Communication Technologies and Architectures for Space Network and Interplanetary Internet

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***Abstract*—Future space exploration demands a Space Network that will be able to connect spacecrafts with one another and in turn with Earth's terrestrial Internet and hence efficiently transfer data back and forth. Currently there are hundreds of active space programs around the world that communicate in outer space. However, the concept of an Interplanetary Internet (IPN) is only in its incubation stage. Considerable amount of common standards and research is required before widespread deployment occurs to make IPN feasible. This paper presents a concise picture of the current space networking technologies and architectures. It discusses the Interplanetary Internet and Delay Tolerant Networking (DTN) concepts along with the various space networks that are currently deployed. The paper also identifies the significant areas of space network design and operation that still require extensive research and development.**

***Index Terms*—Interplanetary Internet, Delay Tolerant Networking, Deep Space Network**

I. Introduction

SPACE Communication and Networking research have added a new engineering and scientific era to the history of Space exploration. The early phase of space communication used radio signal shot towards spacecraft antennas whenever they came into view. Telecommunications software lacked universality and differed from one mission to another. This in turn led individual flight projects to acquire and operate their own specialized space communication network. The immediate answer was to develop a space network that can be interconnected, standardized and evolved over the future decades. Such motivations led to the development of various networking architectures and technologies that could support space communications – such as the Deep Space Network (DSN), Interplanetary Internet (IPN), Delay tolerant Networking (DTN) and so on.

This paper provides a complete picture of networking technologies and communications in deep space. It has been organized as follows. Section II of the paper discusses the general standards and technologies used for networking in space. Two notable deployments are introduced – the CubeSat which helps in satellite research and can be used for space network emulation, and the Mars Reconnaissance Orbiter (MRO) that gives us a perception of the 'close to Mars' deep space network. We discuss other networks that are already deployed to aid space network communications in Section III viz. the Deep Space Network (DSN) and satellite networks such as Telstar and Iridium. Section IV describes the Interplanetary Internet (IPN) and the Delay Tolerant Networking (DTN) technology, both of which acquire considerable importance whenever we discuss deep space networks. The differences between terrestrial and space networks, Interplanetary Overlay Network (ION) and the salient features of the Bundle Protocol are also elaborated in this section. Open research areas and challenges are discussed in Section V and finally in Section VI we conclude the paper.

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II. Space Network technologies and standards

Several satellites from different government space agencies and even private companies have been deployed in orbit over the past decades. As the number of space agencies started to increase, common standards were adopted so as to promote collaboration. The International Space Station (ISS) is a very good example of such efforts. Moreover, with increasing deployments the IPN can gradually build up its backbone to help communicate with the distant planets of the solar system. Figure 1 shows a graphical representation of the future where Earth based Internet will connect with remote networks of the solar system using satellite gateways and the IPN backbone. The remote networks will support different protocols and will connect to the backbone by choosing among satellite gateways that would seamlessly convert between these protocols. However, the present scenario is quite different from this futuristic vision. Today one cannot support a Earth orbiting spacecraft (relay) to a Mars orbiting spacecraft (relay) link, because the cost of constructing transceivers sensitive enough to receive/transmit signals over such large distances is so great that it is impractical to place such transceivers in orbit. We are still awaiting specific innovations that would make Space Networks feasible in the near future. The following sections discuss the common standards, technologies, protocols and notable deployments that will aid space network implementation in the future.

A. Space communication parameters

Space communication parameters are very specific to a mission and the operation or service required as well as the system which provides the service. The U.S. National Aeronautics and Space Administration (NASA) presently operates and maintains three separate tracking networks to support different types of missions - Deep Space Network (DSN), Near Earth Network (NEN) and the Space Network (SN). The DSN supports both Earth orbiting and deep space science missions while the NEN supports non-deep space missions in the 2 and 8 GHz bands range. The Space Network (SN), otherwise known as the Tracking and Data Relay Satellite

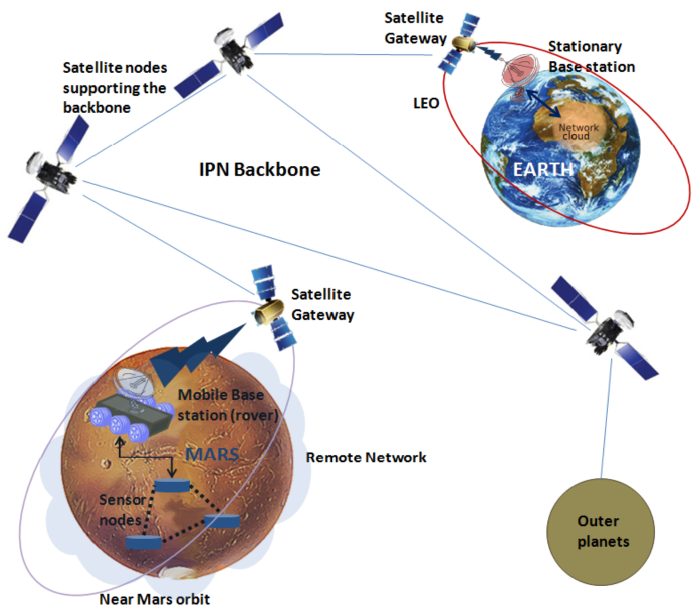


Fig. 1. A graphical representation of future Deep space architecture that portrays remote planetary networks communicating with Earth based Internet. The remote network chooses among mobile satellite gateways to hook up to the IPN backbone. The satellite gateways in turn act as an interface between the remote network and the backbone.

System (TDRSS) consists of seven geosynchronous satellites and ground stations that together operate in the 2, 13-15 and the 26 GHz band. The prime goal is to increase the data rates of satellite communication systems. SN is capable of data rates on the S-band (6 Mbps) and Ka-band (800 Mbps) Single Access (SA) channels. Among the three tracking networks, we concentrate on DSN communication which provides command, telemetric and tracking services to a large number of space missions.

Each service in DSN has its own parameter specifications. The command services of DSN mainly use the S and X band frequencies with Binary Phase Shift Keying (BPSK) modulation schemes. The 70 m antenna used for major space communications has a maximum transmitting power of 20 kW with a maximum uplink data rate of 256 kbps and a minimum of 7.8 bps. The data unit size has maximum and minimum values of about 32,752 bits and 16 bits respectively. Bit error rate for command services depends on a presumed signal to noise ratio at the spacecraft and is around 10^{-7} and the service availability moves within 95 to 98 percent at all times. For telemetric services both near-Earth and deep space missions use the S, X or the Ka band frequencies for communication. Modulation schemes can be Phase Shift Keying (PSK), BPSK or Quadrature Phase Shift Keying (QPSK). Downlink data rates are a maximum of 6 Mbps for deep space and 125 Mbps for near Earth and a minimum of 10 bps. The data unit size and transmitting power depends on further sub-division of telemetric service types and can be found at [1]. Service availability is the same as that of command services while the frame rejection rate is about 10^{-4} to 10^{-5} which in turn determines the data quality. More detailed information about cost and parametric values can be found at [1] which give us a clear idea about communication specifications for space networks.

B. Space Optical Communication

Space communication over the radio has been in use since the 1950s and is still considered as the most efficient means. However, the continuously increasing data from spacecrafts is pushing the frequency for telecommunication from the radio frequency (RF) bands to the optical frequency and near-infrared limits. Earlier, spacecrafts used the S-band (2-4 GHz) frequency for communication. After two decades, technology has shifted to accommodate the X-band (8-12 GHz) and then again after nearly another two decades the Ka-band (around 32 GHz) system is being used for deep space communication. The optical technology is still under research and it would take some more time for it to actually mature and be implemented widely. In Table I we give a comparative study of radio and optical space communication systems. We find that the main motivation for deep space optical communication arises from the fact that the radio frequency which is used for space communication, diverges or spreads over the deep space distances [2]. This considerably weakens the signal. Its reception on Earth becomes very difficult bringing in the need for extremely sensitive equipments. Optical waves offer very high frequencies and they have much less beam spread. The higher directivity of the optical beam also allows higher data/power efficiency (more Mbps for each Watt of power).

The first images sent from space to Earth using optical inter-satellite communication were that between SPOT-4 and ARTEMIS spacecrafts using the SILEX technology on November, 2001 [3] and it allowed a maximum data rate of 50 Mbps. However, the image was transmitted from the spacecraft to the ground station in Toulouse, France over the Ka-band link. In the near future, a new generation of terminals capable of laser communication will form the backbone of the European Data Relay Satellite (EDRS) system to be deployed around 2013 [4]. Data communication would take place at almost a rate of 1.8 Gbps. Atmospheric effects pose a big problem to the optical communication technology. However, it takes advantage of the vacuum in space, and its potential benefits will soon be exploited and commercially implemented in the near future.

C. Space data handling

Enormous amounts of critical data are returned from satellites and space missions every day. They need to be efficiently handled and stored. Horizons is an online data and ephemeris computation service provided by the Solar System Dynamics Group of the NASA Jet Propulsion Laboratory (JPL), based in Pasadena, CA. An ephemeris is a tabulation of computed positions and velocities (and/or various derived quantities such as right ascension and declination) of an orbiting body at specific times. Horizons includes system data of nearly 536,000 and more asteroids, 3000 comets, 170 natural satellites, all planets, the Sun, more than 60 spacecrafts, and several dynamical points such as Earth-Sun L1, L2, L4, L5, and system barycenters. Temporal information can be obtained to the nearest minute [5]. There are three different ways to

TABLE I
COMPARATIVE STUDY OF RADIO AND OPTICAL SPACE COMMUNICATION SYSTEMS ADAPTED FROM [8]

	RADIO	**OPTICAL**
Beam Divergence/ Beam Spread	High beam spread of around 0.15 to 0.25 degrees over a distance of 42,000 km	Much less beam spread of the order of 1 mdeg over the same distance
Antenna size	Antennas with large diameters are needed to capture the faint signals. Antennas on board satellites ranges from 3 to 5 meters in diameter whereas ground antennas are even larger to about 35 to 70 meters in diameter	Antennas designed to receive optical signals are comparatively smaller, for example the optical antenna on ARTEMIS was only 25 cm in diameter
Antenna cost and material	Since the antennas are so huge, lighter structures and materials become needful. It also degrades faster and incurs extra cost	Smaller antennas can be made with durable materials and replacing them is also very cheap
Antenna coverage and tracking accuracy	Radio communication allow a much larger coverage from a single point transmit. Close communication is ideal with radio signals	The coverage is negligible and it is essentially a point to point communication. It also requires a high precision pointing accuracy. Minimal vibration on board can degrade the BER (Bit Error Rate) quite a lot
Data rates	Low data rates	Very high data rates are possible in the range of Gbps
Power consumption	Power consumption is quite high in a range of 30 to 40 W for 1Gb/day data volume	Efficient power consumption because for the same power consumed by the Ka band it can transfer larger volumes of data. However, when data volume decreases the power consumption efficiency falls to the same as that of X band radio frequencies.
Legal issues	There are a set of strict legal specifications when radio spectrum is used for communication	Such legal specifications are at least still not there for optical communications

access the program. It can be done using telnet, email or a web interface. Details about how to connect and obtain useful information can be found in [5]. A Spacecraft and Planet Kernel (SPK) file is a binary file which may be smoothly interpolated to acquire an object's position and velocity at any instant within the file time-span. Such files can be produced by Horizons allowing quick retrieval of data analysis ephemerides without having to repeatedly integrate equations of motion. SPK format files can be read with the help of a software toolkit available at JPL's Navigation and Ancillary Information Facility (NAIF) website [6]. SPK files with ephemeris data of satellites and other larger planetary bodies can also be generated at the NAIF website. Underlying these applications we have the Planetary Data System (PDS) of NASA [7] which is an archive of data products from NASA planetary missions, sponsored by NASA's Science Mission Directorate. NAIF provides a navigation node to NASA's PDS so as to give access as well as archive data from the space programs. The "SPICE" system provided by NAIF gives us data and software suites that the scientists can incorporate in their own applications to read the SPICE data files. The SPICE software and data is friendly to several computing environments such as FORTRAN, C, IDL and MATLAB.

