49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition
4 - 7 January 2011, Orlando, Florida

AIAA 2011-330

A Broadband Multi-hop Network for Earth-Mars Communication using Multi-purpose Interplanetary Relay Satellites and Linear-Circular Commutating Chain Topology

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Bandwidth utilization in the Mars exploration environment has been projected to increase past 1 Gbps duplex within the next decade. At present, all communication is routed through the Deep Space Network and is subject to the variable orbital geometry of Earth, Mars and the Sun. Data Communication speeds, between Earth and Mars, are neither satisfactory nor can they be utilized on a 24x7 basis, due in part to the lack of a space based telecommunication backbone. A holistic assessment of the merits of multi-hop communication in deep space was undertaken during 2009-2010, and a potentially robust new solution, employing a novel Linear-Circular Commutating Chain (LC3) architecture, developed for persistent, broadband connectivity between Earth and Mars. New classes of spacecraft suitable for use as Multi-purpose Interplanetary Relay (MIR) satellites in helio-centric orbit are outlined. Preliminary communication link budget and orbital analysis of a two-constellation MIR satellite network is presented, consisting of a linear chain of satellites (n_1 group, 36 nodes) following Mars, and a circular chain of satellites located inside of Earth's orbit (n_2 group, 292 nodes). Potential orbital tracks are presented for network (365 nodes, including spares) supporting 1 Gbps end-to-end transmission with intermediate switching/trunking facilities, that should be able to be constructed by 2020 and serviced in deep space, using readily available technology practices. The proposed network avoids occultation problems caused by Earth-Sun-Mars geometry, provides redundant capability, and if desired, can be extended with very high capacity Optical links in place of, or in addition to, the RF links. A preliminary space mission concept summary is also included.

Nomenclature

μ_{sun} = Gravitational parameter of Sun
ε_t = Energy of Hohmann transfer orbit
ϖ_e = Longitude of perihelion of Earth orbit
ϖ_m = Longitude of perihelion of Mars orbit
a_e = Semi major axis of Earth orbit
a_m = Semi major axis of Mars orbit
e_e = Eccentricity of Earth orbit
e_m = Eccentricity of Mars orbit
a_t = Semi-major axis of Hohmann transfer orbit
A = Path loss
ABW = Allocated bandwidth
B = Bandwidth
b_e = Semi-minor axis of Earth orbit
b_m = Semi-minor axis of Mars orbit
c_e = Half of distance between foci of Earth orbit
c_m = Half of distance between foci of Mars orbit
C = Carrier power
C_{N2} = Circumference of N_2 orbit track
CR = Code rate
CSF = Carrier spacing factor

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DR = Data rate
E_b = Energy per bit
e_r = Recommended minimum E_b/N_0 for carrier
G_t = Gain of transmit antenna
G_r = Gain of receive antenna
k_b = Boltzmann Constant
$L_{\square em}$ = Length of generic Hohmann transfer orbit from Earth to Mars
M = Fade margin
Ma_e = Major axis of Earth orbit
Ma_m = Major axis of Mars orbit
Ma_{Tn} = Major axis of nth MIR orbit track
MI = Modulation index
n_1 = Number of nodes in MIR satellites in group N_1
n_2 = Number of nodes in MIR satellites in group N_2
N = Noise power
N_0 = Unit noise power
N_{min} = Minimum number of MIR/R spacecraft required
N_{l3c} = Number of MIR/R spacecraft required in LC3 network, with spares
NF = Noise figure
OBW = Occupied bandwidth
OO_m = Orbital offset of Mars orbit
OTS_c = Orbital track separation at closest approach of Earth and Mars orbital track
OTS_f = Orbital track separation at farthest approach of Earth and Mars orbital track
P_r = Received power
P_{rs} = Receiver sensitivity
P_t = Transmit power
r_{soie} = Radius of Sphere of Influence of Earth
R_b = Information bit rate
R_{eo} = Radius of Earth orbit
R_{max} = Maximum distance between MIR satellites
R_{mo} = Radius of Mars orbit
RNF = Receiver noise floor
SR = Symbol rate
T = Temperature
TOF_{em} = Time of Flight for a spacecraft from Earth to Mars
V_{te} = Velocity in transfer orbit at Earth
N_1 = Number of spacecraft in N_1 group
G = Gaps between spacecraft of N_1 group
D_{min} = Target separation between N_1 group spacecraft at closest approach of Earth/Mars orbit tracks
D_{max} = Target separation between N_1 group spacecraft at farthest approach of Earth/Mars orbit tracks
z_{Tn} = Distance between focus (Sun) and end pt. of major axis of MIR/R orbit track, at farthest separation

I. Introduction

Earth based scientists have been actively studying Mars since the 1960's, and have recently remotely operated advanced instruments onboard Landers and Orbiters (e.g., the NASA MGS, MER-A and MER-B missions). Using data returned from the sensors through the Deep Space Network, the international science community has been busily building up detailed surveys of the topology of Mars, its geology and its weather. Each successive generation of instruments onboard new spacecraft brings with them a demand for more bandwidth to downlink science data.. This puts the scientific community in a bind and mission controllers on edge as communication channels across interplanetary distances are still typically limited to data rates of several hundred Kb/s or occasionally a few Mb/s, for a limited duration of time. This slow data rate is primarily due to the large variations in orbit between Earth and Mars and the geometry between two planets around the Sun, limitations of the Deep Space Network and lack of powerful transmitters that can "bridge the gap" efficiently. The limitations of the Deep Space Network are not related to the physical facilities which are state-of-the-art in every respect. According to Lesh, the

DSN architecture is dependent upon the available power at the remote spacecraft, intermittent link connections with changing topologies, planetary rotation and orbits of spacecraft around other bodies in the solar system[1].

It is an interesting fact that numerous proposals for interplanetary communication have been put forward by knowledgeable experts dating back to the 1940's which is investigated in the Literature Review section of this document. However, the two principal requirements of an efficient Earth/Mars interplanetary communications network have so far proven extremely elusive: convenient orbital locations providing persistent line of sight coverage between Earth and Mars that avoid the Sun, and sufficient transmission link budget to allow for high capacity communications with allowance for varying distances in a roughly two year cycle.

In this paper, a novel interplanetary relay communications network concept, entitled Linear-Circular Commutating Chain, or "LC3", based upon current technology practices, is introduced as a potential candidate solution to overcome the stated impediments. The LC3 concept will allow the construction of a persistent broadband network supporting bi-directional communication, at 1 Gbps data rate, between Earth and Mars, within 2020.

II. Hypothesis & Prior Concepts

A. Hypotheses needing testing

In order to accept any new proposal in the form of a space-based, multi-hop communications network as a viable candidate for future interplanetary communications, all of the five hypotheses, of Table 1, have to be found valid. By requiring a holistic determination, instead of a goal-oriented investigation, in this analysis, the researcher has taken the opportunity to look beyond just a few defined topic areas and has considered the "big picture" behind deep space communication and associated inter-disciplinary fields of research.

Table 1. Hypotheses under consideration

Hypothesis #1: A "Multi-purpose Interplanetary Relay Spacecraft" or "MIR Spacecraft" can be designed for long duration service in Deep Space, at an affordable cost.
There are many examples of communications payloads onboard spacecraft at GEO with service life of ~15 years and of multi-decade deep space missions; New designs may be feasible with a target service life of greater than 50 years.
Hypothesis #2: A broadband network can be designed using numerous instances of relay satellites and can provide 1 Gbps full duplex service between Earth and Mars using technology currently available.
Interesting area of research, feasible target as all the variables of RF/optical link budget are well known.
Hypothesis #3: The network can be deployed from a mother vessel spacecraft traveling in Earth-Mars transfer orbit and can be maintained in Deep Space.
En-route deployment/testing are common activities for spacecraft on deep space missions; servicing them on an extended basis is not; However, small robotic spacecraft can conceivably be designed, in the future, to permit on-orbit replacement and replenishment.
Hypothesis #4: The facilities of the network will be adequate for a simulated interactive communications environment at high data rates, even with long one-way light time delay.
Numerous examples of everyday interactive voice response/computer telephony integration applications abound in our daily lives. Two major examples, from the United States: When a passenger wants to book rail travel on Amtrak[†], or a customer wants to contact the final service company American Express[‡], they interact primarily through a very intelligently scripted/programmed interactive voice response telephony application with human-like cues.
Hypothesis #5:The network can be expanded to other applications such as servicing future Space missions and providing Lifeline and Navigation support for expanded travel in the Solar System.
Spacecraft have been constructed for more than one missions at a time, and due to unforeseen events have been forced to be adapted for other tasks not conceived during the mission planning phase, or have been retasked with new functions upon completion of their original objective. Therefore it is not inconceivable that a new satellite network could be equipped with nodal points where other communication networks can be (at a later date) be added to it.

For this analysis, Hypothesis #2 was selected to be investigated in detail through research. Based upon the validity of the hypothesis, additional tasks were incorporated into the research plan, listed in Table 2.

[†] Using a published toll-free telephone number, for domestic calls.

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Table 2. Tasks following verification of Hypothesis #2

Hypothesis	Additional Tasks
VALID	Develop design for a spacecraft able to do the mission. How much telecom payload mass would a MIR require to perform its mission adequately? How many types of spacecraft, and quantity of each type, will be required for the first network? Will there be any redundancy in the system? If so, how? How much spectrum will be required to provide reliable 1 Gbps service between Earth and Mars?
INVALID	Reasons for the invalid result Remedial options allowing direct broadband connectivity

During the preparatory phase of the research work, the following real-world programmatic constraints were placed on the selected hypothesis, due to limitations of time and resources:

Table 3. Programmatic Constraints

Constraint	Description
#1	The network will have to be able to be deployed adjacent to the path of regular spacecraft plying between the two planets by either a robotic mechanism or human crew and stay in service for many decades, with servicing being performed from time to time in deep space.
#2	The network should be available for use regardless of the respective orbital positions of Earth, Mars and Sun.
#3	The first generation of systems that are derived from this research should be able to be developed and deployed as flight-ready models using technology and processes available within the next five (5) years.

B. Literature Review

A general issue preceding the selection of technical components for a viable 1 Gbps communications solution is to justify the actual need, for a broadband network between Earth and Mars. A corollary question is to define (if justified), the type and quantity of communication required in both directions. Such justification can be derived from published topical research articles, past and present mission plans, projection of potential traffic growth in utilization of data for space missions etc. The collated requirements can then be compared to projections of the maximum capability of existing Deep Space Network infrastructure, which is predominantly Earth-centric using a combination of giant dimension antennas and L, S, X and Ka-band RF communication links. Ka-band facilities at the Deep Space Network (DSN) are a relatively new component of DSN Earth Stations compared to introduction of the earlier bands: L-band in 1962, S-band in 1964, X-band in 1977[2].

1. Justifying the Need

Bhasin, Hayden et al. have proposed a three part architecture for a next-generation Mars network consisting of (1) Mars-Earth Backbone Network (2) Mars vehicle proximity networks (3) Mars surface network in order to satisfy their estimate of aggregate throughput in the Gbps range[3]. They have also offered a three-fold Mars Communication Architecture, which allows for evolution in stages: near term (2001-2010), mid-term (2010-2010) and far-term (beyond 2020). In the near term, they propose a mix of X-band and Ka-band equipment on each scientific orbiter sent to Mars and all rovers that are placed on the planet. Communication will be from Mars surface direct to DSN on Earth, or through a single dedicated communication satellite (referred to as ASI Telesat). The mid-term architecture incorporates the presence/requirement of communications with a “Robotic Outpost” that relays data through a “MARSat”, essentially a dedicated communication satellite, direct to Earth. The far-term architecture envisions the need for two-way communications activity and accommodates the need for high volume of data throughput and multiple types by proposing the utilization of Optical Relay at Earth orbit, and also an additional relay at Lagrangian points to accommodate loss of signal when the Sun is between Earth and Mars. They also suggest that Mars may become a communication hub for other activity in the Solar System.

