical/Laser Fine pointing laser tracker	Pointing accuracy		100 nanoradian	
Optical/Laser Efficient deep-space lasercom source	Data rate	New	1 MHz from Mars	100 MHzs from Mars 1 MHz from Jupiter
	Power	New	1–10 W	To 100 W
	Efficiency	New	10%	30%

applications for the BN in real time simulations. The new BN hardware developments are largely focused on very high data rate, high frequency microwave and optical transmission and reception.

3.2. *Access Network (AN)*

The microwave and optical interfaces to the outer edges of the backbone networks for mission spacecraft, vehicles, and other entities comprise the access network. These interfaces, shown in Figure 6, include the remote entity's modem, receiver, transmitter, and antenna as well as the backbone's matching set. Information can also be obtained by direct communication to other spacecraft or landed vehicle or stationary entities. For instance, an over-flying earth observing spacecraft might access data from meteorological buoys and balloons and then integrate that data with its own observations of ocean waves, temperature, etc. to form complete data set files for download and use by anyone. The access network provides the technologies for moving many of the data reduction tasks to the on-board processor.

As future on-board networks become compliant with Internet protocols (IPs) or Internet-like protocols, such as the Space Communication Protocol Specifications (SCPS) posed by the Consultative Committee for Space Data Systems (CCSDS), they will also come to resemble ground-based LANs. In the case of a science spacecraft, the on-board LAN (see Figure 7), a part of the access network, provides the interfaces for the science instrument to access information and services from the on-board resources [7].

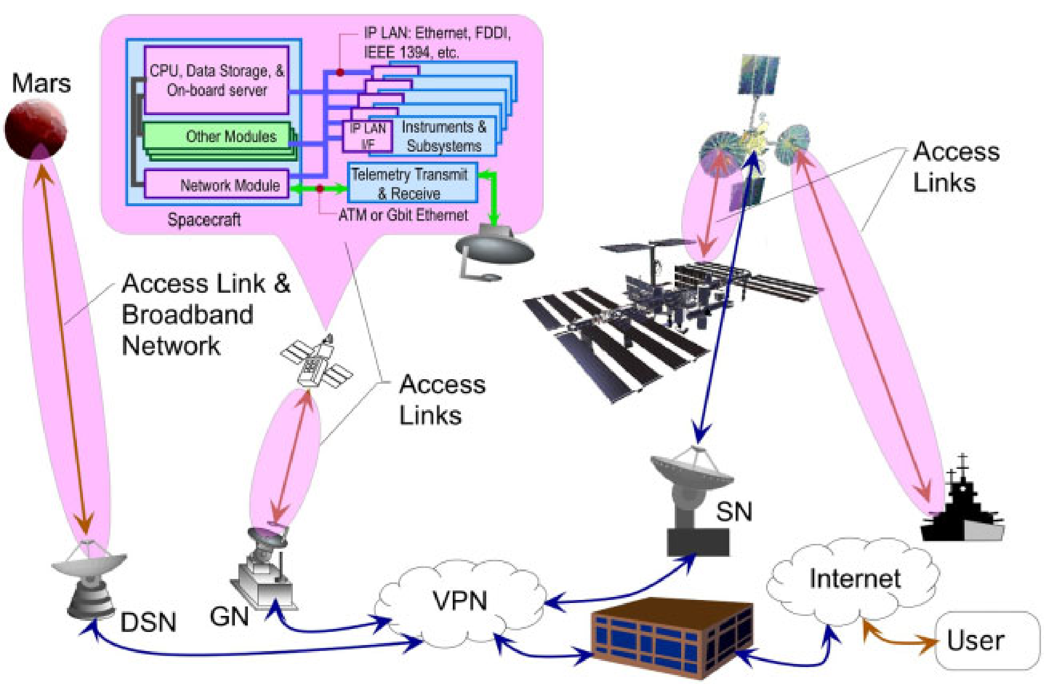

Figure 6. Access network elements.