D. Standards followed by space networks

Space missions are based on some internationally adopted space standards, so as to maintain interoperability among the different space agencies. Some of the standards are mentioned below. The Consultative Committee for Space Data Systems (CCSDS) was formed in 1982 by many of the major space agencies of the world. It is a forum that discusses the problems of the spacecraft and Earth data systems and generates plans for their operation and development. The CCSDS document library contains recommendations which provide detailed technical guidance to space agencies for developing their data handling systems for various space missions. It provides data formats as well as the characteristics and specification of physical and transport layer. More than 500 space missions have already complied with the CCSDS standards [9].

The International Telecommunications Union (ITU) standardizes the rules for use of the radio frequency spectrum. It is the United Nations specialized agency for Information and Communication Technologies (ICT). They allocate global radio spectrum, satellite orbits and develop technologies that would seamlessly blend and improve ICT around the world. Besides the 192 member states, there are also several leading academic institutions and about 700 private companies that are also members of ITU [10]. Along with these standards certain networks such as the Deep Space Network (DSN) needs to comply with other standards like the National Telecommunication and Information Administration (NTIA) standard [11]. It describes rules governing the radio frequency spectrum use in USA by government agencies. Space Frequency Coordination Group (SFCG) [12] is another group of about 30 space civilians and some other organizations who meet periodically to discuss and adopt standards for using the space frequency bands. It is not as formal as the ITU and thus has much more flexibility in terms of adjusting to limitations.

E. Space Communications Protocols

The Space Communications Protocol Specifications (SCPS) are a set of extensions to the already existing protocol set

TABLE II
CLASSIFICATION OF SPACE COMMUNICATION PROTOCOLS (ADAPTED FROM [29])

(1) Changes to TCP	SCTP (Stream Control Transmission Protocol) [13], STP(Satellite Transport Protocol) [14], XSTP (Extended STP) [15], TCP Peach [16], TP-Planet (Transport Protocol-Planet) [17], TCPW (TCP Westwood) [18]
(2) Changes to TCP and/or Network Infrastructure	XCP (Explicit Congestion Control) [19], P-XCP (Proportional XCP) [20], REFWA (Recursive, Explicit and Fair Window Adjustment) [21], SCPS-TP (Space Communication Protocol Standard-Transport Protocol) [22], I-PEP (Interoperable PEP) [24], PETRA (Performance Enhancing Transport Architecture) [25]
(3) Delay Tolerant Networking (DTN)	BP (Bundle Protocol) [26], CFDP (CCSDS File Delivery Protocol) [27], LTP (Licklider Transmission Protocol) [28]

and new protocols that are developed by the Consultative Committee for Space Data Systems (CCSDS) for implementation and to improve the performance of Internet protocols in space environments. The SCPS protocol stack contains the SCPS-FP (extension of the File Transfer Protocol), SCPS-TP (extension and modification of the Transfer Control Protocol), SCPS-SP (security Protocol) and the SCPS-NP (a bit efficient network protocol). All of these protocols are used for different application environments. Some are for near-Earth satellites while others are for deep space communications but almost all of them solve the major problems of space communication - high Bit Error Rate (BER) and long link delays. In [29] the authors have broadly classified the space protocols into three categories as shown in Table II based on current terrestrial Internet protocols and their application. A protocol called the Deep-Space Transport Protocol (DS-TP) have also been proposed in [30] and its main advantage has been identified as its capability of transferring complete files faster than TCP, SCPS-TP or the Saratoga protocol [79]. The LTP (Licklider Transmission Protocol) is another Delay Tolerant point-to-point Network protocol for space communication, which provides retransmission based reliability over links which are characterized by extremely long round-trip times (RTT). The choice of a particular space protocol depends on numerous architectural and mission specific constraints. The authors of [31] discuss a number of considerations while selecting a communication network protocol for deep space.

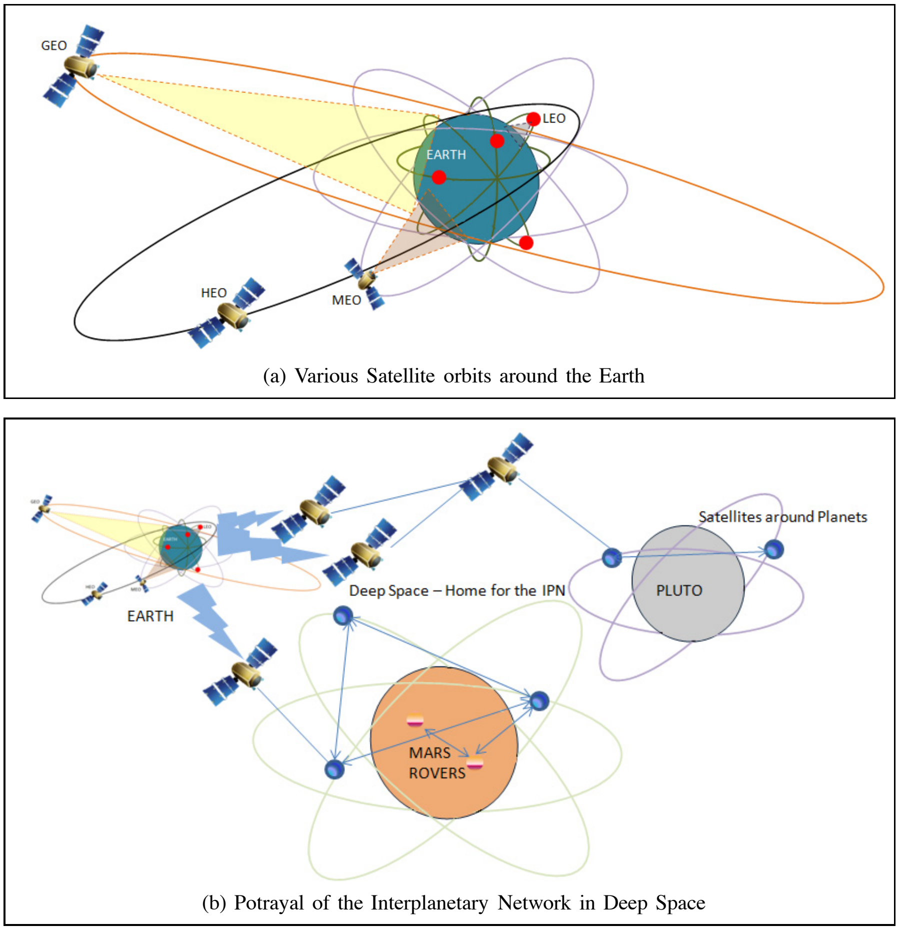
F. CubeSat

A CubeSat is a tiny satellite that weighs at most 1.33 kilograms and is a 10 cm cube which is mainly used for academic research. The 10 cm dimension CubeSats are called as "1U" meaning one unit and the other ones are simply a multiple of that. The cost of a standard CubeSat construction and deployment is estimated to be from $65,000 to $80,000 [32]. Since they have a standard dimension, they can be deployed using a common deployment system called the Poly-Picosatellite Orbital Deployer (P-POD). The design of the P-POD and CubeSat standardization is elaborated in [33]. The CubeSats are designed such that they can be developed and launched in less than two years. There is also a CubeSat Space Protocol (CSP) which is a small network layer delivery protocol developed by a group from Aalborg University in 2008 only for the CubeSats. Its implementation is written in C programming language. The layers of the CSP correspond to the normal TCP/IP model. It has a connection oriented transport protocol (Layer 4), a core for routing (Layer 3) and several networking interfaces (Layers 1-2) [32]. The first CubeSat was launched on June, 2003 from Plesetsk, Russia on board the Rockot launch vehicle containing two Mk.I P-PODs. Future plans include the QB50 project, for launching a total of 50 CubeSats by mid 2013 [34]. It will be an international network used for multi-point, in-situ measurements in the lower thermosphere (90 to 300 km). In the next sub-section we discuss a deployment vehicle used by NASA for Mars exploration.

G. MRO

Mars Reconnaissance Orbiter (MRO) is a NASA multi-purpose spacecraft designed to conduct reconnaissance and exploration of planet Mars from orbit. The Deep Space Network (DSN) serves as the critical link in the Mars program. The US$720 million spacecraft was built by Lockheed Martin under the supervision of JPL. It was launched on August 12, 2005, and attained Martian orbit on March 10, 2006. When MRO entered orbit it joined five other active spacecrafts in orbit of or on Mars: Mars Global Surveyor, Mars Express, Mars Odyssey, and two Mars Exploration Rovers. The most important task for the MRO is to explore the Martian surface and landforms so as to make way for future spacecraft landing. It sends data at a rate that is ten times more than any previous Mars mission – the spacecraft uses a wider antenna dish, a faster computer and an amplifier powered by a bigger solar-cell array to accomplish this [35]. The MRO mission has a payload (elaborated in detail in [36]) which includes the use of Electra [37] an ultra-high-frequency (UHF) radio for relaying commands from Earth to landers on the Mars surface and for returning science and engineering data back to Earth using the orbiter's more powerful direct-to-Earth telecommunications systems.

Setting up a network on Mars requires a number of considerations, one of the most important being constraints such as service planning. For example, relay of data from the MRO will have to be coordinated with its other activities. This will give a duty cycle of only 10% (approx.) for relay. Moreover, the antenna needs to be rotated to obtain a proper alignment. Hence, trajectory and visibility are both important issues to consider during data transmission. The next Mars mission is the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, scheduled for launch in late 2013. The timeline for Mars Reconnaissance Orbiter (MRO) can be found in [38]. Space communication is presently supported by different



(a) Various Satellite orbits around the Earth

(b) Potrayal of the Interplanetary Network in Deep Space

Fig. 2. Various orbital paths are taken by the satellites after they are launched. Each orbit has its own advantage and disadvantages. The design of a satellite system is tied to the market it is intended for and the type of communication services it should be providing. Satellites fall into their destined orbits and then start communication over the deep space network.

networks that have already been deployed. In the next section we discuss the various space orbits to deploy satellites and the current networks that support space communication.