In a subsequent paper[4] this concept is modified to allow for a six level approach: (1) Earth-Mars communication relay spacecraft placed at Earth-Sun L_4 and/or Earth-Sun L_5 in a redundant configuration (2) Earth-Mars communication three using areosynchronous (MSO) relay satellites (3) Earth-Mars communication using four to six communications relay (MHO) in high orbit around Mars (4) Earth-Mars communication acting through a relay (MLO) in low orbit around Mars at low data communication rates[§] (5) Relay of robotic mission commands/data on

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[§] Currently, the current Mars Reconnaissance Orbiter, MRO is such an example.

Mars, in the atmosphere or in orbit around Mars through either MLO, MHO or MSO (6) Future Mars outpost traffic using wireless Local Area Networking (WLAN) for handling voice, video, control and data between various entities over short ranges (approximately 100 m) up to long ranges (approximately 50 Km). Optical links are considered in tandem with RF links for Levels 1-4, 6 but the maximum practical data rate seems to be limited to 100 Mbps instead of the earlier 1 Gbps target of 2001.

This change in expectation may indicate difficulties in achieving the required efficiency of extremely long haul combination of radio antenna arrays/optical adaptive arrays[5-7] and a requirement for redundancy of elements in the transmission and reception chain from Earth to Mars. However, Bhasin and Hayden's earlier prediction of Mars as "a communication hub" seems to have borne out, as there are presently several variations of combined science-communications in orbit around Mars currently constitute the basis for a "network" hub of sorts, involving Mars Exploration Rovers *Spirit* and *Opportunity* (2004, NASA), Orbiters Mars Odyssey (2001, NASA) and Mars Reconnaissance Orbiter (2005, NASA), Mars Express[**] (2003, ESA).

Too much traffic and only few opportunities for Earth-Mars direct communication limit the flexibility of utilizing the DSN to communicate with all the spacecraft[8]. The potential challenges in handling the different telecommunications needs (telemetry and command, science data, high-risk, mission events such as orbital maneuvers, entry/descent/landing maneuvers) with potentially high volume against the constraints (limited mass, energy, data rates) are discussed effectively in various papers [9-11].

The advantages of placing communication relay satellites at various libration zones orbiting the Sun-Mars L_1 and L_2 points, serving as Earth-Mars communication relays has been discussed[12]. However the authors considered a constellation of only two satellites which provide coverage of 12 hours each to Martian surface transceivers and they calculate that this scenario only provides 99.81% coverage of the planet due to the requirements for fixed orbits around the libration points at a distance of approximately $1\text{x}10^6$ Km from Mars. Again, this concept is based upon the conventional Earth-Mars direct communication system, or more accurately: Earth-Libration point relay L_1-Mars or Earth-L_1-L_2-Mars whichever is possible. This is a complicated system that depends upon the position of the relay satellites and their coordinated orbital track across a fair amount of the Solar System. In essence it is a leap of a significant fraction of an AU.

Advocates of expanding the capacity of the DSN to Ka-band note that trends of recent space exploration missions indicate that it is likely that future utilization of the network will be predominantly long-duration observations with data-intensive instruments, in-situ experimentation and complex operations requiring uploads/downloads, instead of simply reconnaissance[13]. An alternative way of explaining this departure from previous precedent is the need to deliver hard science before a skeptical public that justifies the cost of space missions, in a time period that suits the *I-want-it-know-and-I-do-not-want-to-wait* attitude of modern society. The authors discuss the concepts of the following classes of assets in a layered Data System Architecture: Remote, Relay, Local, Central and End User and point out the key benefits of using Relay communication including reduced power and energy requirements and increased data return due to short-range hops.

Ka-band however is susceptible to variations in Earth weather and studies have shown it to be affected by O_2 (Oxygen) absorption[14], where the authors recommend studying the weather forecasting at the local site level for a Deep Space Network station, to estimate the availability of Ka-band communication links, and to consider changing the data rate during a pass to take advantage of good/bad conditions.

The return of science data from a Mars mission is very important, but no mission can start without the spacecraft successfully completing the most challenging phase, which is executing a complex Mars Entry-Descent-Landing sequence without the benefit of assistance from ground controllers[15]. While a solution to this is probably not practical today due to lack of sufficient number of spacecraft, a high bit rate relay in close proximity to the spacecraft entering Mars High and Low orbit vicinity could potentially act as a lifeline for communication if a problem happened and some risk mitigation measures are needed[16]. In absence of such relays, different modulation techniques and advanced signal processing giving a strong signal received at Earth DSN usually provide a substitute mechanism for monitoring the events as they will have happened on Mars with light time delay. This would be beneficial for new mission to Mars, such as the proposed combination of Mars Science Laboratory and Rover Curiosity and the current Mars Odyssey orbiter in 2011.

2. *RF and Optical Carriers*

All space missions flown to date in deep space have used radio communication links as their primary modes of communication and there is a large body of research that outlines methods for increasing the chances of getting high bit rate communications directly from Mars back to Earth and vice versa[17-19], and it should be noted that development in Laser communications have also shown promising results [6, 20-24] for Earth-Mars links. Townes et al.

[**] Using the ESA ESTRACK Deep Space Antennas and NASA's Deep Space Network in Spain and California

highlights the disadvantages of interplanetary Laser links: transporting a 10 Gbps laser link to Mars would result in effectively 100 bits/second unless receive aperture size was increased to between 5m and 10m in size the links used when glare of the Sun would not be an issue for inward facing communication links.

As RF transmitter power budget is severely limited in deep space, extensive use of convolutional codes, Reed-Solomon codes, Turbo Codes in order to provide forward error detection and correction. Recently LDPC codes are estimated to be a better fit for certain deep space communication links compared to Turbo Codes. Also see the “Investigation - Communications Link Coding/Modulation Selection” of this analysis.

From the literature, it is seen that Lasers exhibit very narrow dispersal of beams compared to Radio beams, but that also implies that distant transmitters and receivers must be aligned in precisely complementary bearings for an extended amount of time when a spacecraft is moving, whereas radio transmission can proceed, albeit with minor degradation during spaceflight within a certain “bounding box” which can be plotted taking in account the 3-dB beamwidth of both RF antennas radiation patterns and adjustments in power from the transmitter. Tracking of RF antennas is typically a lesser concern than a Laser beam mechanism which operates at much frequency bands.

Optical communication systems that have one or more systems based on Earth suffer additionally from the influence of atmospheric effects in the form of optical scintillation and of attenuation by clouds which can be reduced by adaptive optics, multiple beams in tandem or site diversity for increasing link availability. However a scan of the selected literature indicates that a single laser beam system at interplanetary distances delivers on average a communication system that barely extends to 100 Mbps, but typically 50 Mbps range or lower performance is reported. By using advanced techniques such as WDM, multiple laser beams with slightly differing frequencies (if power budget is satisfactory) may be used to aggregate the carriers and deliver extremely high bit rates [24]. An example of a high bit rate laser demonstration system from GEO is the result of a 10 Gbps link test[25]. The cost associated with a Laser platform has been found comparable to a RF system[26] but they point out that space based multi-hop systems will provide an advantage if the aggregate links are taken in account, providing 1-100 Gbps of transmission capability. It is however very likely, that with continued technological progress, Lasers are expected be a viable and superior alternative to interplanetary radio links, or a companion communication facility.

3. *Space based Multi-hop networks*

Whereas multi-hop networks are used every day in regular terrestrial microwave communications, the development of a equivalent Space Mission Concept Plan in this regard for implementation does not seem to be a high priority at the current time. In 2000, J. Breidenthal in a major study of the merits of space-based multi-hop inter-planetary networks[26, 27] compared existing/conventional Deep Space Network architectures and found that in terms of downlink bit-rate and cost, a conventional Earth-Mars direct communication link was more “cost efficient” than a multi-hop relay network. The claimed advantage as calculated, however, depended upon an assumption that the cost of building the relay satellites using c. 2000 cost values, were 5 times to 10 times more expensive than ground solutions, setting the stage for a fresh opportunity to investigate how to lower overall cost projects for interplanetary satellites given that the communication satellite industry regularly produces both very complex and expensive (e.g.,*Terrestar-1*[††]) and extremely low-cost spacecraft (e.g., AMSAT, Inc. amateur radio satellites[‡‡]) for a variety of missions. In fact the advantage of numerous multi-hop satellites have been clearly enumerated in the above reference, before the missions of various science-telecommunications platforms to Mars (e.g., MRO, MTO) were conceived.

In 2009, McKay et. al. have proposed the use of Non-Keplerian orbits using low-thrust, high ISP propulsion systems[28] for positioning communication relay satellites for Earth-Mars service. The concept suggest use of large diameter antenna capable of beaming signals across approximately 2 AU distance, from Earth to Earth’s L_3 hover point, after which the signal would be relayed to Mars at a distance of still significant 0.52 AU. Libration positions have been considered before for Earth-Mars communications[12], particularly Earth L1, L2, L4, L5. Meanwhile, from another discipline, the need for a multi-hop network architecture similar to what Breidenthal has proposed has been clearly elucidated by Khan and Tahboub[29] as an “Interplanetary Relay Satellite Backbone Network” zone as part of a space architecture concept including an Earth Zone and Orbiting Zone of nodes in a dynamic network.

[††] TerreStar-1 was launched July 1, 2009 launched by Arianespace has a 60’ antenna operating in the S-Band. http://www.terrestar.com/satellite.php

[‡‡] AMSAT is one of a few amateur groups sponsored by ham radio operators who have built many small-sized communication satellites and operate their own distributed, ground/space control/communications network for general purpose use. http://www.amsat.org/amsat-new/satellites/status.php

4. *Multi-Mission Support and Networking with Internet gateways*

A virtual cornucopia of concepts on space networks have been published in recent years, including store and forward networks, an extension of TCP/IP to interplanetary scale service and standards published and recommended through the CCSDS framework.

A very early concept of a multi-mission complex constellation of Mars orbiting spacecraft (called "microsats") and incorporating the concept of the Areostationary "MARSat" (see "Justifying the Need") has been previously presented with relatively modest data return from a few hundred kbps up to 2 Mb/s using UHF radios[30-32]. To accommodate a common standard for interoperability at the data-link level between various Mars-orbiting spacecraft and Mars surface assets, CCSDS Proximity-1 CFDP protocol has been incorporated into new designs to accommodate message and file transfer[33]. These concepts are in line with NASA's c. 2000 Strategic Plan, dubbed "Code S" allowing "allow the public to participate 'virtually' in the adventure of exploring new worlds" and separately the development of 3m sized Ka-band *inflatable* antennas that provide higher SNR and high power TWTA for Ka-band service[1]

Noreen and Cesarone et al. have at a later date suggested that the networking architecture for Earth/Mars/Moon be considered simultaneously with telecommunication and navigation services in mind, and plans include a modest ground network (for the Moon), a constellation of three Lunar Telecommunications Orbiters and for Mars a pair of areostationary satellites connected to ground stations. All of these space assets should communicate with the Deep Space Network augmented by 12-m antennas[25]. Palmerini has offered a modified plan of four dedicated data relay and navigation satellites, instead of a stationary orbital platform, all placed in a single sun-synchronous dusk-dawn orbital plane in a nadir pointing attitude and passively controlled by gravity gradient [34]. The author claims that the simplified thermal design and constant power input to the solar arrays would allow high transmitter power levels to ensure good transmission capability to the Deep Space Network.