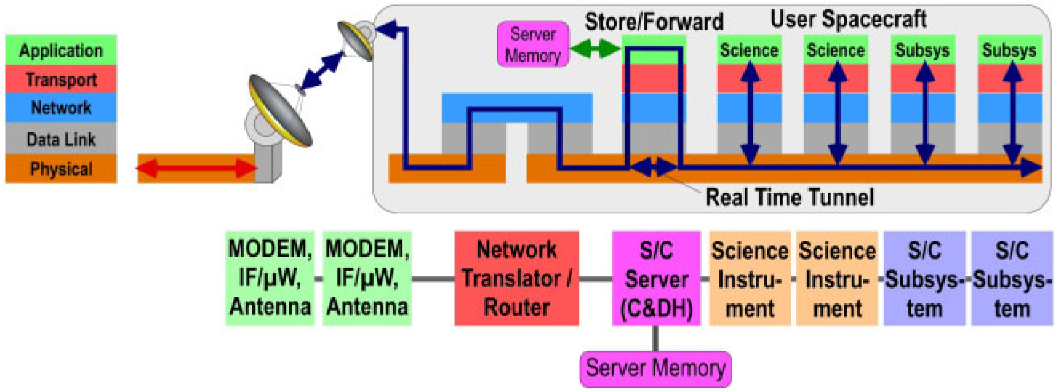

Figure 7. Access link model—for spacecraft to backbone connection.

The information passed over the spacecraft bus might include time and events data from the spacecraft subsystems, co-ordinated science data from other instruments, and overlay data provided from the ground or other spacecraft. Services provided by the spacecraft could then include science data file storage, communications, protocol translation, data routing, autonomous mission operations control [7], high level data product generation, and etc. Further, the instrument, via the on-board server and communication hardware, is able to access a backbone network node that connects the spacecraft to NASA's Intranet, the Internet, and ultimately the user. When the spacecraft is connected to the backbone, and the user is also online, real time communication with on-board LAN-connected instruments, and subsystems is possible. The on-board server, acting as a proxy for the ground-based user, stores data that is gathered during times when the spacecraft is not connected to the backbone and then autonomously relays that data to the ground when a communications path is established.

Table II identifies the new technologies in development for the AN that are used to connect to the BN. These technology developments include the network connection protocols and software and control software for the microwave hardware interfaces. Spacecraft LAN hardware and protocol software are also included as AN developments. The microwave and optical hardware being developed will greatly improve data rates near the Earth and deep into space. Data rates well into the gigabit per second rate in the near Earth environment will be possible with the Ka-band traveling wave tube (TWT) and laser developments shown in the table.

3.3. Inter-spacecraft Network (IN)

Spacecraft that fly in co-operation, such as in constellations, tight formations, or loose clusters, incorporate an inter-spacecraft network for local communications and co-ordination. Such geometries may use a wireless interface (microwave or optical) or a tether interface (wire or fibre optic) to interconnect neighbouring spacecraft. In many concepts the inter-spacecraft network also takes part in the measurement of relative position between spacecraft.

A few geometries for formation and cluster flying are shown in Figure 8. It is possible to assign several ground stations to communicate with each spacecraft in a formation or cluster simultaneously. This type of operation is difficult to co-ordinate, however, and stretches the

Table II. Access link technologies.