III. Space Network Architectures

To acquire information from space, the ground stations need to directly communicate with the spacecrafts. The stations are a part of a terrestrial network and telemetric data can be retrieved from any point on the globe. On the other hand, data can also be routed across a space network and wherever it is required, the data can be retrieved by a ground station at that point. This usually happens for satellite phone networks. In the following sections we describe the various orbits in which satellites can be deployed. Furthermore, we discuss some of the networks that support space communication such as the Deep Space Network (DSN) and satellite phone networks.

A. *Satellite classification based on orbits*

Among the various kinds of satellite classifications, categorization based on distance of orbit from Earth dictates that there are mainly three kinds of orbits – Geosynchronous Orbit (GEO), Low Earth Orbit (LEO) and Medium Earth Orbit (MEO). There is also another kind of orbit called the Highly Elliptical Orbit (HEO). The different satellite systems provide particular communications services exploiting their own strengths and weaknesses, and their design has always been targeted to serve the market demand. We discuss the systems and their characteristics below :

- Geosynchronous Orbit (GEO) systems revolve around the Earth at a fixed distance of 22,300 miles (35,786 kilometers) above the Earth's surface. The satellite's speed at this altitude matches that of the Earth's rotation, thereby keeping the satellite stationary over a particular spot on the Earth. Examples of GEO systems include INTELSAT, Inmarsat, and PanAmSat. Such satellites usually rotate above the equator and hence can cover about one third of the Earth's surface.
- Low Earth Orbit (LEO) is usually defined as the orbit at a distance of 100 - 1240 miles (160 - 2000 km) above the Earth's surface and the satellites have a speed of 7 to 8 km/sec at this altitude. It lies around the Earth between the atmosphere and below the inner Van Allen radiation belt [39]. However, this environment is filled with space debris which is extremely dangerous and damaging and is becoming a growing concern over time. The Japan Aerospace Exploration Agency (JAXA) has recently taken initiative to clear this space debris [40]. Since the LEO satellites are very close to the Earth they can transmit signals with no or very little delay. Moreover, they can work with smaller equipments unlike

a GEO satellite. A very good example of a LEO satellite system is Iridium.
- Medium Earth Orbit (MEO) is also called as the intermediate circular orbit (ICO) and it marks the region above LEO and below geostationary orbit at about 1,500 to 6,500 miles (10,000 km) above the Earth's surface. A MEO satellite rotates at a speed of around 4 km/sec. It has a shorter life expectancy and requires frequent vehicle launches. Telstar one of the most famous experimental satellite is functional in the MEO system.
- The Highly Elliptical Orbit (HEO) system is very different from all the other systems. It follows an elliptical path rather than a circular path and satellites rotate at a speed ranging from 1.5 to 10 km/sec. A HEO satellite moves faster when it is closer to the Earth and slower when it gets farther away. This design helps in maximizing the amount of time it spends over densely populated regions. Examples of HEO systems include Ellipso [41].

The GEO satellites are mainly used for transmissions of high-speed data, television signals and other wideband applications. MEOs are generally used for geographical positioning systems and LEO satellites serve for data communication such as e-mail, paging and videoconferencing. They also provide the under developed regions on Earth with satellite phone service. Satellites in HEO also provide aid to communication such as the Sirius Satellite Radio positioning two satellites on top of North America. The difference between LEO and GEO system lies in the phenomenon of satellite echo or delay. Although radio waves travel at the speed of light, it still takes almost 0.25 seconds for a signal to bounce up to a geosynchronous satellite and back down again. Adding up the various other delays in processing the call, this gives rise to the annoying satellite echo and delay that we all dislike. However, the time for a round trip to a LEO satellite is a mere 0.005 seconds, which is unnoticeable [42]. The closer distance to a LEO satellite also implies that a smaller antenna and weaker transmitter can be sufficient. This also allows greater portability and low battery consumption. LEO satellites seem to be superior to GEO satellites from a customer's perspective, but from the service operator's point of view due to its small coverage area a large number of satellites are needed to build up a complete global network. Moreover, it has a shorter life span because it is more influenced by the Earth's gravitational pull. Effects of interference and fading on such systems have been studied in [43]. All the above orbits are shown in Figure 2a. Beyond all these lies the Deep Space shown in Figure 2b which we will discuss next in Section III-B. According to the International Telecommunications Union (ITU) deep space starts at a distance of 2,000,000 km (1,242,742 miles approx.) from the Earth's surface and is considered to have different communication mechanisms.

B. Deep Space Network

A new concept called the Deep Space Network (DSN) came to the forefront in the late 1950s as a separately managed and operated communications facility that would support all deep space interplanetary missions. Keeping track of vehicles in the deep space is very much different from that of low Earth orbit (LEO) vehicles. They are visible for longer periods of time and hence the network requires very few antennas spread over the Earth's surface. However, the antennas also need to be extremely powerful as is the present 230-ft antenna of DSN that is capable of tracking a spacecraft traveling more than 16 billion kilometers (10 billion miles) from Earth [45]. The DSN is an extremely sensitive network that tracks almost three dozen spacecrafts each year. It acquires telemetry and radiometric data that give information for very accurate navigation. More details about the DSN evolution and functionalities have been discussed in [44]. The improvement in deep-space telecommunications performance can be assessed from two major events - the 1959 Pioneer 4 lunar flyby and the Voyager Neptune 1989 encounter. The improvement was 12 times in magnitude [2] and it was the outcome of the evolution of both ground and spacecraft technologies. Additional ground network antennas, amplifiers (with lower noise microwave), coding, frequencies (with higher operating capabilities), and receivers that are computer-controlled, account for much of the improvement along with increased spacecraft transmitter power and antenna size. In the following sections we discuss the details of the DSN Communication facilities, its limitations and future technologies.

1) DSN Communication Facilities: Pictures and data are continuously being collected by the spacecrafts and explorers in space and sent to the Earth. The NASA DSN on the Earth provides the vital two-way communications link that guides and controls planetary explorers, and brings back the images and new scientific data. There are three deep-space communications facilities placed approximately 120° apart around the world: One at Goldstone, in California's Mojave Desert, the second is near Madrid, Spain and the third one is located near Canberra, Australia [47]. This strategic placement permits constant observation of spacecraft as the Earth rotates, and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world. Each of the locations have 8-14 hour of viewing period for direct contact with the satellites and they are controlled by the Network Operations Control Team (NOCT) at JPL's Deep Space Operations Center.

The complexes are located far from heavily populated areas and hence the very weak signals from distant spacecrafts are not contaminated or obscured by radio interference from electrical power lines, radio and television stations, or household and industrial appliances. Each complex is situated in a semi-mountainous, bowl-shaped terrain to shield against radio frequency interference from neighboring areas on Earth's surface [45] and has at least four deep space receiving and transmitting stations equipped with ultrasensitive receivers and large parabolic dish antennas that are steerable, high-gain and parabolic reflector in nature. For high-power uplink transmissions, 230-ft diameter antennas are equipped with transmitters that deliver up to 400 kilowatts of power. All the receiving and transmitting stations are operated remotely from a central signal processing center at each site. Those processing centers have electronic systems that control and point the antennas, receive and process telemetry data, transmit commands, and generate spacecraft navigation data. After each of the data has been processed it is then sent to JPL at

Pasadena, California, for further processing and distribution to scientists.

DSN uses microwave radio signals for deep space communications because microwave beams have an unique characteristic to travel in a straight line. It can be reflected from a smooth surface and can also be focused by a lens or a curved reflector to increase its strength or brightness. With increasing frequencies, the beam is narrower and can be brought into a tighter focus. High frequency microwave signals allow more space signals to be concentrated within a narrow beam which results in a high signal to noise ratio. As a spacecraft travel outwards from the Earth, its signal steadily decreases in power so that by the time it returns to a DSN antenna on Earth from a planetary encounter, it can be of extremely low wattage – about 1,000 billion times weaker than the signal received by a TV set from a commercial television station and the signal is usually degraded due to background radio noise that is naturally radiated from all objects in the universe. NASA is currently employing more research into the development of high frequency communication for future use.

Microwave radio is also used by several Earth relay stations for television, radio, cellular telephones and radar communications. Such other signals, transmitted nearby on adjacent frequencies, often interfere with the very weak deep space signals. To be able to detect the correct deep space probe in the midst of unwanted noise, engineers design receiving systems with noise-combating telemetry coding techniques, high signal sensitivity, efficient antennas, and low-noise receivers. Precision pointing of a deep-space antenna is also very important. The antennas must also be able to track at very precise rates of about thousandths of a degree per second to remain pointed at the spacecraft since the Earth rotates at 0.004 degrees per second. The largest antennas of facilities are often called for space mission emergencies. The DSN facility antennas have well proved their capabilities. One good example is the famous Apollo 13 mission, where limited battery power and inability to use the spacecraft's high gain antennas reduced signal levels below the capability of the Manned Space Flight Network, and the use of the biggest DSN antennas (and the Australian Parkes Observatory radio telescope) was critical to saving the lives of the astronauts [46].

2) Limitations of DSN: The efficiency of current DSN has been limited by a number of challenges that we are going to discuss in this section. Firstly, the DSN site at Canberra, Australia is the only one in the southern hemisphere. There are no DSN antennas in South America or southern Africa, thus limiting the coverage in the southern hemisphere. Secondly, there are certain "legacy" missions that still need support and sometimes even the biggest antennas need to be involved. For example, the Voyager satellites have been operating long past their original mission termination date. It is still returning scientific data which needs to be gathered. Thirdly, the deferred maintenance of the 230-ft antennas cause them to be out of service for several months at a time. They are also reaching the end of their lives and would soon require replacement. The new facility will be an array of smaller dishes. Finally, the major problem is the DSN's need to support increased number of missions. By 2020, the DSN will be required to support twice the number of missions it was supporting in 2005. Due to decay and lack of replacement of the existing antennas increased mission support will continue to be an ongoing problem.