Given the increasing possibility of high availability in an inter-planetary communications network, the advantages of adapting and converting the Deep Space Network into a internet-friendly, inter-planetary network have already begun to be considered in detail[35], however conventional TCP/IP protocols have already been shown that they cannot be used in deep space effectively on an as-is basis[36, 37]. Alternatives network mechanisms have been considered and presented[38] as well as statistical models considering link resource, space dynamic events and operation constraints[39]. Newer schemes derived from computer network theory have also been proposed that incorporate prioritized scheduling for different types of traffic and other issues such as high latency, low throughput, short link duration, link asymmetry, link dynamics and outages[40].

5. *Bandwidth Needs Estimation*

Bandwidth estimates for communication needs from Mars to Earth seem to have a habit of increasing over time. According to 2004 estimate by Bhasin and Hayden, the requirement for Mars science data bandwidth may be as much as 20 Mbps uplink and 100 Mbps downlink[41] which was soon replaced by a different estimate of 440 Mbps aggregating a single bundle of HDTV feed from Mars Base, HDTV video feed from a human Transport, and Hyper-spectral Imaging from a Rover and Transport, along with live Radar feed[25]. This figure has now been replaced with a different estimate of 980 Mbps[18]. The estimate includes allowances for simultaneous mission activity with possibly four science orbiters and eight robotic surface vehicles, two astronauts active in base station, and four astronauts roving away from base station in two human transports. Should a colony of humans succeed in joining robotic explorers on Mars sometime in the next half century, the simultaneous bandwidth required for a combination of regular, exploration, science, medical and personal activities may well be much more estimated thus far.

Table 4. Prior Proposal Summary for Earth-Mars Networks

Communications Technology	At Mars	At Earth
RF	On ground via High Gain	DSN
RF	Relay Satellites in LEO with comms to ground terminal	DSN
RF	Relay Satellites in Areostationary Orbit	DSN
RF	Relay Satellites in Mars Synchronous Orbit	DSN
RF	Relay Satellites in Mars Synchronous/Areostationary	DSN via Lagrangian relay
RF & Optical	Relay Satellites in LEO or Areostationary Orbit; other comms by RF	DSN

One obvious shortfall for the communication schemes enumerated in Table 4, for Mars/Earth traffic is a reliable method for high bit rate communication at all times during the year, particularly when Mars and Earth are occulted with each other. According to Breidenthal, as mentioned earlier, this problem could be overcome if, instead of directly traversing Mars/Earth distances, transmissions were relayed using short hops between nodes in a chain of relay satellites. This chain would provide alternative routes from one planet to another. Communication would be sent between an “Earth Zone” to “Mars Zone” via the distributed backbone network providing the interplanetary relay, and receive the benefits of space based “multi-hop” communication such as higher data rate, more availability. As these relay satellites are going to have to work in deep space for very long periods, some consideration will also have to be incorporated for ongoing sub-system upgrade/refurbishment options and refueling requirements for propulsion needs.

C. Technology Reference Platforms

1. *Mars Reconnaissance Orbiter*

The research tasks for this concept, included developing a reference platform for transmit and receive based upon a space-qualified system design, and possibly an operational spacecraft platform already in Mars orbit that has been used for megabit/s data communication to Earth. The MRO was chosen in order to develop an initial configuration of an interplanetary relay spacecraft, which will be developed in a later section of this document, along with a first order approximation of the numeric quantity of nodes to connect Earth and Mars.

NASA’s Mars Reconnaissance Orbiter was launched in August, 2005 with a combined mission of conducting science observations from low orbit and acting as a telecommunication relay to other orbiters and rovers. The spacecraft uses an advanced spacecraft bus design provided by Lockheed Martin Space Systems comprising six science instruments and three engineering payload elements. The overall configuration of the spacecraft is a nadir pointing instrument cluster embedded in a central frame equipped with two banks of gimbaled solar panels. There is a 3-meter solid parabolic HGA affixed to a gimbaled mount on the top of the frame with capability for simultaneous X-band (8 GHz) and Ka-Band (34 GHz) service. The two LGA were used low bit-rate communication during launch and MOI and are now used when the spacecraft has to be put into safe mode. There is an additional UHF antenna for communication with other orbiters and landers from the MEP currently operating on the surface of Mars. The six science instruments (HiRISE, CRISM, MCS, MARCI, CTX, SHARAD) are primarily for the science mission. The three engineering payloads include ONC (Optical Navigation Camera), Electra (UHF communications and navigation package and a 35W TWTA Ka-band transmitter connected to a second RF port on the HGA. A detailed review of the design and performance of the MRO telecommunications system is available[42].

The MRO Ka-band payload has been used to validate high bit-rate data communication from Mars to Earth when the alignment of the two planets is favorable for the link budget and the facilities of the Deep Space Network are available for Ka-band reception. According to publicized specifications, the Boresight gain in the Ka-band for the 3-m, transmit antenna is 56.4 dBi with a half-power beamwidth of 0.18 degrees. As this is an experimental payload, the Ku-band transmitter output TWTA is directly fed through a secondary port into the HGA feed.

The results of the Ka-band transmissions from Mars were directly received on ground stations on Earth, which had to rely on two principle classes of impediments for good results: First, the link budget parameters including distance, transmit power, received power, line of sight between the Orbiter and Earth DSN ground stations had to be satisfied for adequate BER; Second, the effects of weather on the usability of Ka-band transmissions had to be accounted for, during the time the tests were being conducted. All Ka-band downlink transmissions have used BPSK and the maximum data rate achieved has been 5.22 Mbps with (255, 233 Reed-Solomon) code.

According to the published breakdown of the components of the MRO, the Ka-band payload with 35W nominal output TWTA had a total mass of 2.3 Kg (including power converter) compared to the total mass of 107.7 kg of all telecommunication components (including UHF subsystem, X-band transponders, other TWTA, X-band and Ka-band antennas, HGA gimbal and drive motors, waveguide and coax assemblies and other accessories).

2. *Spacecraft Antennas and Power Systems*

In a conventional communications scenario, higher bandwidth transmission from the vast distances of deep space, or missions to another planet, can only be reliably achieved using very large antennas or increasing the transmission power to the same antenna, or more likely, a combination of both. Other techniques such as compressing the bit stream (introducing delay) or employing different modulation techniques (requiring computing power) have drawbacks that are not easily overcome and could be fatal to a transmission that is being received at extremely low signal levels. The short window of opportunity to acquire the signal, synchronize with the carrier, demodulate the information imply that the most preferred method for increasing the chance of receiving these “carriers”, should employ methods for either sending more signal from the source (effectively increasing transmitter EIRP) or better receiver apparatus in the Deep Space Network (effectively improving G/T).

While increases in the Deep Space Network can be relatively easily accomplished by new equipment, a spacecraft, once deployed, has to depend upon what it outfitted with at the time of design. However, a large antenna onboard the spacecraft is a liability as it may not easily fit inside of the payload fairing on a conventional booster rocket, or the sheer mass of the antenna or high power amplifier required may require additional delta-vee resources for orbital maneuvers from Earth to the target destination. If a mission need is determined that a large antenna is required, designs of the spacecraft have to be carefully adapted to allow storage of all the elements in a compressed volume, to be deployed in space when the mission is on the way. With regard to the MRO previously discussed, the large 3m HGA was sent to space in the "stowed" position, and deployed after separation from a folded state and was deployed after the solar panels were unfurled for the first time. Other issues affecting the capability of a communications system may include the choice of having redundant modules or not for service and an optional matrix switching mechanism for sharing transmission paths/intermediate frequency paths in order to allow cross-band operation among radio elements. In the case of the MRO, the spacecraft has redundant X-band equipment but does not have a backup Ka-band transmitter and was never equipped with a Ka-band receiver. However data can be simultaneously streamed (using different communication protocols) through the low data rate X-band transmitter and the high data rate Ka-band transmitter if required.

Given the challenges of high bandwidth communication from deep space and interplanetary missions, NASA and the global aerospace industry have spent several decades in research studying the best way to solve the needs of the mission user community and also solve the requirements to be limited to small amounts of mass that has to be up-lifted in relatively small volumes available on a conventional rocket booster payload fairing, or, the Space Shuttle cargo bay. Lightweight antenna structures providing aperture areas of 6m to 25m have either been deployed in space or are becoming available at the present time[17, 43]. Deployable mesh reflectors have low mass density (typically, 1-2 Kg/m^2) and average surface accuracy. Solid, non-deployable reflectors have mass densities of ~3-4 Kg/m^2 and very high surface accuracy, reflectivity and efficiency. Solid reflectors have been deployed in the harsh environment in space with very good results, and new mechanisms have been developed to produce foldable, deployable solid antennas that can be remotely unpacked from its stowed position and assembled while in space. However, the mass-penalty of having a electro-mechanical deployment system has to be taken into account in the spacecraft budget.

In recent years, inflatable antenna systems have once again received attention for use as large, lightweight, deployable deep space antennas. Historically, inflatable balloons have been used as combination antennas and relays in the upper atmosphere or in LEO and one of the most earliest projects of this class were the two Echo balloon satellites launched by NASA. A publicly available image of ECHO II, which was a 41.1m diameter balloon built with polyethylene compounds, is shown in Figure 1. In collapsed form, the entire balloon fit into a 41-inch canister, which was flown onboard a Thor Agena rocket in 1964. It is obvious that the vast inner volume of such a large balloon could conceivably house a flexible antenna mechanism that would be protected from harsh elements of deep space and both the inside and outside walls of the balloon itself could be used as a substrate within which embedded RF elements could be placed to form a large directional antenna. Other types of inflatable antennas use pre-formed material to take the shape of parabolic reflectors that fill out when pressurized and deployed in space, e.g., the STS-77 Inflatable Antenna Experiment.[44, 45]

Figure 1. ECHO II in hangar

Newer technologies that have not yet been flown in space merit consideration according to Hodges et al. as the results have shown promise and may open up avenues for much larger antenna installations than before[17]. Flat surface antennas, or "Reflectarrays" can be produced for particular frequencies with very low mass-densities which imply they may be able to be used for extremely large apertures (currently 10m designs are under development) if a support tensioning mechanism is available. Active phase arrays and discrete element lenses employing arrays of printed circuit radiators may also be prevalent in the future for deep space mission antenna needs.

Should future spacecraft operating in the Mars vicinity require higher orders of Ka-band transmission output, an onboard power combining network and linearizer network could be employed to combine to several thousand watts of RF (e.g. 10 kW) output power from a single transceiver feeding a bank of TWTA or SSPA. However it may also be possible at the present time to source from manufacturers of space qualified RF sub-systems, a compact and lightweight module that produces several thousand watts (e.g. 1-3 kW) of RF in the Ka-band as long as it is provided with an adequately power supply in the form of enlarged solar panels and efficient battery sub-system. Power capacities may ultimately be limited only the available power source onboard the spacecraft.

D. Space-based multi-hop networks between Earth and Mars

It is clear that for high speed communication between Earth and Mars, there are two solutions currently in popular consideration (Mars-Earth direct and relays through Lagrangian points) and one latent idea (space based multi-hop) that could merit investigation if the cost of building satellites were to become very low.