Technology	Parameters	State-of-the-art	Near term	Future
Software protocol modules Space data direct delivery to multiple clients	Multicast delivery regimes	Unsecured GEO broadcast without acknowledgement	Unsecured to 10 clients	Secure to > 10 Clients
Hardware & protocol software Spacecraft network devices	S/C NIC, Hub, router Activities	MILSTD1553, 1773	TCP/IP compatible now under evaluation Evaluate IP HW/SW functionality, throughput, reliability, security and encryption, network management, mass, power, volume, and cost.	
Hardware	S/C LAN's:	IEEE1553, RS422, VME	IEEE1394a, CAN	IEEE1394b, 1G Ethernet,
Local area network for space based instrument control	Wireless LAN's:	None	802.11b, ATM	Wireless 1394, 802.11a
Control software *Ad hoc* networks in space & surface	Software: Software network:	Control data rate Mission unique, early CCSDS	Control X-mit power, pointing IP, SCPS	Control position IPv6
Software				
IP infrastructure for distributed space systems	See Broadband Network Technologies above			
RF hardware High efficiency miniature TWTA	 Frequency: Tx power: Efficiency: Size/mass:	 Ka-band 10 W 27% 11 cm at 1.1 kg	 Ka-band 20 W 60% <5 cm at 0.4 kg	 W-band
RF hardware SiGe radio frequency solid state power amplifier	Frequency: Tx Power: Efficiency:	8.4 GHz 0.26 W 28%	8.4 GHz 5 W 40%	

RF hardware Constant efficiency traveling wave tube high power transmitting sources	Frequency Power Efficiency	8–32 GHz 10 W 30%	32 GHz 10–30 W 50%	To 100 GHz To 50 W To 30%
RF software Mod., coding, and interference cancellation in satellite & hybrid wireless networks	Frequency reuse: Bit error rate:		4:1 4–6 dB improvement	
RF hardware Low power SOI CMOS transceiver	Frequency: Data rate at distance: BER:		437.1 MHz 0.1–10 Kbps @ 1000 km 2.5 dB	
RF hardware Multibeam antennas reconfigurable antennae	See broadband network technologies above			
Laser hardware Liquid crystal based beam steering device	Steering angle: Pointing accuracy:		Milliradians Sub-microradian	Microradians <100 Microradians
Laser hardware Efficient deep-space lasercom source	See broadband network technologies above			

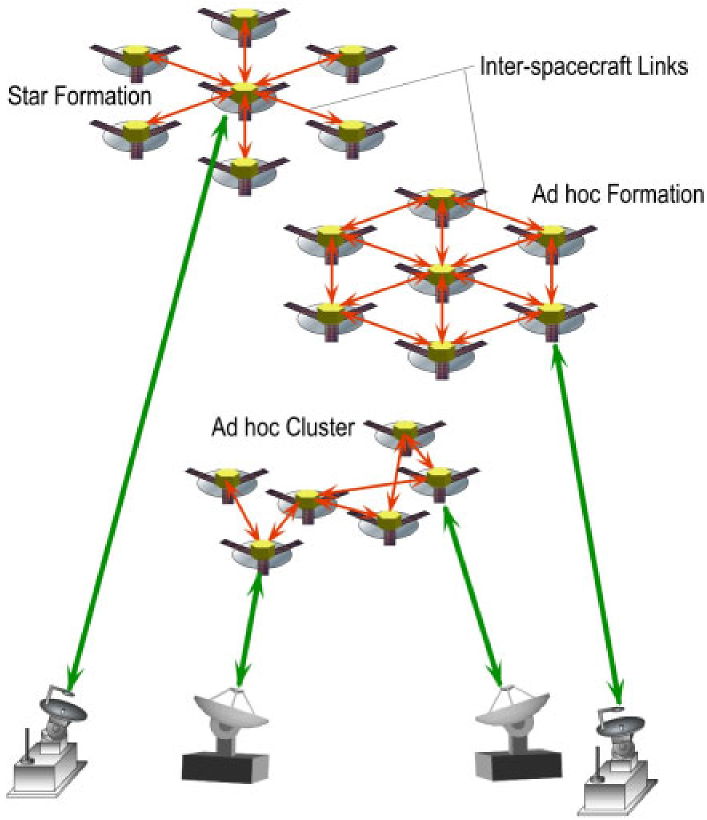

Figure 8. Inter-spacecraft network elements.

capability of the backbone. For that reason, a good solution is to assign a single member of the formation to handle the access network interface responsibilities between the formation and the backbone network. Tight flying star formations that use a single spacecraft to co-ordinate the operation and control of the formation's members might also use that spacecraft to handle the communications tasks.