3) Future Technology - An array-based architecture: The 111-ft and 230-ft antennas which are still used by the DSN are very bulky and old. They have also become less reliable and contribute to a huge amount of the ratio of antenna gain to system temperature for the DSN. Moreover, the technology is several decades old and does not comply with present automated devices. Interfacing has become more expensive. Also, these antennas operate only up to the X-band frequencies (8.4 GHz), where bandwidth is limited by spectrum allocation to a total of 50 MHz, which is then shared among the multiple space missions. Future space missions require large bandwidths, and hence it is necessary to change to higher Ka-band frequencies, (262 or 32 GHz), where larger spectrum allocations are available for space communications. All of these limitations and requirements have lead to a new array-based architecture proposed by authors in [48] and [49]. Array-based architectures offer an attractive approach to a reliable, cost-effective, and flexible next-generation DSN. The architecture of a DSN array is shown in Figure 3 which has been adapted from [48]. The DSN array central is connected to the three regional array centers one at each of the three DSN facilities. Each regional array center would be connected to downlink and uplink antennas at the site. Each site would in turn have downlink antennas that could be arrayed to receive at X-band (88.8 GHz) and Ka-band (2533 GHz) and uplink antennas with suitable transmitters for uplinks at 7.2 GHz band. This helps in increasing the receiving sensitivity drastically and there is also a significant lowering of system temperature. The architecture and implementation plan for an array-based DSN, would offer cost-effective and robust telemetry, tracking and command (TT&C) services with a flexible and highly reliable future DSN for NASA's continuously evolving missions. In combination with an advanced set of radio arrays, laser communications and orbital relay, future missions are expected to relay tens or even hundred times more data than they transmit today.

C. Satellite Phone Service and Private Satellite Networks

Satellite phones provide ultimate global coverage that normal cell phones are unable to give. 85% of the Earth's surface is still out of regular phone signal because they are not close enough to cell phone transmitting towers. Satellite phones use either the LEO satellites or geosynchronous (also called geostationary) satellites. Most satellite services permit data as well as voice to be sent and received. However, all such services have very slow data bandwidths, typically in the realm of about 2400 baud (ten to twenty times slower than a regular dialup modem, and 50+ times slower than broadband) [42]. To name a few of the satellite phone service providers, we have Inmarsat Satellite Phone Service [50] which started its operation in 1979 and has a good coverage from its network of geosynchronous satellites. However, its service does not extend all the way to the north or south poles and it has the annoying satellite echo/delay. The Thuraya satellite phone service [50], which started operating in 2001 has very little

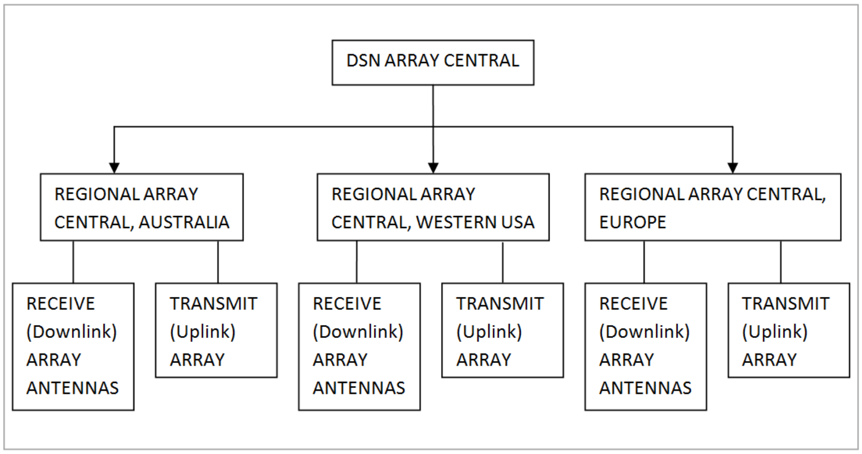


Fig. 3. The architecture of a DSN array. It is to be deployed at all three sites at or near each of the three longitudes. The uplink and downlink antennas are physically kept separate from one another. Arrayed small antennas are used for downlink and nonarrayed larger, monolithic antennas for uplink (adapted from [48]).

global coverage. Globalstar Satellite Phone Service [50] came out in late 1999 and is now available in much of the world. Globalstar has good coverage in most major countries, but if one travels outside the 120 countries in which they provide coverage, the phone becomes useless. It uses 44 LEO satellites for coverage but one pays for outgoing as well as incoming calls which results in a major setback for commercialization. The best provider seems to be Iridium with 66 LEO satellites and providing a full global coverage. In between several ups and downs it still stands today as the most reliable satellite phone service provider and looks forward to an even brighter future. In the next two subsections we briefly discuss the two private satellite network companies – Telstar and Iridium.

1) Telstar: Telstar [50] is the name given to a number of consecutive satellites that were launched and became the first satellite used to relay television signals. The first Telstar satellite was built by Bell Labs and launched by NASA on 10th July 1962. As a result of the relatively low orbit, the ground stations were able to see the satellite simultaneously for a period of only 30 minutes, three to four times a day. The Telstar 1 communication package comprised a single transponder with a bandwidth of 50 MHz and an output power of about 3 Watts. The Earth station antennas had to be very large because of the low power flux density at the Earth's surface. However large they might be, yet they had to follow the relatively rapid movement of the satellite. The satellite transponders also needed very high gains (of the order of 100 dB) because the signal suffered from large attenuations. Frequency of about 6 GHz was used for transmissions to the Telstar and the satellite converted it to frequencies of about 4 GHz. Though Telstar 1 had been the lead to start a new era of the amicable use of technology, it itself became a victim to it. During the cold war, the huge increase in radiation overwhelmed the fragile transistors and Telstar 1 went out of service on December, 1962. There are several more Telstars that were launched later and is in orbit today as the satellites continue to improve our "communication through space" [51].

2) Iridium: The Iridium satellite network is the only commercial satellite constellation in the world with a fully meshed network offering complete coverage of the whole Earth including the poles, oceans and the airspace. Iridium provides both voice and short burst data (SBD) satellite services and the satellites can be tracked through the website [52]. The inter-satellite links operate at approximately 23 GHz [54]. It is a significant technical feature of the Iridium Satellite Network that enhances system reliability and capacity and reduces the number of gateways or Ground Earth Stations (GESs) required to provide global coverage. The communication channels used by the constellation is divided into two broad categories, system overhead channels and bearer service channels. Bearer service channels include traffic channels and messaging channels, while system overhead channels include ring alert channels, Broadcast Channels, acquisition and synchronization channels.

The Iridium satellite network uses L-Band (1616-1626.5 MHz) uplink and downlink transmissions. It provides 4.8 kbps for voice. The Iridium data service has been designed such as to provide a minimum throughput of 2.4 kbps user-generated information unlike other companies like Globalstar provide much higher data rate of 56 kbps [55]. Iridium directly beams its signal from the satellite phone to the nearest satellite that it can reach. Then it is routed among the satellites until it reaches a satellite that can send the call down to the recipient. Theoretically a single Iridium satellite can handle up to about 1100 calls simultaneously. The current satellites are presumed to remain functional at least through 2014 [42]. Iridium NEXT will be the second generation replacement constellation of satellites. These new satellites will be launched in 2013 to provide service through 2030 [53]. After our discussion of the various space networks we move onto the next section which describe an automated Interplanetary Internet (IPN) and the DTN technology.

IV. Interplanetary Internet and Delay Tolerant Networking

The Interplanetary Internet (IPN) is a still to be implemented computer network in space. The term IPN was first coined by Internet evangelist Vinton (Vint) Cerf in 1997, as he envisioned a future Internet that would interconnect stations on the Earth, moon and other planets in the solar system. It is a store-and-forward "network of Internets" in support of deep space exploration that is often disconnected, has a wireless backbone with error-prone links and delays ranging to tens of minutes, even hours, even when there is a connection. The round trip times can be as large as 40 minutes long for the cis-Martian (on the near side of) channel and even more than 100 minutes for a channel from Jupiter to Earth [29]. The IPN backbone is quite different from the terrestrial Internet as we have summarized in Table III. One can also look into [56] for learning the differences between IPN and pervasive networks.

The connections between traffic hubs in an IPN is interrupted when planetary rotation or orbital motion takes a transmitting entity out of the line-of-sight (LOS) to the receiving entity. There may also be extreme environmental conditions such as solar storms and magnetic interferences that challenges network communication. The existing terrestrial Internet and the TCP/IP suite will not be able to handle the constraints (like long and variable delay, frequent network partitioning, data rate asymmetry and packet loss and errors [57]) posed by such extreme conditions. Moreover, the power availability is extremely limited in spacecrafts, and even worse that the spacecrafts which are farther away from Earth have back dated technology than the ones launched recently. This imbalance in resource towards the critical end makes the challenge even bigger.

In 2002, Kevin Fall started to adapt some of the ideas of the IPN to terrestrial network and first coined the term Delay Tolerant Networking (DTN) and its motivation is made clear in [58]. Recently, several tests have been made with the DTN in space that has verified the feasibility of IPN. One of them is the DTN Bundle protocol tested using the UK-DMC satellite built by Surrey Satellite Technology Ltd (SSTL) in 2008 [59]. Again in 2008, NASA performed an experiment called the Deep Impact Network Experiment (DINET), using the Epoxi satellite and nine other ground based nodes that altogether simulated a Mars local planet network [60]. The experiment validated the Interplanetary Overlay Network (ION) software which is an implementation of the DTN architecture. NASA has also tested DTN communication on the International space station in 2009 along with the University of Colorado's BioServe Space Technologies using a Commercial Generic Bioprocessing Apparatus (CGBA) [61].

A number of protocols have evolved from the existing Internet protocol suite to support the DTN architecture and have focused on specific DTN characteristics. The DTN transport protocol does not involve an end-to-end communication like Transport Control Protcol (TCP), instead it employs a store and forward approach where the data is stored and moved incrementally throughout the network in the hope that it will finally reach its destination. Another approach can be to send the message repeatedly so that at least one copy reaches the destination. In the second scenario more amount of local storage and internode bandwidth is required [62]. DTN itself primarily speaks of delay in a network which can be of three major kinds: propagation delay through the medium; queuing delay within relay points, source, and destination; and clocking delays associated with transmitting an atomic unit of data onto the medium [57]. Propagation delays over the medium can be long due to speed-of-light delays to cross long distances (e.g., deep space). It could also be long due to the propagation medium (e.g., acoustic/underwater). On the other hand queuing delays within relay points are affected by traffic and service rate. Nodes in a DTN can have scarce power supply, for example solar charged battery which might not be enough to run a fast processing unit, thus leading to data queues. Clocking delays occur when an erroneous data is received but it is not recognized and resent until the whole data is fully received. In a slow multi-hop network, the per packet delay can be quite large for big packets. Another contributor to overall delay mechanism is the processing delay which is comparatively low. However, sometimes it becomes a noticeable factor in the overall delay.

Research in DTN has been covering a vast range of environments and each of the entities in the environment have their own set of characteristics and features. For example, each node or hub in space network might have different resource capability which will govern the way in which they will transmit among each other. They will also have to balance their various functionalities – a Mars rover that is destined to collect samples during a red sandstorm might not be able to process and relay signals during that time. Moreover, the time for which two entities remain within line-of-sight is pretty fixed and the duration is known in advance. Hence, transmissions can be scheduled beforehand and routing decisions is not the major player. This might not be the case for other environments like a vehicular DTN or underwater environments. Hence, the DTN protocol is very much application specific.