Mars-Earth direct concept has definite drawbacks, based upon the huge variation in line of sight distance between Earth and Mars, approximately 0.38 AU (Mars Opposition) and 2.67 AU (Mars Conjunction). The presence of the Sun at the center of our solar system complicates the direct concept greatly. Communication capability is severely degraded when the line of sight between Earth and Mars passes through regions of hotter thermal noise (e.g.3000K in the corona, instead of typical 300K clear sky at 30 GHz) or is obstructed by the body of the Sun itself.

The concept of using the Lagrangian points as a relay point has some benefit, as the variation in distances between the two planets are minimized. The links should be stable when they are setup, but the great distance between the two stable points may come at a high cost of a less than efficient communications link budget. If a fleet of spacecraft are not deployed to Lagrangian points, then the entire link will be dependent upon the weakness in its smallest element, the relay spacecraft itself. In fact, all variations of Earth-Mars direct concept also suffers from this single-point-of-failure risk, if for example, the MRO should catastrophically fail, then the capability of conducting science operations on Mars is surely to be severely hampered for a long time.

If the alternative concept of space based multi-hop communication is reviewed in some detail, it is seen that Breidenthal has derived potential application areas for placing numerous relay satellites in various orbits[27]. However, the easiest configuration of placing relay satellites in a Hohmann elliptical transfer orbit alongside the path that a spacecraft will follow as it leaves Earth for Mars rendezvous, has several weaknesses which are enumerated in Table 5.

Table 5. Problems with Placing Relay Satellites in Hohmann Orbits

There are many solutions to the problem of an elliptical transfer orbit from Earth to Mars and back. However there are no solutions that provide the most convenient connections between the two planets for a single batch of relay satellites.
A series of satellites can initially be placed on a Hohmann type orbit, but they will be orbiting the Sun as per Kepler's Laws of Motion and will frequently drift out of phase with the motion of both Earth and Mars. Therefore after a while, the relay satellites will be unable to make reliable communication.
If several batches of relay satellites are planned to be placed in parallel to selected elliptical orbits , it is likely that there will be gaps in the coverage of the satellite chain, as the orbit of Earth and Mars diverge widely and come closer in regular intervals but over a long period.
When only a certain portion of the satellites are usable due to orbital mechanics and limitations of the link budget, the rest of the satellites are not very useful.

Alternatively, W.J. Hurd, who has been acknowledged by Breidenthal in his paper[27] to have provided a concept called “Minimal Earth Ring”, suggests that a few number of relay stations at or near Earth orbit could be tasked to act as long distance switching/exchange points with Mars, should a terminal be setup on the planet, or through an orbital gateway to communicate across the gap between the two orbits as long as it has the link budget ability to close the connection directly. This may be “elegant” but the data rate is likely to be lower than our desired target due to the long distance. What is interesting about this concept is the simplicity in having the exchange points co-orbiting Earth which makes it potentially easy to service and upgrade if so required.

Breidenthal subsequently addresses several large scale options for placing numerous satellites in orbit around the Sun, and explains the benefits/disadvantages of the Commutating Ring family of solutions (single, double with bridge, neighbor groups). Through his approach of developing an efficiency and cost model, it is possible to predict the estimated distance for each terminal in the network and the potential bandwidth gain throughout the network. A potential use of the “spare nodes” as message storage nodes has been suggested to take advantage of the fact that appreciable number will always be idle at any time. As Mars and Earth are relatively small compared to the length of the orbit they travel, this fact will also mean the cost of building and operating the required large network will not be able to be recovered in a short period of time. As an alternative solution to using many hundreds of terminals in a network, the author outlines the tantalizing possibility of increasing data throughput nearly 500 times by the use of using a single commutating ring populated by 48 active terminals and augmented by four terminals each in neighbor orbits of the two planets.

III. Developing a New Proposal

Based upon the findings of the Literature Review, it is likely that the preferred method of establishing interplanetary communication will change, from Earth-Mars direct to Earth-Mars through relay systems, in the near future. Different engineering techniques will have to be evaluated gradually through a trade study process to analyze the pitfall of each new option, and industrial partners will have to be convinced to invest time and effort into design the "next generation" of advanced spacecraft necessary to deploy deep space communication networks. To aid in that decision making process, a new suggestion is hereby presented, through a methodical investigation, analysis and selection process, that will utilize elements of Breidenthal's single commutating ring concept, J.W. Hurd's Minimal Earth Ring concept, and a novel proposal for a new satellite relay constellation connecting the orbital paths of Earth and Mars. The plan will focus on the key concept that can be stated: "Bring Mars communications terminals as close to Earth as possible using relay nodes, delivering gigabits through an efficient link budget", in an effort to comply with the key constraints enumerated in Table 3.

A. Investigation – MIR Spacecraft Communications System Block Diagram

It is proposed that individual MIR satellite systems architecture remain simple as simple as possible (Figure 2, Figure 3), as it will be primarily used for communications relay services, albeit with onboard digital processing for demodulation/modulation and routing/switching functions. All information (data) to be transmitted is provided as input to the baseband signal processing system, which may include routing/switching fabric, first. After suitable encoding for forward error correction, compression, encryption, protocol spoofing/adaptation and optional framing the processed data is given to a modulator where the data is impressed upon a low level RF carrier and up-converted in multiple stages to the appropriate final transmit frequency. At this stage, the output of the carrier is fed into a power amplifier sub-system which amplifies the output power by many thousands of times and delivers it via a waveguide to the antenna into deep space. As the carrier signal travels through space, it is affected by impairments such as thermal noise, other RF sources, galactic RF sources and absorption by different gases in vacuum or in the atmosphere of planets. The receiving system must have a sensitive antenna and optionally a Low-noise amplifier connected directly to the feed (not shown in figure) to maximize the chance of acquiring a carrier from deep space. The received signal down converted and then fed into the demodulator for conversion back to baseband information, or processed in digital form through an optional digital signal processor.

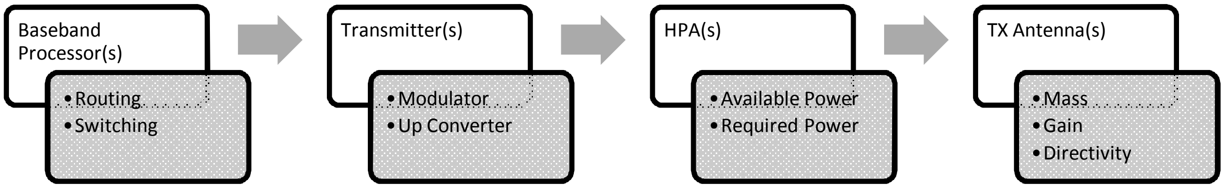

Figure 2. TX path diagram

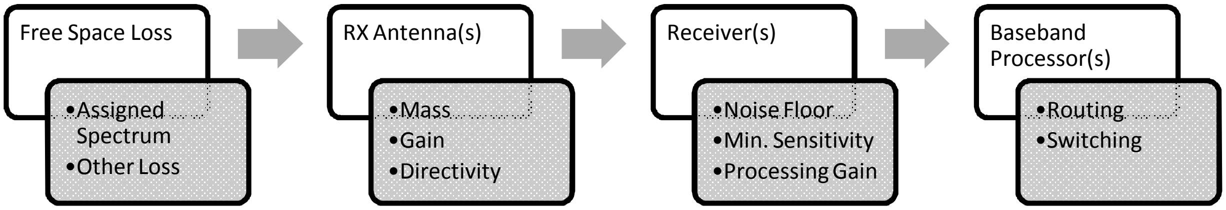

Figure 3. RX path diagram

By extension, the MIR satellite systems architecture can be modified to create high capability, digital, interplanetary communications switching platforms, in deep space, if additional transceivers, antenna arrays, HPA arrays, signal processing sub-systems are employed. The addition of these optional transceivers/antennas, on selected spacecraft, may provide broadband communications network relay capability for future deep space exploration missions that may not have optimum line of sight back to Earth's orbital position at critical phases.

B. Investigation - Communications Link Coding/Modulation Selection

In the field of deep space communication, recent (e.g. last 5-10 years time frame) advancements in forward error correction coding methods for digital communication have resulted in spacecraft able to send higher bit rates with lower probability of error in a power-limited channel, which at times is very close to the theoretical Shannon limit.

Until recently, deep space mission spacecraft designers primarily used a combination of BPSK with a convolutional encoder (inner codec) along with a Reed-Solomon outer codec in order to deal with low levels of received Signal to Noise ratio (SNR). With the advent of Turbo codes at various rates, the use of old-style FEC and Reed-Solomon has been replaced by computation engines that interleave predetermined punctured or non-punctured codes into the outgoing data stream for subsequent error detection and correction at the receiver end where there is a convolutional decoder (e.g., Viterbi decoder) which takes the Reed-Solomon corrected block output and produces a bitstream with very minor errors.

Comparatively, LDPC is a relatively new method of coding/decoding which requires large degree of computation power, but it has been shown to be easier to decode at lower SNR than Turbo coding or Reed Solomon and conventional FEC[46]. For a desired BER of 1E-7 (1 bit error in 10^7 bits/s) of a digital carrier at the receiver, per LDPC/BER chart[47], the received E_b/N_0 should exceed 1.5 dB. To allow for good decoding even during deep fading in the channel, an arbitrary margin of 3 dB is recommended, so the recommended minimum E_b/N_0 , or e_r , is set to 4.5 dB.

C. Investigation - Microwave Link Budget Analysis

A common method of assessing a microwave link is the "power balance equation"[48]

$$P_r = P_t - L_t + G_t - A + G_r - L_r \tag{1}$$

where P_r represents carrier power received in dBm, or minimum required receiver sensitivity at zero signal fade margin, and P_t represents the transmitter power output in dBm. Losses L_t and L_r are placeholders for miscellaneous signal losses in waveguide, coupling, or other mismatch in transmitter and receiver respectively, expressed in dB. G_t and G_r are antenna gain figures for the transmit and receive antennas respectively, in dBi. A hypothetical Ka-band receiver with noise figure (NF) of 15 dB was adopted as a reference model for a MIR satellite receiver application. The MRO Ka-band downlink/HGA specifications were adopted as reference model for the MIR satellite transmitter application. Receive/Transmit antennas were chosen to be symmetric for ease of modeling.

Assumption

$$NF = 15\,dB;\; e_r = 4.5\,dB \tag{2}$$

From specifications for the 3.0m Ka-band High Gain Antenna and Ka-band Transmitter onboard the MRO[42]

$$P_t = 35\,Watts = 45.4\,dBm \tag{3}$$

$$G_t = G_r = 56.4\,dBi\ (\text{boresight gain, transmit}) \tag{4}$$

We know for a digital carrier with power C, channel noise power N, information bit rate R_b, bandwidth B

$$\frac{C}{N} = \frac{E_b}{N_0} * \frac{R_b}{B} \tag{5}$$

For our hypothetical carrier the ratio of energy per bit to unit noise power (unit less)

$$\frac{E_b}{N_0} = 10^{e_r/10} \tag{6}$$

The proposed communications channel, with a 1 Gbps data rate, will have white Gaussian noise in addition to the signal carrier. Noise power, in dBm, can be calculated in a straightforward manner by the equation:

$$N = k_b * T * B \tag{7}$$

where k_b is the Boltzmann Constant, T is the temperature expressed in Kelvins. Presence of high noise power levels will result in degraded service quality unless the level of the carrier, measured as C/N, or S/N ratio (C=carrier, S=signal) is so high that the noise level does not prevent the acquisition of carrier, and its subsequent demodulation. Excess signal strength contributes to the quality of the service at the expense of capability (e.g., range, transmit power, receive/transmit antenna mass) and is usually estimated as Fade Margin, M in dB.