In *ad hoc* formations or clusters, the access link with the backbone network may be passed off to any one of the members. The member that accesses the backbone would act as a conduit for the other members to send their data to the backbone. The figure shows only a few possible co-ordinated structures. NASA will continue investigating these and other structures to find optimum ways of operating each, identifying the technologies needed to make them work, and synthesizing requirements for those technologies.

Figure 9 indicates that the wireless inter-spacecraft communications network could, in effect, be treated as an extension of each spacecraft's on-board LAN so that they meld into a common formation LAN. With this simple construct, data sharing for distributed processing can be accomplished easily with file transfers between instruments computers on different spacecraft as though the LAN existed in a laboratory on Earth.

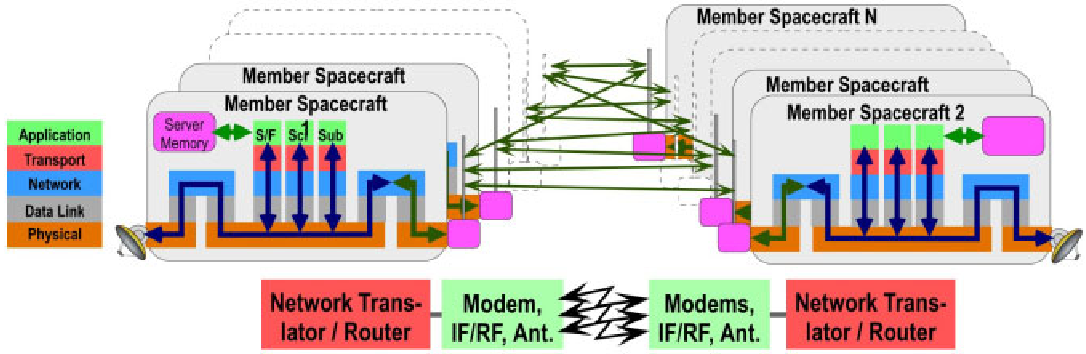

Figure 9. Inter-spacecraft link model—for spacecraft to spacecraft connections.

Table III shows those technologies under development that address the needs of inter-spacecraft communications. Hardware and software technologies that particularly benefit the inter-spacecraft network are those that result in highly agile microwave beam pointing antenna and receiver/transmitter systems capable of operating at data rates above 1 Gbps while handling simultaneous spacecraft conversations. Quality of service (QoS) selection is important to all NASA missions as some data are not time critical, while other data sets, such as video and voice, may have some losses, but must be sent on a fixed periodic schedule. While QoS is not as critical for many missions (since they can be guaranteed the entire access link to the backbone when the mission has connected because a ground antenna can only communicate with one mission at a time), it is critical for some missions and will be addressed in network development. QoS for inter-spacecraft communications can be handled by scheduling media access control with schemes that incorporate space division multiple access, time division multiple access, code division multiple access, or combinations of these.

Several testbed and software developments are relevant to the inter-spacecraft network. Much of that effort is directed at testing of commercial and new concepts for media access control (MAC) to maximize data rates in transfers between simulated spacecraft.

3.4. Proximity Link (PN)

Closely spaced, landed and airborne entities (vehicles, stations, sensors, balloons, etc.) will intercommunicate using low power proximity networks in an *ad hoc* fashion. As shown in Figure 10, entities in a local area form a flexible network to pass data between them and to pass data to entities designated as co-ordinating nodes. Over-flying orbiters can act as short term members of the landed *ad hoc* group by passing data between entities that cannot 'see' each other well enough to communicate. The over-flyers would also relay the group's finished data to earth and pass mission tasks from earth to the group.

The proximity network protocol structure shown in Figure 11 is similar to, but simpler than the IN structure shown in Figure 9 in that many of the entities will be operated with a single controller and will not incorporate internal LANs. The data rates will likely be somewhat lower due to the use of low power consumption communication and computing components. Most

Table III. Inter-spacecraft link technologies.