Study of a DTN system has been separated into two broad categories – *DTN service targets* and *System constraints* [62]. Service target refers to delivery ratio which informs us about the reliability of the system and delivery delay that is actually the latency to be accounted for. System constraints include the storage space availability and energy constraints of the network, given that we mainly work with mobile and battery powered devices in a DTN [62]. Based on these characteristics of the system, DTN has been categorized as terrestrial and space based networks, which we briefly discuss in the following two sub-sections.

A. Terrestrial DTN

Several Earth based applications that need to survive and communicate in harsh environments have implemented the DTN technology. A few of them are - tracking of wildlife, military operations, underwater communication, enhancing Internet "hotspot" connectivity in rural areas in third-world countries and so on. All of these environments have one thing in common and that is a large amount of delay in transmission, which encourages data storage at nodes in the network. One good example of terrestrial DTN implementation is DakNet [63] which has been able to provide connectivity in remote villages of developing countries such as India and Cambodia. The DakNet wireless network takes advantage of the already functional communication and transportation infrastructure. It transmits digital data over short point-to-point links between kiosks and portable storage devices, called mobile access points (MAPs) that is mounted on and powered by a passenger

TABLE III
SUMMARIZING THE DIFFERENCES BETWEEN TERRESTRIAL INTERNET AND IPN

	TERRESTRIAL INTERNET	**IPN**
POWER AVAILABILITY	Not critical	Of Overriding importance
DELAY	0.1 sec	10 to 10,000 seconds
SIGNAL TO NOISE RATIOS	For wired network it's quite high. For Terrestrial MANET, SNR is low and it's a function (power, node density).	Very low SNR and it's a function (power).
INFRASTRUCTURE	Fixed or may be mobile	Always deployable and mobile
TRANSMISSION MEDIUM	Copper or Fiber, FSO, RF, IR	Primarily Free Space - Laser or RF, causes high BER.
DEPLOYMENT COST	Relatively low or moderate	High and is a function (mass)
OPERATIONS COST	Relatively low	High and is a function (reliability)
REPAIR AND UPGRADE COST	Relatively low	Very High

bus. The Karnataka state government in India have computerized land records that are stored in district headquarters, quite far away (40 km) and not accessible to villages without phone lines. The bus, equipped with a MAP brings digital information from the district and transfers it to a computer in a WiFi-enabled village kiosk. Requests are also collected at the same time. Whenever a bus passes by a kiosk a brief session of about 2 minutes and 34 seconds is set up and data transfer take place at an average of 20.9 Mb unidirectionally at a data rate of close to 2.47 Mbps. The total cost of the DakNet MAP equipment used on the bus is $580, and the equipment used to make a village kiosk is $185 and the investment is quite reasonable. There are several other implementations of DTN like ZebraNet [64], UMassDieselNet [65] which proposes MaxProp, a protocol for effective routing of DTN messages. DriveThru [66] is another kind of DTN that provide hotspots at every street corner so that mobile users can access them to obtain intermittent connectivity and acquire local updates as well as Internet access. All these networks are propped by the DTN architecture and they try to resolve problems in Earth based challenged environments. We discuss and summarize the major features of the DTN architecture below:

- A DTN-enabled application send messages also known as the Application Data Units or ADUs, in complete units.
- At the bundle layer the ADUs are transformed into Protocol data units called "bundles" which is then stored and forwarded by the DTN nodes. Bundles can further be broken into bundle fragments and also reassembled as and when required during transmission. Fragmentation can be done pro actively or reactively [69] such that partially forwarded bundles are not retransmitted.
- An End point Identifier (EID) identifies a bundle source and destination and it is expressed syntactically as a Uniform Resource Identifier (URI).
- An EID may also refer to more than one DTN nodes for multicast destinations.
- The DTN architecture have remodeled the URI scheme giving it a lot of flexibility. It can be constructed based on DNS names, or it can be database queries or even intentional names or expressions [70]. For example, we can have EIDs such as "dtn://myMachine/dtntrans" and "dtn://everyoneWithinArea1000miles"
- Each DTN node should have persistent storage to store bundles which survive till system restart.
- A priori knowledge of the bundle's size and service requirements are provided to aid the bundle layer with routing decisions.
- DTN supports late binding, which means that binding a bundle's destination to a particular set of bundle identifiers may take place at the source, in transit or at the destination. This in unlike the Internet's early binding approach. It is advantageous because the delay in such architecture may exceed the time of binding validity. Moreover, resources are limited and this approach considerably reduces administrative and mapping overhead.
- The DTN architecture defines three priority classes that guides the routing and scheduling algorithms - Bulk, Normal and Expedited.
- Delivery options such as custody transfer request, report when bundle delivered, deleted or forwarded, confidentiality, authentication or error detection request and so on are supported by the architecture which gives the applications much more flexibility.
- Administrative records are used to report bundle status and custody signals.
- The DTN can be represented as a multigraph where vertices may be interconnected with more than one edge. An edge can have significant amount of delay and constant capacity and when the capacity is strictly positive the period of time is called as a "contact". Contacts are classified into a number of types based on their performance characteristics [69].
- DTN also implements end-to-end reliability/ acknowledgments for the applications that would request for it. However, it pushes the responsibility or transfers custody of a bundle towards its destination.
- Time synchronization and time stamps become important for DTN networks in order to identify bundle and fragments for routing, bundle expiration time computations and application registration (registering to the network

Version (1 byte)	Bundle Processing Flags (SDNV)
Block length (SDNV)	
Destination scheme offset (SDNV)	Destination SSP offset (SDNV)
Source scheme offset (SDNV)	Source SSP offset (SDNV)
Report-to scheme offset (SDNV)	Report-to SSP offset (SDNV)
Custodian scheme offset (SDNV)	Custodian SSP offset (SDNV)
Creation Timestamp time (SDNV)	
Creation Timestamp sequence number (SDNV)	
Lifetime (SDNV)	
Dictionary length (SDNV)	
Dictionary byte array (variable)	
Fragment offset (SDNV, optional)	
Total application data unit length (SDNV, optional)	

(a) Primary Bundle Block format

Block type	Bundle Processing Flags (SDNV)	Block length (SDNV)
Bundle Payload (variable)		

(b) Bundle Payload Block format

Fig. 4. The two basic Bundle Protocol block formats (redrawn from [26])

so that it can accept ADUs destined for a DTN endpoint with an EID) expiration.

- Security in terms of Denial of service have also been considered within the architecture.

Armed with an overview of the Terrestrial DTN architecture, we move on to space DTN systems and experiments which is further challenged by a totally different environment from terrestrial applications.

B. Space DTN

The most important motivation for DTN use in space communication results from making IPN a real networking environment. In a terrestrial DTN when a connection is set up there is no way that an enormous delay can occur (delay is then limited by Earth based Internet speeds). On the other hand in space DTN architectures, even when there is a full connection delays can be huge. This makes them very different from terrestrial DTN architecture. In space DTN, certain issues such as routing and storage congestions have not been researched until now because routing paths and duration of connectivity are always known in advance. Moreover, it is a sparse network with only a handful of relay nodes. The Internet Research Task Force (IRTF) DTN Research Group (DTNRG) has investigated more into security and transport layer issues. As an outcome we have the Bundle Protocol that sits in the Application layer of our current Internet model. The important capabilities of the protocol can be summarized as below and is stated in [26]

- Custody-based retransmission
- Ability to cope with intermittent connectivity
- Ability to take advantage of scheduled, predicted, and opportunistic connectivity (in addition to continuous connectivity)
- Late binding of overlay network endpoint identifiers to constituent Internet addresses

In this section we introduce the terms associated with the Bundle Protocol mechanism. More information about DTN based space protocols can be found in [23]. The Bundle Protocol uses the 'native' Internet protocols (not necessarily TCP/IP) to communicate within the Internet. The Convergence Layer Adapter (CLA) forms an interface between the Bundle Protocol and a common internetwork protocol and it offers important functions to the Bundle Protocol Agent (BPA) – a part of the node that provides bundle protocol services. More about the CLA services is mentioned in [26]. A bundle node is the one that sends or receives data. It can be a thread running on the system, an object in an object oriented programming environment or may be a special purpose hardware device. The bundle endpoint is a group of such bundle nodes that can offer Bundle Protocol functionalities and they identify themselves with a single string called as the "bundle endpoint id". The bundle endpoint can be a single node or a single bundle node can also be a part of many endpoints. Whenever a bundle node decides to forward a bundle it does so and marks the destination as the bundle endpoint.

Binary representation of the hexadecimal number
0x4234 : 0100 0010 0011 0100
We neglect the first zero and consider the other values
It is then encoded as 3 octets
{1 000000 *1*} {1 *0000100*} {0 *0110100*}

Fig. 5. Example of the SDNV encoding scheme for hexadecimal number 0x4234

The Bundle Protocol data unit is referred to as a "bundle" and it contains at least 2 or more blocks of protocol data. The first one is called the primary bundle block and it may be followed by sequence of Bundle Protocol blocks that can be used to support Bundle Protocol extensions such as the Bundle Security Protocol (BSP) [67]. Among them there must be at most one block that acts as the payload block. The ending block in the sequence must have the "last block" field set to 1, which will indicate it as the last block. Figure 4a and 4b show the primary and the payload bundle block respectively [26]. The Bundle Protocol tries to use as minimum bandwidth as possible while transmission. This has been accomplished with the help of self-delimiting numeric values (SDNV) encoding technique. In this technique any positive numeric value is encoded into N octets, the most significant bit (MSB) of the last octet is set to 0 while all the other octets have their MSBs as 1. The other 7 bits of every octet contain relevant information. An example of the encoding scheme is shown in Figure 5 for hexadecimal number 0x4234.

The Bundle Protocol of DTN architecture has always considered security as a very important aspect of its design. The DTN environment has very limited resources, such as scarce bandwidth, small storage available at nodes and intermittent connectivity. To cope up with it the Bundle Protocol allows only authorized users to send bundles over the network. Moreover the environment has large delays where data resides on various nodes for comparatively long period of time and hence the sender should be even more concerned about data integrity and confidentiality. All the internal bundle-aware overlay networks should be able to send data over the nodes preserving complete data security. There are three security-specific bundle blocks - the Bundle Authentication Block (BAB) that provides authenticity and integrity to bundles on a hop-by-hop basis, the Payload Security Block (PSB) provides bundle authenticity and integrity from "security-source" to "security-destination" (A "security source" may not be the actual point of origin of the bundle but instead it is the first point of security awareness in the network) and finally the Confidentiality Block (CB) provides payload confidentiality. Details about the security blocks can be found in [26] and [67]. The generic Internet also has another common security issue known as the denial-of-service attack which the DTN architecture robustly defends. [68] elaborates a few possible denial-of-service attacks against DTN and also proposes a set of countermeasures in accordance with the author's model. Security issues related to space DTN have been discussed in more details in [71].