Table 6. Selected Coding and Modulation Parameters

BPSK Modulation
Code Rate of 0.5 was used with LDPC
Roll-off factor was assumed to be 0.2 for digital filter
Carrier Spacing Factor assumed to be 1; only one link/transmitter chain

Following the assumptions of Table 6, $R_b = DR = 1 * 10^9 bps;\ MI = 1; CR = 0.5;\ RF = 0.2;\ CSF = 1\, and\, B = OBW$ where DR is the Data Rate in bits per second, MI is Modulation Index which 1 for BPSK, CR is Code Rate, RF is Roll-Off Factor for spacing (unitless), CSF is Carrier Spacing Factor (Unitless) and OBW is Occupied Bandwidth in Hz. We can now derive the Fade Margin, M using Noise Power, N (dBm), Receiver Noise Floor, RNF (dBm), Receiver sensitivity, P_{rs} (dBm), Received Power, P_r (dBm), Hypothetical antenna gain, G (dBi), Free Space Loss A (dB), Symbol Rate, SR (symbols/s). We assume for our analysis a carrier frequency, F of 32.2 GHz and $L_t \rightarrow 0\ dB$ and $L_r \rightarrow 0\ dB$. Therefore,

$$SR = \frac{DR}{CR*MI} = 2 * 10^9 symbols/s \tag{8}$$

$$ABW = OBW * CSF = \big(SR * (1 + RF)\big) * CSF = 2.4 * 10^9 Hz \tag{9}$$

$$N = -80.028\ dBm \text{ (T=300K, 30 GHz, Cold Sky)} \tag{10}$$

$$N = -70.028\ dBm \text{ (T=3000K, 30 GHz, Solar Corona)} \tag{11}$$

$$RNF = N + NF \tag{12}$$

$$P_{rs} = RNF + (C\ /\ N) \tag{13}$$

$$\lambda = 9.31 * 10^{-3}\ m \tag{14}$$

$$G_t = G_r = 18 + 20\log(F, MHz\,) + 20\log\,(D, meters) \tag{15}$$

$$A = 92.5 + 20\log(F, GHz) + 20\log(Range, Km) \tag{16}$$

$$P_r = P_t + G_t - A + G_r \tag{17}$$

For links with $P_r \geq P_{rs}$,

$$M = P_r - P_{rs} \tag{18}$$

D. Investigation - Link Budget Test Cases

Deep space communication links are usually power-limited, rather than spectrum limited. Adopting a goal of increasing M, several test cases, defined in Table 7, were considered varying Transmit Power, Antenna size and Noise in order to investigate the suitability of establishing 1 Gbps rate deep space communication links, operating between hypothetical MIR satellite in a fully symmetric arrangement. For each case, M was calculated for ranges varying from 50,000 to 7.5 million Km and the results graphically plotted in Figure 4 for all positive values. Test Case #2 provided a result that the maximum range of the hypothetical 35W Ka-band transmitter would be limited to 133,548 km using 3m sized parabolic antennas. Test Cases #5, #6, #8 showed good/acceptable fade margins for distances between 1 million kilometers (avg 14.79 dB) and 4 million Km (avg 5.32 dB), above e_r level. Test cases #3, #4, #7, #8, with T=3000K were used to compare the efficacy of the various links passing through regions adjacent

Table 7. Test Case Parameters

Case	Pt	D	T
#1	10	3	300K
#2	35	3	300K
#3	10	3	3,000K
#4	35	3	3,000K
#5	10	30	300K
#6	35	30	300K
#7	10	30	3,000K
#8	35	30	3,000K

to the Sun's corona, which invariably shortens range coverage.

Test Cases #5 and #6 showed promising high data rate service capability, across very long distances, due in large part to the gain provided by the large antennas (30m, 77.7 dB), to almost 7 million Km. In this preliminary analysis, the benefits/drawbacks of using LDPC with higher orders of modulation have not been considered. Such an analysis maybe necessary if multiple carriers are required, necessitating use of bandwidth-limited modulation schemes as well as power-limited error correction/detection coding methods.

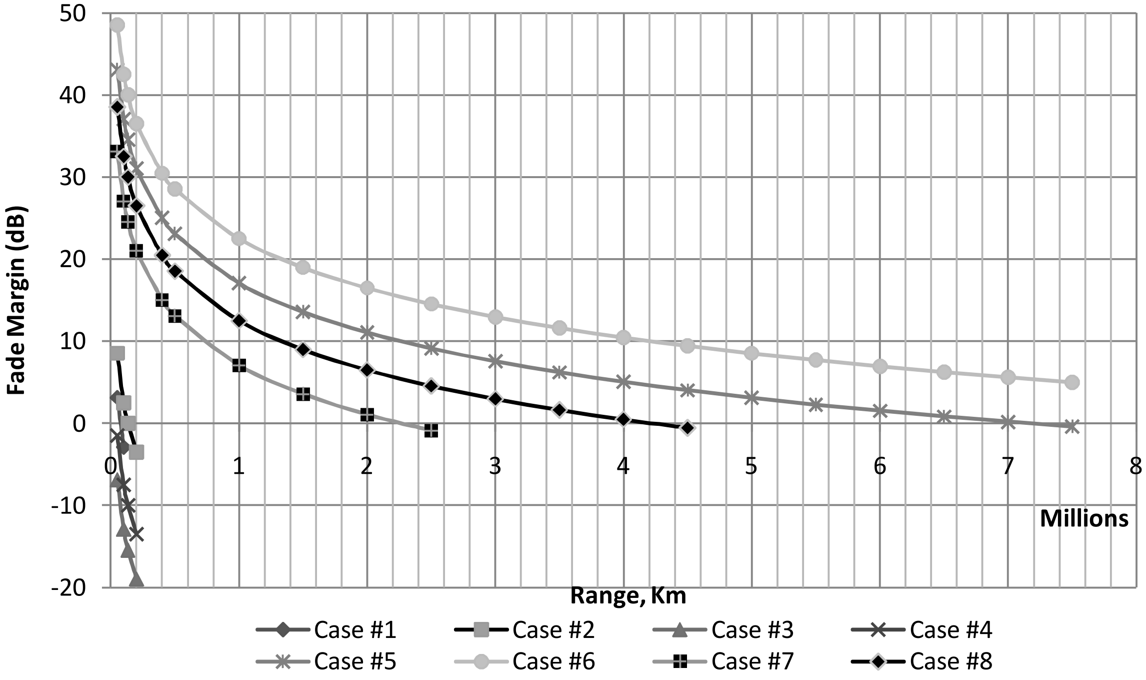

Figure 4. Fade Margins for MIR/R Ka-band 1 Gbps Communications Channel

What is evident about this basic model is that it is not dependent upon any orbital geometry. The principal factors are: information data rate, modulation and coding technique, occupied bandwidth, distance (range), transmit power, antenna diameter (antenna gain) and receiver sensitivity and miscellaneous losses due waveguide loss, and perhaps absorption of interplanetary matter/gases, if any.

For interplanetary links, if transmission power cannot be increased, and bandwidth is constant due to the modulation technique, then the only other practical issue that can result in a better link is to either reduce distance between nodes (highly undesirable) or increase antenna gain (desirable, and somewhat feasible). This simple link budget model has been used with modified data in the remaining sections of this analysis.

E. Investigation – Large Antenna Sizes

Antenna sizes were investigated using Eq. [15] to ascertain the potential gain that could be achieved if the size were increased. In this analysis, the drawbacks of using large mass antennas (e.g., with large diameter/apertures) have not been taken into account. It was seen that the theoretical gain increased in a non-linear fashion from 57.7 dBi gain to 77.7 dBi if the antenna size could be increased from 3m to 30m in aperture size, shown in Figure 5. Table 8 displays the theoretical gain values of selected parabolic antenna diameters in common use. The impressive potential of the ECHO II antenna (41.1 m dia., 80.43 dBi theoretical gain) and the 60-kg mass STS-77 Inflatable Antenna Experiment[44, 45, 49] (14.6 m, 71.44 dBi

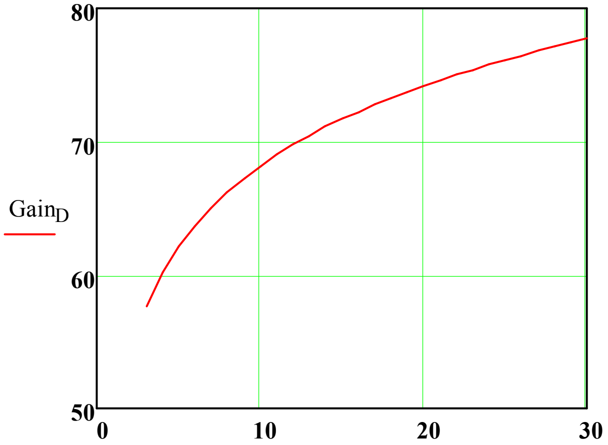

Figure 5. Parabolic Antenna Diam. (m) vs. Gain (dBi)

theoretical gain) indicate the advantages of inflatable antennas over conventional designs. Deployable antennas using lightweight materials are also available[43, 50] and could be a credible solution for MIR satellite high gain antenna needs in deep space.

F. Investigation – Orbit Determination of MIR Nodes

Two scenarios were developed to investigate the placement of MIR satellite nodes in a space based multi-hop communication network.

Table 8 Gain Figures for Selected Parabolic Antenna Sizes

Dia. (m)	3	9	12	14.6	15	18	21	24	27	30	41.1
Gain (dB)	57.70	67.24	69.74	71.44	71.68	73.26	74.60	75.76	76.78	77.70	80.43

In the first scenario 1 Gbps spacecraft/spacecraft communication links were investigated for the placement of 200 (an arbitrary, but reasonable, number) hypothetical MIR satellites along a Hohmann Transfer Orbit between Earth and Mars. In the second scenario, the same number of satellites were placed in the void space between Earth and Mars orbital tracks as well as Earth and Venus orbital tracks in heliocentric orbits.

1. Scenario – 200 MIR Nodes in Hohmann Transfer Orbit

From a reference,[51] the radius of the Earth's orbit, R_{eo} ($1.496*10^8$ Km), the radius of Mars orbit, R_{mo} ($2.278*10^8$ Km), the gravitational parameter of the Sun, μ_{sun}($1.327*10^{11}$ Km^3/s^2), the length of a generic Hohmann transfer orbit at Mars perihelion, L_{hem} (Km) was derived using the analytical method below.

Note, it is necessary to avoid the Sphere of Influence (SOI) for Earth and Mars in our placement of nodes.

The semi-major axis of the Hohmann transfer orbit, a_t

$$a_t = \frac{R_{eo}+R_{mo}}{2} = 1.887 * 10^8 Km \tag{19}$$

The energy of the Hohmann transfer orbit, ε_t

$$\varepsilon_t = -\frac{\mu_{sun}}{2*a_t} = -351.616\, Km^2/s^2 \tag{20}$$

The velocity in transfer orbit at Earth, V_{te}

$$V_{te} = \sqrt{\left(2\left(\left(\frac{\mu_{sun}}{R_{eo}}\right) + \varepsilon_t\right)\right)} = 32.724 \frac{Km}{s} \tag{21}$$

The Time of Flight for a spacecraft from Earth to Mars, TOF_{em} :

$$TOF_{em} = \pi\sqrt{\left(\frac{a_t^3}{\mu_{sun}}\right)} = 2.235 * 10^7 s \tag{22}$$

Can be used to find the length of the Hohmann Transfer orbit from Earth to Mars

$$L_{hem} = V_{te} * TOF_{em} = 7.315 * 10^8 Km \tag{23}$$

A maximum distance between spacecraft, R_{max}, of 3.658 million km (0.024 AU) was then derived for the desired range between two MIR satellites in a constellation of 200, ignoring consideration of arc length.

$$R_{max} = \frac{L_{hem}}{200} \tag{24}$$

Using the maximum capability of the reference Ka-band transmitter (35 Watts output), 3.0m HGA on both transmitter and receiver, and T=300K noise factors, it was determined that the link would be impossible due to a negative E_b/N_o fade margin of 28.75 dB.