Technology	Parameters	State-of-the-art	Near term	Future
Testbed				
High-throughput distributed spacecraft	Physical MAC layer:	CDMA & TDMA	TCeMA	
	Accessibility:	Not available on demand	On-demand	Dynamic multiple connections
	Tx power:	New	Dynamic control	Smart control
Study				
Clusters/constellation architectures	Report:	Phase I tech Assessment and gap and feasibility completed	Phase I Tech Assessment and gap and feasibility completed	Study report for six satellite Leonardo missions
Protocol studies				
Advanced technologies for next generation in-space communications networks	Protocol studies:	'Smooth' satcom TCP, autonomous routing, MAC for mobile ad-hoc, multicast authentication, security, space caching schemes	Architectures for multipoint to multipoint comm., multipoint testbed, space and IPN simulation	
Software				
IP infrastructure for distributed space systems	See broadband network technologies above			
Hardware				
Local area network for space based instrument control	See access link technologies above			
Control software				
Ad hoc networks in space & surface	See access link technologies above			

RF hardware RF-microphotonics	Frequency:	None	Ka-band	Ka-band
	Bandwidth:	None	Development	X10
	Sensitivity:	None	Development	X10
	Power:	None	Development	/10
	Size:	$10 \times 10 \times 2$ cm	Development	/20
RF hardware Multibeam antennas reconfigurable antennae	See broadband network technologies above			
RF hardware Low power SOI CMOS transceiver	See access link technologies above			
Laser hardware Liquid crystal based beam steering device	See access link technologies above			

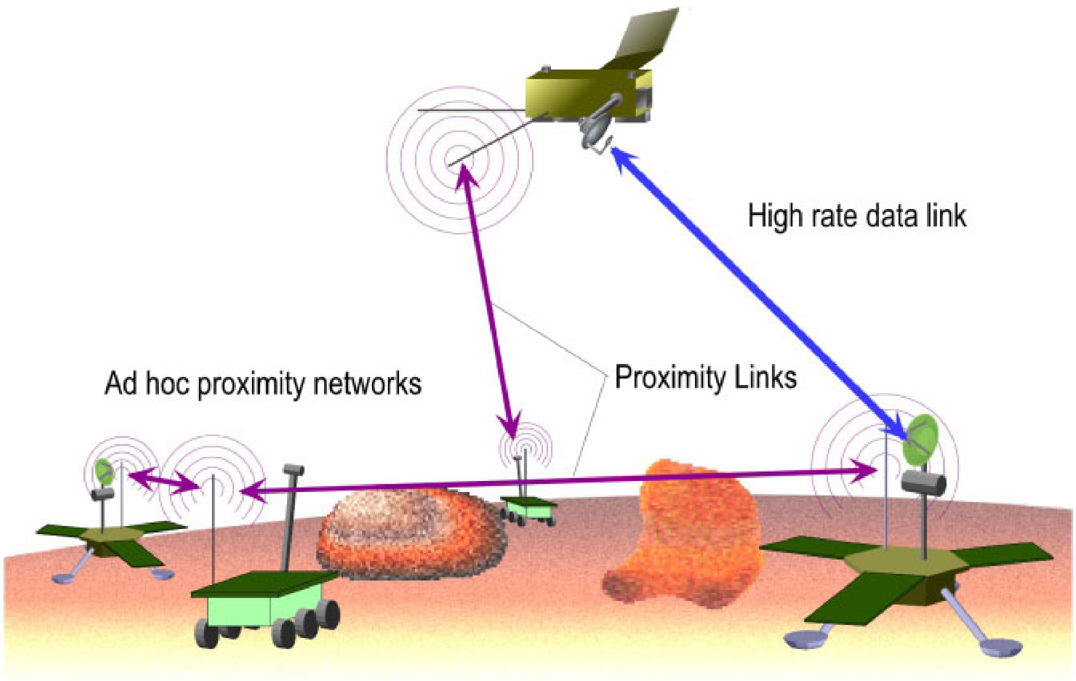

Figure 10. Proximity link elements.