In Figure 6 we have shown an implementation architecture for DTN where we have a central bundle forwarder, which can be the Bundle Protocol Agent (BPA) of a node to forward bundles (based on routing algorithm decisions) to the Convergence Layer Adapter (CLA), storage or local application. The arrows represent interfaces through which the bundle forwarder interacts with the applications, CLAs and management processes. Implementing these interfaces using inter-process communication rather than normal procedure calls has been quite beneficial for the development of the architecture. These interfaces carry bundles or directives that are represented as tiny green and yellow boxes respectively. The native Internet protocols provide different semantics that is not helpful to the DTN architecture. It is the task of a group of protocol-specific CLAs to provide the necessary functionalities required to carry the bundles on each of the required protocols [75]. Next in Section IV-C we describe the recent experiments on space DTN architecture.

C. Recent Experiments on Space DTN

1) UK-Disaster Monitoring Constellation (UK-DMC): The bundle protocol intended for IPN was first tested and demonstrated on board the UK-DMC satellite built by Surrey Satellite Technology Ltd (SSTL) on August, 2008. The transfer process did not have high propagation delays, but instead it was intended to check the proactive fragmentation capabilities of the bundle protocol which would even allow a large file to be send over the network during a single contact opportunity to a ground station. There are seven UK-DMC imaging satellites in the low Earth orbit (LEO) which have 5 to 14 minutes of contact time during a scheduled pass to a ground station (ground stations are interconnected through terrestrial networks), in its complete 100 minute orbit [76]. The image taken by the satellite was broken into bundles and required three passes to be transferred to the ground and finally to a "DTN sink" as demonstrated in Figure 7. If the satellite were to transfer it to a single ground station it would take approximately three orbits for a sink to obtain the complete file (considering minimum delays over the terrestrial network). However, the UK-DMC satellite did it in only one orbit by transferring the image bundles to separate ground stations and then reassembled it over the terrestrial Internet at the sink using the bundle protocol of DTN architecture. The experiment also shows that Saratoga can be used as a bundle convergence layer.

The UK-DMC satellite had the following payloads on board:

- The Cisco router in Low Earth Orbit (CLEO) which is used to check whether a router can function effectively in orbit [74]. It has not been used in the bundle protocol testing of DTNRG.
- Three Solid-State Data Recorders (SSDRs). Two of them have constrained operating system firmware size limit of 1 MB, and storage capacities of 1 GB and 512 MB RAM.
- It has an uplink of 9.6 kbps, and downlink of 8.134 Mbps. Both links use the already proven IPv4/Frame Relay/HDLC commercial-standard protocol stack developed for space use by Hogie et al. [77]. IPv6 have also been tested over these links using the Cisco LEO router [78].

The then operational file transfer protocol by SSTL that was used on the UK-DMC satellite was Saratoga version 0. The latest operational DMC satellites have quite fast downlinks, capable of 20, 40 or even 80 Mbps. Newer satellites are expected to provide 200 Mbps or more, without any significant increase in uplink rates. This huge difference in rates and with the need to fully utilize the available downlink capacity to transfer data within the limited time, motivates much of Saratoga's [79] design. It was improved on the implementation of an earlier protocol used by SSTL called the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP) [84]. More details about the experiment like ground development and testing, file naming conventions, channel emulation and experimental successes and failures, and significant problems recognized in the bundle protocol have been discussed by Ivancic et al. in [76].

2) *Deep Impact Network Experiment (DINET):* On October and November 2008, NASA performed its first test with DTN in close cooperation with the Epoxi project. The experiment (mainly performed to simulate a Mars *local planet network*) was called the Deep Impact Network Experiment (DINET), and almost 300 images were sent to the spacecraft from various JPL nodes over a period of 1 month. Demonstrations were performed twice a week. The complete network constituted of 10 nodes [72] - One is the Deep Impact Epoxi spacecraft (that is located at 80 lightseconds from Earth and acts as Mars relay orbiter) itself and the other nine are on the ground at JPL and they simulate Mars landers, orbiters and ground mission-operations centers.

The course of the experiment is summarized below:

- October 18, 2008 - The Interplanetary Overlay Network (ION) DTN software which has been explained in the next subsection was successfully uploaded on the Epoxi spacecraft and data was seen to be sent and received from the DINET Experiment Operations Center.
- October 20, 2008 - Images were sent to the Epoxi spacecraft and three hours later the same images were transmitted and successfully received at JPL over the first instances of IPN.
- October 22, 2008 - During pass 2 of the experiment 264046 bytes (five images) were successfully delivered making 97.6% (approx) link utilization.
- November 3, 2008 - On the 5th DSN tracking pass an additional 1587420 bytes (35 image files) were delivered via the IPN to image reception software in the DINET Experiment Operations Center.

The total period of the DINET experiment was divided into two configurations. In the first configuration no artificial data loss was injected into the network, whereas in the second configuration 3.125% of all LTP segments were randomly discarded when received at the spacecraft and at each of the three simulated Mars nodes. Even on the forth tracking pass of each segment, the contact between Epoxi and a node was broken and a short cross-link was set up over another direction in the network. In [60], the authors considered several metrics such as Path utilization rate, Delivery acceleration ratio, Multipath advantage and ION node storage utilization and then finally discuss their findings. In [80] we also have tables giving the data capacity of the network, the actual data sent during the experiment and also the storage utilization values. Several ground and space based experimental setup and technical details are also given.

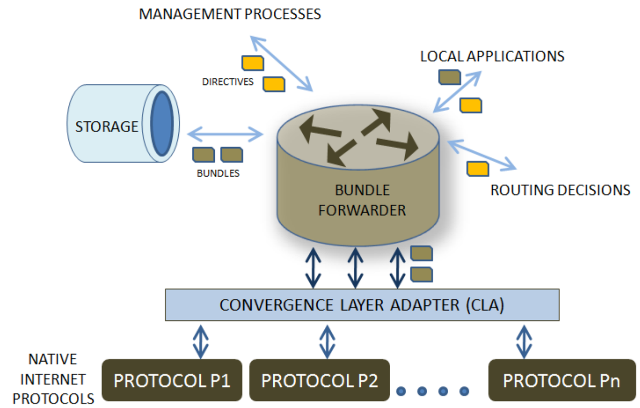


Fig. 6. An example of DTN Implementation Architecture : The architecture shows how a bundle forwarder interacts with the other components and utilizes various protocols for data transmission (adapted from [75])

3) *Experiment on-board the International Space Station (ISS):* NASA's Huntsville Operations Support Center (HOSC) has also been testing the DTN technology on the International Space Station (ISS) in collaboration with University of Colorado. It has deployed the bundle protocol in a Bundle Protocol Agent (BPA) to the Commercial-Grade Bioprocessing Apparatus 5 (CGBA5) and carried out a series of tests. The CGBA5 is primarily an environmental control chamber for life science experiments but along with that it also provides a computational/communication platform that has a 1 GHz Intel Celeron processor (32-bit), 1 GB RAM, 4 GB solid-state disk and an operating system Linux 2.6.21 [61]. The Rack Interface Computer (RIC) on board the ISS serves as the IP gateway to the ISS payload LAN. We find that the RIC frame size is 96 bytes for uplink and 1248 bytes for downlink. However, the CGBA5 applications can submit data units upto the size of 2048 bytes regardless of the RIC frame size. The uplink and downlink bandwidth provided by the channel is 150 and 400,000 bits per second. There's an uplink via S-band and two downlink paths: S- and Kμ-bands. The S-band is viewed as the primary payload uplink and telemetry downlink path with relatively low data and command rate such that the bandwidth and command slots are pre-allocated. On the S-band uplink, the command rate is 8 commands per second, that is driven by an onboard 10 Hertz (Hz) clock. The uplink bandwidth is in turn dynamically allocated, in order to provide the facility with varying size uplinks [73].

This program has helped in establishing a long term, readily accessible communications test bed onboard the ISS. Later deployments has also made CGBA4 a communication computer used for tests that transmit messages between ISS and ground Mission Control Centers. All the data is monitored and controlled by the Payload Operations Control Center (POCC) at the University of Colorado, Boulder. Till now only point-to-point communication takes place between space crafts. Moreover, manned labor is required to schedule transmission time, duration and the destination. The successful ISS testing have added yet another router to the gradually evolving

Interplanetary Internet supported with the DTN technology that will no more require human beings to operate and control transmission activities, thereby saving a lot of labor cost.

D. Interplanetary Overlay Network (ION)

Interplanetary Overlay Network (ION) is an alternative product of the Jet Propulsion Laboratory to implement DTN in Interplanetary environments. It is open source, modular, easy to modify and we can also plug in our own routing protocol. It implements the bundle protocol as in [26] along with the CCSDS File Delivery Protocol (CFDP) and the Licklider Transport Protocol (LTP) found in IRTF RFCs 5325 [28], 5326, and 5327. There are certain constraints that the ION must overcome in order to cope up with space environments: 1) Data transmission is slow and highly assymetrical in space communication, typically in the order of 256 Kbps for downlink and 1 to 2 Kbps for uplink. 2) Current spacecrafts have embedded systems and implement real time operating systems (RTOS) such as VxWorks and RTEMS, those of which might not always implement protected memory models as in terrestrial processors. 3) Flight computers must be radiation hardened so that they can efficiently operate in harsh space conditions. Adding this characteristic make the processors several times slower. Moreover, the flash memory on spacecraft limits the data input and output rate. 4) Data is always transmitted in the form of bundles and hence the per-bundle processing overhead must be kept as minimum as possible.

In Table IV we summarize the different parts and functions of the ION software infrastructure built in C programming language. ION uses a simple header compression scheme to improve transmission efficiency called the Compressed Bundle Header Encoding (CBHE). It is database centric unlike its predecessor DTN2 [73]. The node architecture and processing within the node has been elaborated in details in section V of [81]. Currently the DTNRG is in an effort to establish a worldwide collection of nodes running BPAs that represent the DTN implementations of DTN2 and the ION [82].

TABLE IV
DIVISIONS IN THE ION INFRASTRUCTURE

Personal Space Management (PSM)	It performs the private and dynamic management of a pre-allocated system memory, by continuous allocation of small objects from the memory block as and when needed.
Simple Data Recorder (SDR)	SmList is a linked list in shared memory using the help of PSM. SDR helps in the management of persistent objects in the non-volatile memory with the help of the SmList. It uses a transaction mechanism to maintain data integrity.
Platform Library	It provides an abstract operating system that simplifies the development of portable software.
Zero-Copy Objects (ZCO)	It minimizes the number of times protocol payloads must be copied as they move up and down the protocol stack.