Keeping the antenna size and average target distance constant, and increasing transmitter power output, the link was able to be mathematically closed, using a what-if analysis. It was observed that that the required transmitter power would have to be in the range of approximately 26.2 KW Ka-band output, which is a difficult price to pay for a link with a range of only R_{max}, for each transmitter link. An alternative configuration was then analyzed where the HPA size was kept at a maximum of 35W output, but a different sized antenna (D=20m) was used, and the resultant link budget fade margin was found to be 4.2 dB, above threshold, for the desired BER of 1E-7.

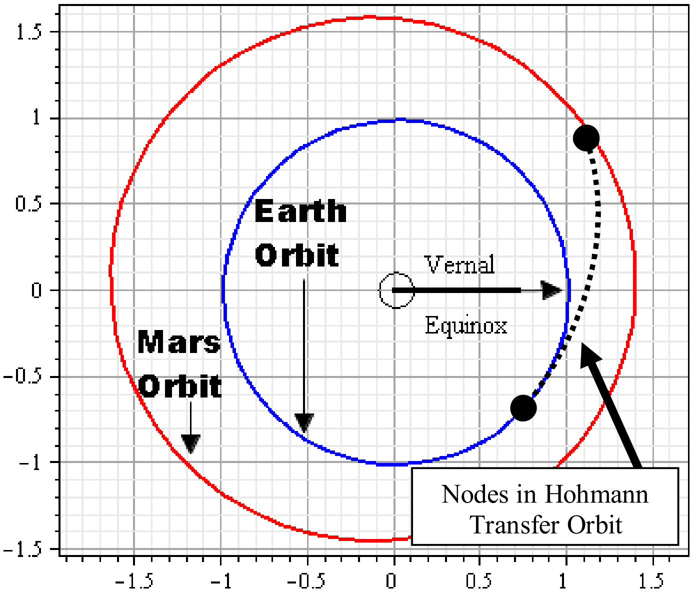

Figure 6. MIR Nodes in Hohmann Orbit (Both Axes AU)

Therefore in this first scenario, it is evident that 200 nodes separated by 0.024 AU can could conceivably establish a reliable 1 Gbps service network, if the all of the spacecraft were equipped with dual 20m Ka-band antennas and dual relays with 35W output transmitters. While this result is admirable, it does not however solve the problems mentioned by Breidenthal[27] where the nodes on the Hohmann transfer arc (, are expected to drift out of phase from Mars and Earth and will be useless over time unless supplemented by numerous other "chains" of MIR satellites. The system will also be plagued with issues enumerated in Table 5.

2. *Scenario – MIR Nodes in Heliocentric Orbits.*

A second case was investigated with various groups of assumptions defined in Table 9, where three groups of spacecraft have been conceptualized: Gateway Group, Relay N1 Group and Relay N2 Group. Each hypothetical s were conceptually equipped with antennas, transmitters and receivers capable of establishing 1 Gbps connectivity at 0.0.24 AU, with 20m Ka-band antennas, in a switched, communications relay arrangement. In this sample scenario, special consideration was given to the fact that the orbital tracks of Mars and Earth are always separated by a finite distance with respect to each other at various points in their orbit.

In the current analysis, power/propulsion requirements were not studied. An assumption is being made that the hypothetical satellites will have the ability to be refueled/replenished on orbit. In this regard, recent progress reported on the development of a micro-Cathode Arc Thruster (μCAT) by Zhuang[52] shows the early potential of using micropropulsion for deep space missions, such as the LC3 MIR satellite application under consideration. The μCAT, requires mainly upon electrical power to convert solid conductive propellant to plasma at exit velocity. The propulsion material, could be Titanium or other metal, is likely to be reloadable through mechatronic methods, and is expected to be usable with both high and low duty cycles over many decades, for long duration mission capability. Sample orbits for the N1 and N2 groups were determined by utilizing the Earth Mean Orbital Elements (J2000) provided by NASA Planetary Fact Sheet.[§§] It was seen that the orbital eccentricity of Mars, e_m, is greater than that of the orbital eccentricity of Earth, e_e and the two planetary orbits around the Sun are concentric ellipses with a shared focus, which is the position of our Sun, with the following characteristics:

a_e	semimajor axis of Earth orbit	1.00000011 AU
a_m	semimajor axis of Mars orbit	1.523662 AU
e_e	eccentricity of Earth orbit	0.01671022
e_m	eccentricity of Mars orbit	0.09341233
ϖ_e	longitude of perihelion of Earth orbit	102.94719 degrees
ϖ_m	longitude of perihelion of Mars orbit	336.04084 degrees

[§§] http://nssdc.gsfc.nasa.gov/planetary/factsheet/, retrieved December 6, 2010

Table 9. Assumptions for Scenario 2

Assumption Set #1	**MIR/G Group** **MIR/Gateway Group**	- A group of up to 3 MIR satellites will be placed in stationary orbits around each host planet (i.e., Areostationary around Mars, Geostationary around Earth) and denoted as MIR/Gateway or MIR/G spacecraft for the network. - Each MIR/G spacecraft will function as individual switching/communications relay nodes with broadband RF links between adjacent neighbors, and provide communications to the closest member of one of the N_1 or N_2 groups (below).
Assumption Set #2	**MIR/R (N1) Group** **MIR/Relay N1 Group**	- A first group of approximately 35 MIR satellites, denoted the N_1 group, will be placed in heliocentric orbits as part of a dedicated constellation. Each member of this group will be referred to as a MIR/R or MIR Relay Satellite. - The N1 group of satellites will, in loose formation, orbit the Sun, while traversing the region of deep space, between the orbit of Earth and Mars, chasing the planetary motion of Mars and avoiding the Sphere of Influence of both planets in approximately a "linear chain", towards the Sun, from Mars. - For preliminary orbit determination purposes, it is assumed that no significant perturbation will be observed in this region for a heliocentric communications relay satellite of relatively miniscule mass, and that course corrections are possible with an adequate replenishable propulsion system. - Each MIR/R satellite will have the capability to close a 1 Gbps link at a maximum distance of 0.024 AU, with respect to adjacent satellites. - The innermost N_1 spacecraft will be able to establish connectivity to multiple N_2 group spacecraft for continuous service, by using different antennas/transceivers simultaneously in tandem.
Assumption Set #3	**MIR/R (N2) Group** **MIR/Relay N2 Group**	- A second group of MIR/R satellites, denoted the N_2 group will be placed in heliocentric space, orbiting the Sun, in the inner solar system, just inside of Earth Orbit. - Members of the N_2 group will be placed in a "circular chain" within the same orbit, while avoiding the Sphere of Influence of Earth. - For preliminary orbit determination purposes, it is assumed that no significant perturbation will be observed in this region for a heliocentric communications relay satellite of relatively miniscule mass.

The semi minor axis of Earth (b_e, 0.999860485 AU) and Mars (b_m, 1.516999802 AU) were calculated and used to draw two simple ellipses, EO and MO in a graphic application, with center (0,0) to initially model the orbits. The two sets of foci for Earth and Mars were denoted f_{1e}, f_{2e} and f_{1m}, f_{2m} respectively with the Sun at position f_{1e} and f_{1m}. As the orbits actually share a common focus ($f_{1e} = f_{1m}$) but different foci and major/minor axis, it is necessary to calculate an orbital offset to shift the major axis of Mars, to the correct position in relation to the major axis of Earth.

Half of distance between foci of Earth orbit

$$c_e = a_e * e_e \tag{25}$$

Half of distance between foci of Mars orbit

$$c_m = a_m * e_m \tag{26}$$

Orbital Offset (OO_m) of Mars and Earth orbit, with respect to Earth orbit, where $f_{1e} \equiv f_{1m}$

$$OO_m = c_e - c_m \tag{27}$$

Therefore we can calculate the co-ordinates of the foci of both orbits

$$f_{1e} = (c_e, 0), f_{2e} = (-c_e, 0), f_{1m} = (c_e, 0), f_{2m} = (c_e - 2c_m, 0) \tag{28}$$

And the major axis of both orbits

$$Ma_e = 2 * a_e, Ma_m = 2 * b_m \tag{29}$$

The radius of Earth's Sphere of Influence[51], (r_{soie}, 925000 Km), was used to plot two additional ellipses that share the same eccentricity, and foci as Earth orbit. The inner ellipse $ESOIIN$ was drawn with a smaller major axis, Ma_{soiein} compared to the major axis, $Ma_{soieout}$of the outer ellipse $ESOIOUT$.

$$Ma_{soiein} = Ma_e - r_{soie} \tag{30}$$

$$Ma_{soieout} = Ma_e + r_{soie} \tag{31}$$

Ellipses, $EO, ESOIIN, ESOIOUT$ were drawn and rotated around the focus f_{1e} by the angle ϖ_e in a counter clockwise direction, and similiarly the ellipse MO was drawn and rotated by the angle $\varpi_m$in a counter clockwise direction. For orientation, an unrotated line representing the vernal equinox, in the direction of the constellation, Ares was incorporated in the diagram.

From visual observation it was estimated that the at closest approach, the Orbital Track Separation, OTS_c is approximately 0.38 AU and at farthest approach, the Orbital Track Separation, OTS_f is approximately 0.67 AU (See Figure 7) which is a coarse estimate, but suitable for this preliminary analysis as the two orbits do not share the same longitude of perihelion. The regions are located diametrically opposite each other at two ends of the Major Axis of Mars orbit. Within these two regions, all the spacecraft of the N_1 group have to travel in elliptical orbit while avoiding: $EO, MO, ESOIIN, ESOIOUT$. Using the assumptions of Table 9, we can calculated the required separation between orbital tracks.