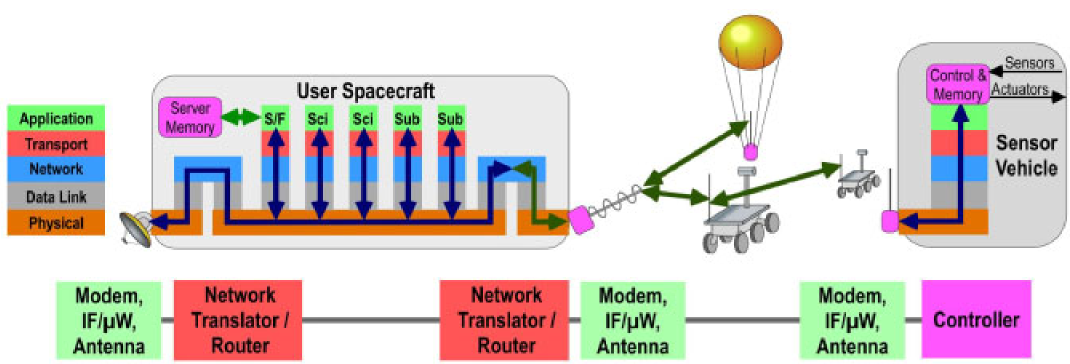

Figure 11. Proximity link model—Sensor net (landers, rovers, aerobots, airplanes, etc.) and to relay spacecraft.

simple sensor vehicles may be considered as connected (by PN) to a mother vehicle's LAN. The mother vehicle or lander may be considered to be a laboratory with remote roving sensors.

At higher data rates this *ad hoc* proximity network concept also provides a model for handling communications in the vicinity of the International Space Station (ISS). As activities around ISS increase with Shuttle and Soyuz arrivals/departures and human/robotic maintenance and build activities, the local communications system must be able to

Table IV. Proximity link technologies.

Control software Ad hoc networks in space & surface	See access link technologies above
RF hardware Low power SOI CMOS transceiver	See access link technologies above

autonomously reconfigure to accept new arrivals and drop-off those that leave. This proximity network can then be used to provide communications between all moving entities as well as provide a means of warning of impending collisions. The same network would provide video connectivity for an ISS co-ordinator to teleoperate robots or monitor and guide human activity.

The PN technologies identified in Table IV are control software for *ad hoc* networks and a low power silicon on insulator (SOI) CMOS transceiver. These technologies are also important for access to the backbone network.

4. CONCLUSIONS

This paper has described a new architecture to meet NASA's communications needs in the future. The requirements of NASA's enterprises, ESE, HEDS, and SSE, have been discussed.

The architectural variations encountered by each enterprise can be described in terms of a set of four architectural elements. The requirements of these elements have been identified and addressed with new technology developments initiated NASA. The suggested elements are the backbone networks, access networks, inter-spacecraft networks and proximity networks. By implementing commonality in wireless hardware developments and deriving each element's functionality from the Earth-bound Internet's technologies and protocols, cost savings can accrue from common use of these technologies; and the advantages of direct data distribution can be realized without the need for human assistance along the route.

Rather than develop entire new infrastructure to support a single mission, it is desirable to define and implement new architectural elements that can be evolved over time by adding new capability to service the new mission as well as any other new mission that may need similar services.

The implementation of advanced architectures will require high capacity, high rate, reliable microwave or optical communication technologies for the backbone for near Earth and deep space. Primary enablers for these advanced architectures include miniaturization of reliable network technologies and mobile protocols that are delay insensitive and operate with minimum data overhead. All in-space architectural elements will, in general, require highly miniaturized, low power, mass and volume network and wireless hardware. In addition, more interactive layer-based architectures and protocols and intelligent components will enable autonomous operation of the mission spacecraft and of the architectural elements within the infrastructure.

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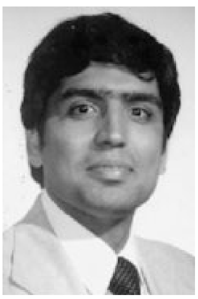

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