V. OPEN RESEARCH CHALLENGES

Space based data is continuously increasing and people have also started to rely on them significantly. As the data increases, more number of spacecrafts and equipments need to be deployed to support such high data volumes which in turn leads to increased complexity. Hence, the future space communication architecture should inherently start shifting from circuit switched (human operated) communication to a more flexible automated network architecture. Moreover, there is another design aspect that is acquiring importance over time which requires aerospace systems to be capable of serving multiple roles over a large period of time - a system with an inherent capability of growth and adaptation [83] to meet the ever increasing demand and change in technology. The future work involves the development of a reliable Interplanetary Internet (IPN) built on top of the Delay Tolerant Networking (DTN) architecture with efficient routing protocols. Spacecrafts, Planets and Earth based stations keep moving in and out of sight. It is very challenging to route data over the IPN nodes to the destination and this area still requires extensive research.

As the IPN becomes more robust and needs to exchange more telemetric data in future, it will be unacceptable to have two separate networks namely the terrestrial Internet and the Interplanetary Internet. The two networks will need to seamlessly merge with one another which might bring up the requirement for an overlay network on top of the DTN architecture. It will logically make both the networks act as one connected web. The DTN routing, congestion control and security is very different from the standard Internet and hence it will become challenging to build an overlay network that can emulate the Internet.

A limitation in space environment is the time interval during which data is sent from sender to the receiver. This constraint makes security necessary and protocols should efficiently implement secure data transmission. In space environment there is very little or no fear of data being tampered with by human intervention. Loss of data due to environmental conditions is of greater concern. Space environments can be even more destructive and unpredictable than on Earth terrestrial environments and they can even last for longer periods of time. In such conditions sending data over a link once, successfully and securely become very important. Secure data transmission over space networks is still under investigation.

Free space optical communication is also gaining importance as we are moving into the future. More work is required in this area as it promises very high data rates which makes it the only next generation communication means for space networks. Such high speed data needs and their feasibility has been well discussed by the author in [85]. Several experiments are underway which test the feasibility of such Interplanetary laser communication. One of the recent space experiments is the Mars Laser Communication Demonstration (MLCD) flying aboard the Mars Telecommunications Orbiter and built in NASA's Goddard Space Flight Center, the Jet Propulsion Laboratory and MIT's Lincoln Laboratory. It is expected to receive data at a rate of 1 Mbps when Mars and Earth are at the

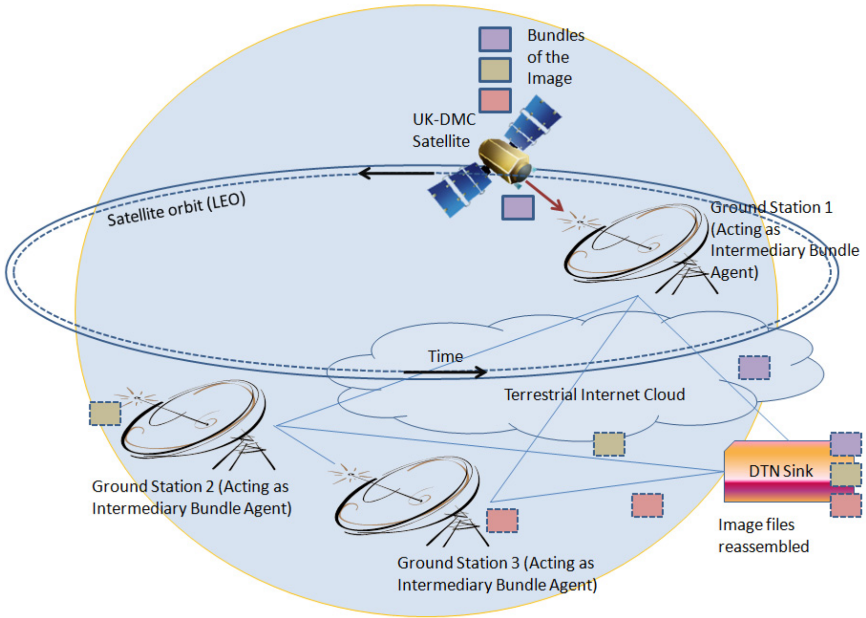


Fig. 7. Use of Bundling and fragmentation over a number of passes of the satellite. The complete image file is first broken into three bundles and each of them is then sent over to the ground station at each pass when the satellite and a particular ground station can communicate with one another. The separate bundle files are then sent over the terrestrial Internet to the DTN sink, where they were again coagulated to form the single image file. The bundles were sent hop by hop over the terrestrial network. The ground stations act as the Bundle Agents which can query the source on the SSDR using the Saratoga protocol.

farthest points from one another. However, it might take a few more decades before complete optical space communication is feasible.

VI. Conclusion

The paper has bridged relevant information about past and present space communication technologies, available protocols and major networking experiments in the field. Space deployments such as the CubeSat, Mars Reconnaissance Orbiter (MRO), Telstar and Iridium networks have been discussed to provide insights into the existing network architectures. Terrestrial and space Delay Tolerant Networking (DTN) has been discussed separately with more stress on space DTN protocols and architectures. A few DTN experiments have also been briefly discussed along with the Bundle protocol in terms of its packet formats and mechanism of operation. The most important space communication network is known as the Deep Space Network. Its communication facilities, site antennas and the constraints of the network have been explored in detail. We have also provided a comparison of the orbits, namely LEO, MEO, GEO and HEO in which satellites can be deployed. Finally we identified several open research challenges which must be addressed before the Interplanetary Internet (IPN) becomes a reality.

Space communication has been evolving rapidly over the decades. In the near future, space DTN experiments will overcome the limitations of near earth networks. Once we have a robust protocol to support network in space environments, then the IPN moves one step forward towards its deployment. More DTN experiments emulating Space Networks are under development and are soon to be tested in the coming years. We can envision a direct high speed Internet connection from our homes to our neighboring planets in the solar system within a few more decades.

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References

[1] "DSN Service Catalog", DSN No. 820-100, Rev. E, JPL D-19002, Jet Propulsion Laboratory, latest copies available at: http://deepspace.jpl.nasa.gov/advmiss.

[2] H. Hemmati, "Deep Space Optical Communications", 2006: Wiley.

[3] Z.Sodnik, B.Furch and H.Lutz, "Optical Intersatellite Communication", Selected Topics in Quantum Electronics, IEEE Journal of , vol.16, no.5, pp. 1051-1057, Sept.-Oct. 2010.

[4] "European Data Relay Satellite (EDRS)", Space News. http://www.spacenews.com/civil/esa-and-germany-reach-agreement-data-relay-system.html.

[5] "HORIZONS User Manual", NASA, JPL. http://ssd.jpl.nasa.gov/?horizons_doc.

[6] "SPICE", NAIF. http://naif.jpl.nasa.gov.

[7] "Planetary Data System (PDS)", NASA. http://pds.jpl.nasa.gov.

[8] M. Toyoshima, "Trends in satellite communications and the role of optical free-space communications", Journal of Optical Networking. vol.4, issue 6, pp. 300-311 (2005).

[9] "The Consultative Committee for Space Data Systems (CCSDS)", http://public.ccsds.org.

[10] "International Telecommunications Union (ITU)", http://www.itu.int.

[11] "The National Telecommunication and Information Administration (NTIA)", http://www.ntia.doc.gov.

[12] "Space Frequency Coordination Group (SFCG)", https://www.sfcgonline.org.

[13] R. Stewart et al., "Stream Control Transmission Protocol", Request for Comments, RFC 4960, http://tools.ietf.org/html/rfc4960, September 2007.

[14] T. Henderson and R. Katz, "Transport protocols for Internet-compatible satellite networks", Selected Areas in Communications, IEEE Journal on , vol. 17, no. 2, pp. 326-344, February 1999.

[15] M. Elaasar, M. Barbeau, E. Kranakis and Z. Li, “Satellite transport protocol handling bit corruption, handoff and limited connectivity”, IEEE Transactions on Aerospace Electronic Systems, vol. 41, no. 2, pp. 489-502, April 2005 .

[16] I. F. Akyildiz, G. Morabito and S. Palazzo, “TCP Peach: a new congestion control scheme for satellite IP networks”, IEEE/ACM Trans. Networking, vol. 9, no. 3, pp. 307-321, June 2001.

[17] O. B. Akan, J. Fang and I. F. Akyildiz, “TP-Planet: a reliable transport protocol for interplanetary Internet”, Selected Areas in Communications, IEEE Journal, vol.22, no. 2, pp. 348-361, February 2004 .

[18] C. Casetti, M. Gerla, S. Mascolo, M. Sanadidi and R. Wang, “TCP Westwood: End-to-end congestion control for wired/wireless networks”, Wireless Networks (WINET) Journal, vol. 8, no. 5, pp. 467-479, September 2002.

[19] D. Katabi, M. Handley and C. Rohrs, “Congestion control for high bandwidth-delay product networks”, SIGCOMM02, August 2002.

[20] K. Zhou, K. Yeung and V. O. K. Li, “P-XCP: a transport layer protocol for satellite IP networks”, Global Telecommunications Conference, 2004. GLOBECOM ’04. IEEE , vol.5, no., pp. 2707- 2711, 2004.

[21] T. Taleb, N. Kato and Y. Nemoto, “REFWA: An Efficient and Fair Congestion Control Scheme for LEO Satellite Networks”, IEEE/ACM Trans. Networking, vol. 14, no. 5, pp. 1031-1044, October 2006 .

[22] “Space Communications Protocol Standards - Transport Protocol (SCPS-TP)”, CCSDS, Blue Book. http://public.ccsds.org/publications/archive/714x0b2.pdf as retrieved on October 2006.

[23] “Rationale, Scenarios, and Requirements for DTN in Space”, CCSDS 734.0-G-1, Green Book, http://public.ccsds.org/publications/archive/734x0g1e1.pdf, August 2010.

[24] SatLabs Groups, “Interoperable PEP (I-PEP) transport extensions and session framework for satellite communications: air interface specifications”, Issue 1a-27, October 2005, retrieved from http://www.satlabs.org.

[25] M. Marchese, M. Rosei and G. Morabito, “PETRA: Performance enhancing transport architecture for satellite communications”, IEEE J.Sel. Areas Commun., vol. 22, no. 2, pp. 320-332, February 2004.

[26] K. Scott and S. Burleigh, “Bundle Protocol (BP)”, IETF Request for Comments RFC 5050. http://tools.ietf.org/html/rfc5050, as of November 2007.

[27] “CCSDS File Delivery Protocol (CFDP)Part 1: Introduction and overview”, Informational Report, CCSDS 720.1-G-3, Green Book, NASA, Washington D. C., USA. http://public.ccsds.org/publications/archive/720x1g3.pdf as of April 2007.

[28] S. Burleigh, M. Ramadas and S. Farrell, “Licklider Transmission Protocol (LTP) - Motivation”, IETF Request for Comments RFC 5325. http://www.rfc-editor.org/rfc/rfc5325.txt as of September 2008.