N_1	Number of spacecraft in N_1 group
G	Gaps between spacecraft of N_1 group
D_{min}	Target separation between N_1 group spacecraft at closest approach of Earth/Mars orbit tracks
D_{max}	Target separation between N_1 group spacecraft at farthest approach of Earth/Mars orbit tracks

$$N_1 = 35 \tag{32}$$

$$G = N_1 + 1 \tag{33}$$

$$D_{min} = \frac{OTS_c}{G} \tag{34}$$

$$D_{max} = \frac{OTS_f}{G} \tag{35}$$

MIR/R Orbit tracks *Tn* (where *n*=1..34) were determined by keeping the first focus of the ellipses, f_{1Tn}fixed and equal to f_{1e}, and a new second focus, f_{2Tn} determined for each orbit. The end points of the major axis at OTS_f, P_{cTn} and at OTS_c, P_{fTn}were used to determine the length of the major axis, Ma_{Tn}, and the difference on the x-axis between $f_{1Tn}$and P_{fTn}, $z_{Tn}$was used to determine the x-axis coordinates of f_{2Tn}.

$$P_{cTn} = ((n * D_{max}) - a_m + OO_m, 0) \tag{36}$$

$$P_{fTn} = (a_m - (n * D_{min}) + OO_m, 0) \tag{37}$$

$$z_{Tn} = \left| f_{1e}[x - axis\ cordinate] - (P_{fTn})\ [x - axis\ coordinate]\ \right| \tag{38}$$

$$f_{2Tn} = \left((n * D_{max}) - a_m + OO_m + z_{Tn}, 0\right) \tag{39}$$

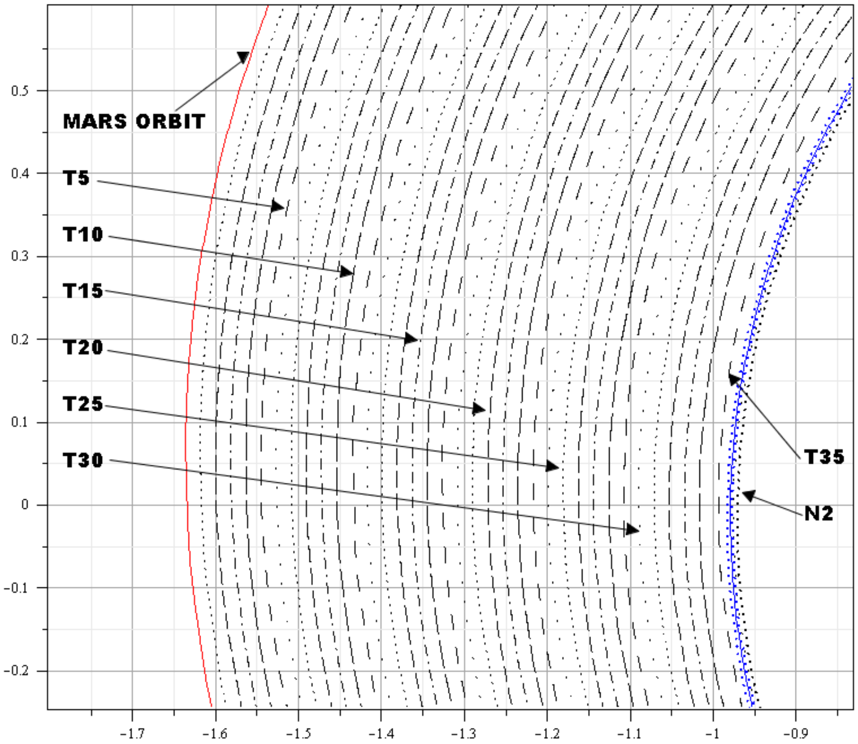

Figure 7. LC3 N1 Group Orbits Cross Section (Both Axes in AU)

Ellipses for orbit tracks T1 through T34 were constructed and rotated by ϖ_e degrees in a counter clockwise manner. It was observed that for $n = 35$ or $n = 36$, MIR/R orbits following the formula above, would enter into the sphere of influence of Earth, denoted by $ESOIOUT$ and $ESOIIN$ ellipses. Therefore the 35th orbital track, $T35$was adjusted in an outward direction as $R_{max} > D_{max} > D_{min}$, and an extra 36th orbital track, $T36$ included inside of Earth orbit in such a manner that for both tracks, the maximum distance between the tracks would be less than or equal to than D_{max}at all times during its orbit around the Sun, avoiding Earth and its Sphere of Influence.

The equations for T35 orbital track ellipse are provided below:

$$P_{cT35} = ((34 * D_{max}) + R_{max} - a_m + OO_m, 0) \tag{40}$$

$$P_{fT35} = (a_m - (34 * D_{min}) + OO_m + (0.4 *\ r_{soie}), 0) \tag{41}$$

$$z_{T35} = \left| f_{1e}[x - axis\ cordinate] - (P_{fT35})\ [x - axis\ coordinate]\ \right| \tag{42}$$

$$f_{2T35} = (((34 * D_{max}) + R_{max}) - a_m + OO_m + z_{T35}, 0) \tag{43}$$

The equation for orbital track T36 is actually based upon the original orbital track of Earth, where the foci are f_{1e} and $f_{2e}$and the ellipse has a major axis of Ma_{T36}, with a rotation of ϖ_e degrees counter clockwise. This is the only track of the N_1 group that operates entirely within Earth orbit.

$$Ma_{T36} = (Ma_e - (1.5 * r_{soie}) \tag{44}$$

Keeping in mind the restriction of R_{max} between T35 and T36, and the fact that Earth MIR/G spacecraft have to connect only to the N_2 group, the N_2 group orbit was strategically placed inside of Earth orbit (Figure 8) with a smaller major axis, Ma_{N2} and rotated by ϖ_e, with the same eccentricity as Earth orbit, represented by the ellipse, $N2$.

$$Ma_{N2} = Ma_e - D_{max} \tag{45}$$

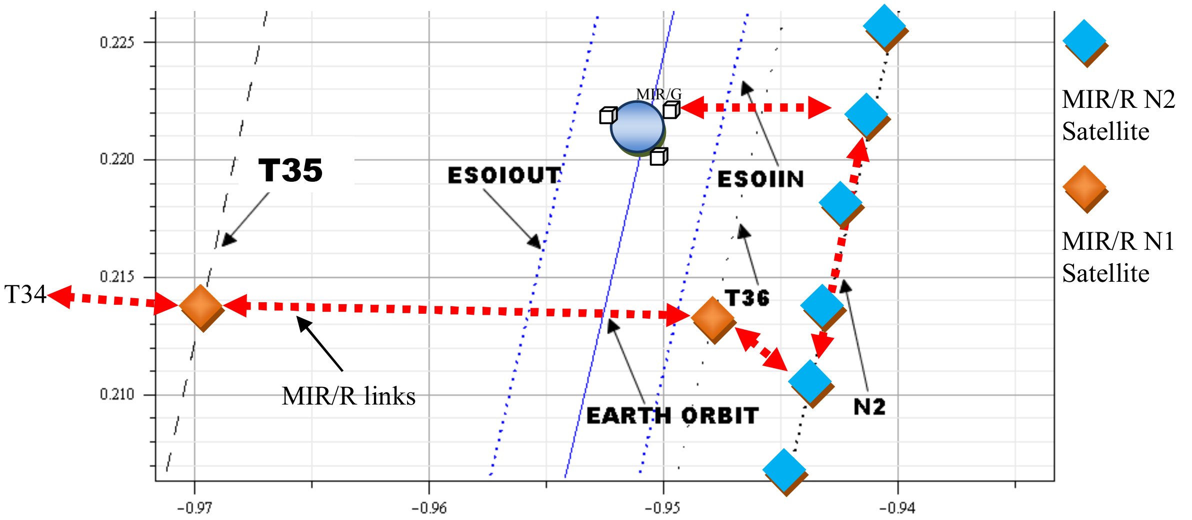

Figure 8. Close-up of LC3 orbits T35, T36, N2 region (Both Axes in AU)

The circumference of the orbit track $N2$, C_{N2} was found to be 6.2246 AU, which was used to calculate coarsely the number of MIR/R spacecraft required for full coverage, around the orbit, ignoring consideration of arc length:

$$n_2 = \left\lceil \frac{C_{N2}}{R_{max}} \right\rceil = 256 \tag{46}$$

If the minimum number of MIR/R spacecraft required is, N_{min}

$$N_{min} = n_1 + n_2 = 35\ (T1..T35) + 1(T36) + 256(N2) = 292 \tag{47}$$

It can be observed that, at first glance, this configuration of MIR/R spacecraft, (e.g., 35W Ka-band transmitters, 20 meter diameter antennas), allows transmissions to proceed independent of the orbital geometry of the Sun, Mars, Earth. All of the MIR/G spacecraft, the MIR/R N_1 group spacecraft in a linear chain, and the MIR/R N_2 group spacecraft in a circular chain work together in a “Linear-Circular Commutating Chain” or as an “LC3 interplanetary network” capable of providing persistent, 1 Gbps bi-directional data communications between Earth and Mars.

The number of required spacecraft, and the orbital tracks in heliocentric space will vary with the transmission capability of the spacecraft and the size of the antennas being used for directing the signals. For redundancy and extra capacity in establishing high bit rate communications across interplanetary distances, there should be spare spacecraft already deployed at strategic points in orbit. Assuming 25% on-orbit spares, the total number of MIR/R spacecraft required to establish a LC3 interplanetary network, N_{l3c}, is therefore:

$$N_{l3c} = 125\% * N_{min} = 365 \tag{48}$$

The flow of communication is expected to follow, in general, a standardized process. An example of broadband communication from Mars to Earth is shown in Figure 9 and the entire network is shown in Figure 10. A potential snapshot of the N_1group chasing mars, and interfacing with the N_2group which is relaying communication traffic between the two planets is shown diagrammatically in Figure 8, and in conceptual form in Figure 11.

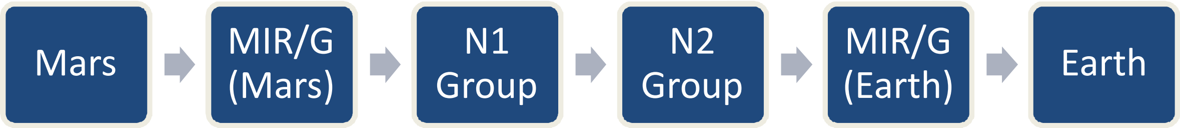

Figure 9. Communication Flow Between Segments of the LC3 Network

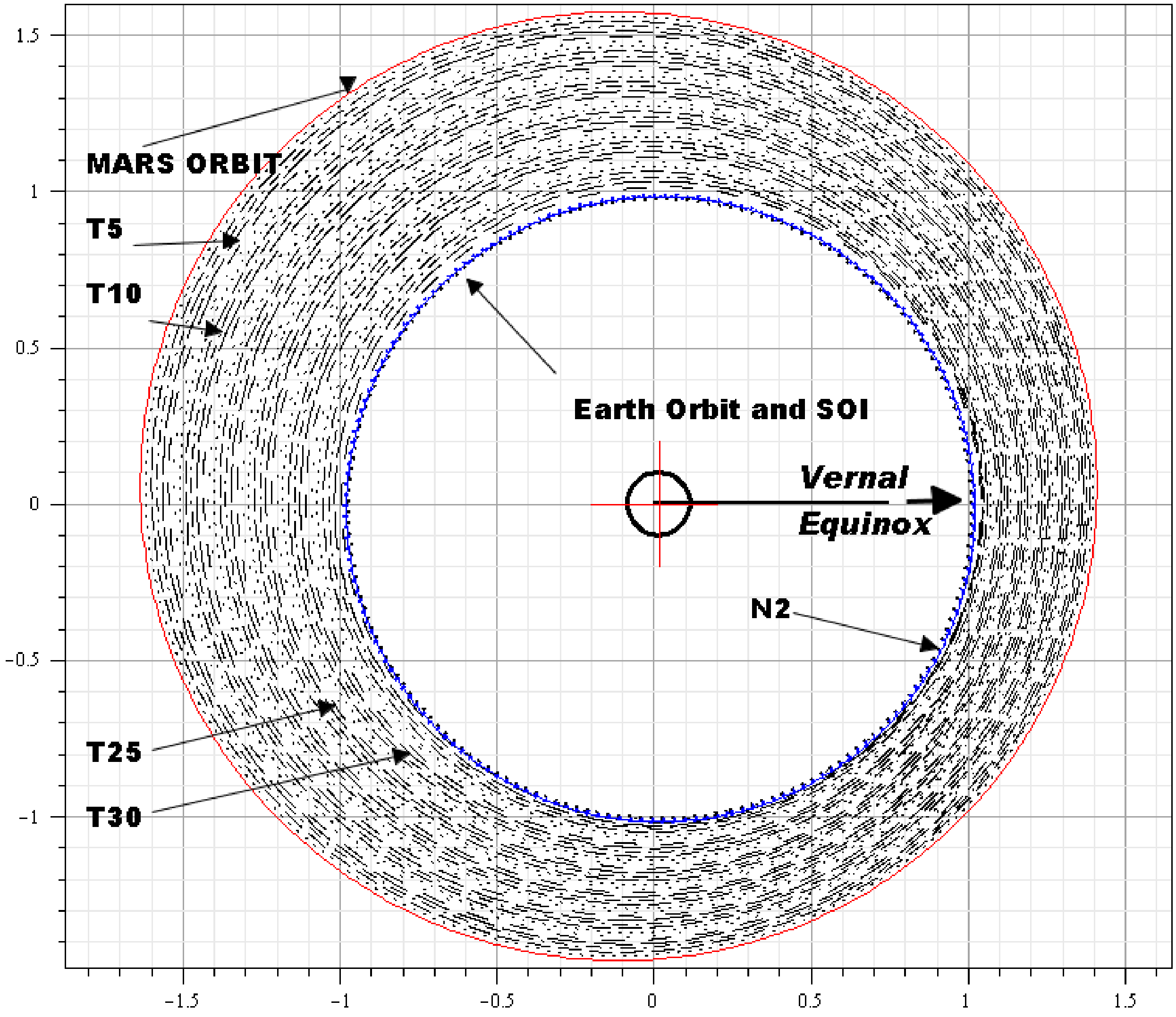

Figure 10. Linear-Circular Chain Network (Both Axes in AU)