[29] R.Wang, T.Taleb, A.Jamalipour and B.Sun, “Protocols for Reliable Data Transport in Space Internet”, IEEE Communications Surveys & Tutorials, vol. 11, no. 2, second quarter 2009.

[30] I.Psaras, G.Papastergiou, V.Tsaoussidis and N.Peccia, “DS-TP: Deep-Space Transport Protocol”, IEEE Aerospace Conference 2008, Big Sky, Montana, USA, pp. 1-13, March 2008.

[31] L.P.Clare, J.R.Agre and T.Y.Yan, “Considerations on communications network protocols in deep space”, IEEE Aerospace Conference, vol.2, pp. 2/943-2/950, 2001.

[32] “CubeSat”, Wikipedia. http://en.wikipedia.org/wiki/CubeSat.

[33] R.Nugent, R.Munakata, A.Chin, R.Coelho and J.Puig-Suari, “The CubeSat: The Picosatellite Standard for Research and Education”, AIAA Space 2008 Conference and Exposition, San Diego, California, 2008.

[34] “QB50”, Von Karman Institute. https://www.qb50.eu/project.php retrieved as of 2009.

[35] “Mars Reconnaissance Orbiter Factsheet”, NASA. http://www.jpl.nasa.gov/news/fact_sheets/MRO.pdf.

[36] Jr C.D.Edwards, T.C.Jedrey, E.Schwartzbaum, A.S.Devereaux, R.DePaula, M.Dapore and T.W.Fischer. “The Electra proximity link payload for Mars relay telecommunications and navigation”, IAC-03-Q.3.A.06, 54th International Astronautical Congress, Bremen, Germany, 29 September - 3 October 2003.

[37] E. Satorius, T. Jedrey, D. Bell, A. Devereaux, T. Ely, E.Grigorian, I. Kuperman and A. Lee, “The Electra Radio”, Chapter 2 in Autonomous Software-Defined Radio Receivers for Deep Space Applications, JPL Deep-Space Communications and Navigation Series, J. Hamkins, M.Simon, J. Yuen, Eds. Wiley-Interscience, October 13, 2006. http://descanso.jpl.nasa.gov/Monograph/series9/Descanso9_02.pdf.

[38] “Timeline of Mars Reconnaissance Orbiter”, NASA. http://www.nasa.gov/mission_pages/MRO/mission/timeline.html.

[39] “Van Allen Radiation Belt”, Wikipedia. http://en.wikipedia.org/wiki/Van_Allen_radiation_belt.

[40] “Fishing net to collect space debris”, Telegraph. http://www.telegraph.co.uk/science/space/8296288/Fishing-net-to-collect-space-debris.html.

[41] “Ellipso”, http://www.ellipso.com/.

[42] “About Satellite Phone Service”, The Travel Insider. http://www.thetravelinsider.info/phones/aboutsatellitephoneservice.htm.

[43] F.Vatalaro, G.Corazza, C.Caini and C.Ferrarelli : “Analysis of LEO, ME0 and GEO Global Mobile Satellite Systems in the presence of Interference and Fading”, Selected Areas in Communications, IEEE Journal on , vol.13, no.2, pp. 291-300, February 1995.

[44] J. Layland and L. Rauch, “The Evolution of Technology in the Deep Space Network - A History of the Advanced Systems Program”, JPL Publication 95-20,Jet Propulsion Laboratory, Pasadena, California.

[45] “Deep Space Network”, JPL, NASA. http://deepspace.jpl.nasa.gov/dsn/.

[46] “Manned Space Flight Network”, http://www.enotes.com/topic/Manned_Space_Flight_Network.

[47] “Space Today Online covering Space from Earth to the Edge of the Universe”, Space Today Online, http://www.spacetoday.org/.

[48] D.S.Bagri, J.I.Statman, and M.S.Gatti, “Proposed Array-Based Deep Space Network for NASA”, IEEE.

[49] B.E.MacNeal, D.S.Abraham and R.J.Cesarone, “DSN Antenna Array Architectures Based on Future NASA Mission Needs”, Aerospace Conference, 2007 IEEE , pp. 1-8, March 2007.

[50] “Communications Satellite”, Wikipedia. http://en.wikipedia.org/wiki/Communications_satellite.

[51] “Satellite News Digest”, http://www.sat-nd.com/.

[52] “Iridium Satellites”, Real Time Satellite Tracking. http://www.n2yo.com/satellites/?c=15.

[53] “Iridium Satellite Phones”, SatPhoneUSA. http://www.satphoneusa.com/iridium/.

[54] Manual for ICAO Aeronautical Mobile Satellite (ROUTE) Service, Part 2-IRIDIUM, Draft v4.0, 21 March 2007.

[55] “History of the Handheld Satellite Phone”, Globalcom. http://www.globalcomsatphone.com/articles/history.html.

[56] M.Marchese, “Interplanetary and pervasive communications”, Aerospace and Electronic Systems Magazine, IEEE , vol.26, no.2, pp. 12-18, February 2011.

[57] V.Cerf, et al., “Delay-Tolerant Network Architecture:The Evolving Interplanetary Internet”, IPN Research Group, INTERNET-DRAFT, August 2002, valid through February 2003.

[58] K. Fall, “Delay-Tolerant Network Architecture for Challenged Internets”, SIGCOMM, August 2003.

[59] “DTN testing using Bundle protocol”, Surrey Satellite Technology Limited. http://www.sstl.co.uk/news_and_events/latest_news?story=1254.

[60] J.Wyatt, S.Burleigh, R.Jones, L.Torgerson and S.Wissler, “Disruption Tolerant Networking Flight Validation Experiment on NASAs EPOXI Mission”, 2009 IEEE.

[61] A.Jenkins, S.Kuzminsky, K.K.Gifford, R.L.Pitts and K.Nichols, “Delay/Disruption-Tolerant Networking : Flight test results from the international space station”, Aerospace Conference, 2010 IEEE, pp. 1-8, March 2010.

[62] I. Psaras, L. Wood and R. Tafazolli, “Delay-/Disruption-Tolerant Networking : State of the Art and Future Challenges”, Technical Report, University of Surrey, UK, 2010.

[63] A.S.Pentland, R.Fletcher and A.Hasson, “DakNet: Rethinking Connectivity in Developing Nations”, Computer, vol.37, no.1, pp. 78- 83, January 2004.

[64] P.Juang, H.Oki ,Y.Wang , M.Martonosi, L.S.Peh and D.Rubenstein, “Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet”, Proceedings of the 10th international conference on Architectural support for programming languages and operating systems, October 05-09, 2002, San Jose, California.

[65] J.Burgess, B.Gallagher, D.Jensen and B.N.Levine. “MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks”, INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings , pp. 1-11, April 2006.

[66] J.Ott and D.Kutscher, “Drive-thru Internet: IEEE 802.11b for “automobile” users”, Proceedings of INFOCOM, vol.1, pp. 4, March 2004.

[67] S.Symington et al., ”Bundle Security Protocol Specification”, IRTF Request for Comments RFC 6257, http://tools.ietf.org/html/rfc6257, as of May 2011.

[68] M. S. Uddin, A. Khurshid, H. D. Jung, and C. Gunter, “Denial in DTNs”, UIUC, Tech. Rep., 2010.

[69] V. Cerf et al., “Delay Tolerant Networking architecture”, Request for Comments RFC 4838. http://tools.ietf.org/html/rfc4838, as of April 2007.

[70] L. Clare, S. Burleigh and K. Scott, "Endpoint naming for space delay / Disruption Tolerant Networking", Aerospace Conference, 2010 IEEE , pp. 1-10, 6-13 March 2010.

[71] S.Farrell and V.Cahill, "Security considerations in space and delay tolerant networks", Proceedings - SMC-IT 2006, 2nd IEEE International Conference on Space Mission Challenges for Information Technology, 2006.

[72] "NASA successfully tests first Deep Space Internet", NASA. http://www.nasa.gov/home/hqnews/2008/nov/HQ_08-298_Deep_space_internet.html.

[73] K.Nichols, M.Holbrook, R.Lee Pitts, K.K.Gifford, A.Jenkins and S.Kuzminsky, "DTN Implementation and Utilization Options on the International Space Station", SpaceOps 2010 Conference, April 2010.

[74] P. Hochmuth, "Cisco in Space", Network World, 31 October 2005.

[75] K.Fall and S.Farrell, "DTN: an architectural retrospective", Selected Areas in Communications, IEEE Journal on , vol.26, no.5, pp. 828-836, June 2008.

[76] W. Ivancic, L.Wood, P. Holliday, W.M. Eddy, D. Stewart, C. Jackson and J. Northam, "Experience with Delay-Tolerant Networking from Orbit", ASMS 2008, Bologna, pp. 173- 178, August 2008.

[77] K. Hogie, E. Criscuolo and R. Parise, "Using standard Internet Protocols and applications in space", Computer Networks, special issue on Interplanetary Internet, vol.47 no. 5, pp. 603-650, April 2005.

[78] W. Ivancic, D. Stewart, L. Wood, C.Jackson, J. Northam and J. Wilhelm,"IPv6 and IPSec Tests of a Space-Based Asset, the Cisco router in Low Earth Orbit (CLEO)", NASA Technical Memorandum 2008-215203, May 2008.

[79] L. Wood et al., "Saratoga: A Scalable Data Transfer Protocol", Network Working Group, IETF, http://tools.ietf.org/html/draft-wood-tsvwg-saratoga-09#page-4, September 26, 2011.

[80] R. M. Jones, "Disruption Tolerant Network Technology Flight Validation Report, DINET", JPL Publication 09-2, NASA, February 2009.

[81] S. Burleigh, "Interplanetary Overlay Network: An Implementation of the DTN Bundle Protocol", Consumer Communications and Networking Conference, 2007. CCNC 2007. 4th IEEE, pp. 222-226, January 2007.

[82] "DTNBone", Delay Tolerant Network Research Group. http://www.dtnrg.org/wiki/DtnBone

[83] J.M. Lafleur and J.H. Saleh, "Survey of Flexibility in Space Exploration Systems", International Astronautical Congress, 2008.

[84] "CCSDS File Delivery Protocol (CFDP)", CCSDS 727.0-B-2, Blue Book.http://public.ccsds.org/publications/archive/727x0b4.pdf, retrieved as of October 2007.

[85] T.Iida, Y.Arimoto and Y.Suzuki, "Earth-Mars communication system for future Mars human community: A story of high speed needs beyond explorations", Aerospace and Electronic Systems Magazine, IEEE , vol.26, no.2, pp. 19-25, February 2011.

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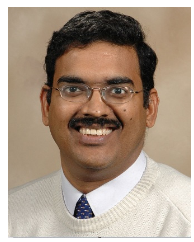

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