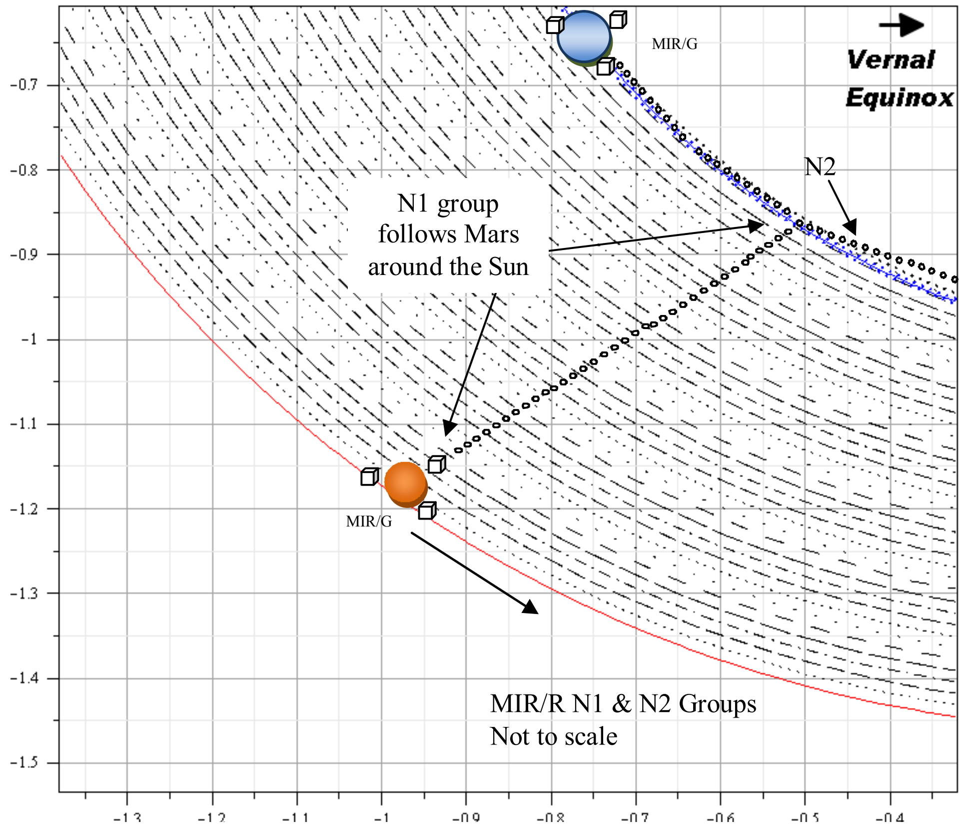

Figure 11. Concept Diagram (Linear-Circular Commutating Chain)

G. Investigations - Network Applications

The hidden cost to interplanetary networking is the time delay for communication to/from one side to another. Due to network latency, availability of channels, one way light time delay, and the position of the planets, future Earth-Mars communication system users may have to wait up to 30 minutes at most to receive their communication packets. This may be similar to, for example, the early days of the development of the Internet, where users interacted with a time sharing host, through dial-up/leased line networks using UUCP and USENET and successfully collaborated and converted messages between networks automatically. To accommodate the *interactivity* needs of future communities utilizing the LC3 interplanetary broadband network with communication delays, the potential applications are proposed in brief in Table 10.

Table 10. Framework of Proposed Deep Space Communication Applications

Framework	Potential Applications
Long Term Missions	Command and Control Family Health Care Education, Research and Development Governance Solar System Navigation Commerce and Materiel handling
Short Term Missions	Command and Control Health Care Solar System Navigation Commerce
Synthetic Communication[53]	Simulation of intelligence through *avatars*
Smart Communication[53]	1:M automated agent for batch communication

H. Investigations - Topology

The network will operate in a series of interconnected topologies:

.

There will be an orbital fleet of MIR/G spacecraft in areostationary orbit.
There will be an orbital fleet of MIR/G spacecraft in geostationary orbit.
MIR/G spacecraft of Earth will connect to the $\boldsymbol{n_2}$group of MIR/R satellites in Earth co-orbit.
MIR/G spacecraft of Mars will connect to the $\boldsymbol{n_1}$group of MIR/R satellites in heliocentric orbit following or leading the planet
Both $\boldsymbol{n_1}$and $\boldsymbol{n_2}$groups of MIR/R satellites will be able to negotiate communication protocols and initiate exchanges of traffic autonomously and to choose their best network partner spacecraft.

On Mars, users and/or terminals will be connected to their most convenient ground network and connect through the appropriate MIR/G platform under most situations through fixed satellite stations. If the user is mobile or in the field, they will have to communicate directly with the stationary orbital platform MIR/G and request a local circuit back to the base, or an outbound channel to access the Earthbound transmission channels.

If a local spacecraft is travelling in interplanetary space and is near a suitably equipped MIR/R satellite, it could potentially request a temporary connection to exchange traffic which can go either to Earth or Mars, or any other destination that the MIR/R can address by looking up a routing table of all active nodes in networks. The members of n_1 group of MIR/R satellites will be able to network with each other depending upon their dynamic position and their mandate to keep Mars connected to the inner regions of the solar system at all times. The n_2 group will be servicing Earth transmissions through Earth's own fleet of MIR/G relay satellites but it will also act as a convenient communications "ring road" to allow far away spacecraft (opposite side of Sun) to connect and share a communication channel back to Earth, or if so desired to the Moon and Mars from their current location.

This would allow the Deep Space Network facilities to be used more efficiently and "look time" increase as the remote spacecraft will have an easier time to connect to Earth networks. This will be possible as all of the MIR/R satellites are essentially flying telecom exchanges, albeit for deep space communications.

I. Investigations - Communications Payload

It is proposed regular MIR/R satellites should contain a comprehensive communications payload, apart from the spacecraft bus, similar to Table 11. A hypothetical quad system configuration, based upon MRO and STS-77 data is shown.

Table 11. MIR/R Communications Payload Breakdown

Assembly	Mass, Kg	Total mass, Kg	Spacecraft power input, W	RF power output, W	Note/Reference
		356.80			
Ka-Band TWTA (8 sets)	9.2		320+	136	35 W Nominal
Diplexers and brackets	7.2				
Waveguide and Transfer Switches	6.0				
Other Microwave Components	5.6				
Miscellaneous TWTA hardware	0.8				
HGA Inflatable Ka-band 20 meters dia. (4 sets)	328				SPARTAN/IAE[49] @60kg/unit/14.6m
HGA gimbals and drive motors		180	56		Not verified
Waveguides and coax		33.2			
Switching/Router/Mux		20	30		Estimated
LGA, UHF kit		11.5		5	
Telecom Total		601.5	406		

It is understood that MIR/G configurations will have to be designed depending upon the bands that will have to service as a bridge between power-constrained deep space environments and bandwidth-constrained Earth local RF/space environment where there are many more options for high bandwidth, power un-constrained and computationally unrestricted coding. For example, a MIR/G could conceivably take the Ka-band traffic and remodulate it onto Ku-Band or another higher band for retransmission to Earth.

J. Synthesis

As outlined in investigated in sections A-I, the limited case solution of 200 nodes distributed over an Hohmann elliptical transfer orbit does not satisfy the programmatic constraints enumerated in Table 5. While, it is probable that, based upon the literature reviewed for this analysis, MIR/R satellites compliant to the specifications and functionalities of Table 9 and Table 11 may indeed be able to be developed by 2020, and it may be possible to deploy them from a mother vessel spacecraft enroute to Mars, or vice versa, the single Hohmann arc of MIR/R satellites cannot by terminals on Earth and Mars at all points in their respective orbits. In fact, the minimum energy Hohmann orbit is only valid in certain orbital configurations of the Earth/Mars positions on the ecliptic which cannot satisfy the needs of a persistent broadband communications network.

Based upon the rejection of the single Hohmann arc, coarse numerical analysis investigation of the other configurations of multi-hop communication networks were considered briefly (not shown in this analysis) including Two-Petal Elliptical Transfer, Minimal Earth Ring, Single Commutating Ring, Two Commutating Rings with Bridge, Neighbor Orbit and Commutating Ring with Neighbor Groups. While these solutions complied with the three programmatic constraints of Table 3, the complexity of deploying and maintaining many constellations of nodes, cast aspersions as to the efficacy of the strategies. Therefore in this analysis, planetary orbits were modeled in MAPLE based upon reference data from NASA data sources and analysis/investigation has been undertaken in detail. By renewing focus on the primary objective of using a proposed space based “multi-hop” communication network to bring Mars communication closer to Earth as much as possible, and by realizing the inherent benefit of having a cluster of captive spacecraft following Mars around its orbit, with an elongated pattern towards Earth orbit (*not* towards the circumference of Mars orbit, or Earth orbit), a new solution was able to be rapidly developed.

The “Linear-Circular Commutating Chain” and n_1, n_2 group solutions allows all nodes will be able to close the microwave link budget at 1 Gbps up to 0.024 AU, so if the nodes are varied somewhat in their orbital arrangement, they will not be affected by any link outage. In the case of the first group $n_1$being used in a linear fashion, the end points of the group toward the Earth orbital track will be able to connect to any number of the 256 n_2 MIR/R spacecraft, which will ultimately connect to Earth via MIR/G via a ring network topology. Therefore there will not be a need for any supplementary MIR/R satellites in the orbital arc of Mars and this network will almost certainly be able to be utilized all of the time as both groups of satellites will be flying in space with orbits that, staying within the crucial 0.024 AU range between MIR/R satellites, have been placed away from any planetary body Sphere of Influence. Finally, it should be noted that the choice of using 200/35/36 or 256 satellites was based upon “an arbitrary, but reasonable number” choice and can be adjusted to accommodate better spacecraft design and capability. Ideally, a rigorous numerical analysis study needs to be commissioned to find the optimum number with a first order estimate of the required total project cost, propulsion requirements for launch, deployment and service and service capability, which may lead to an actual space mission being designed to validate the LC3 network potential benefits. To aid researchers who are interested to discuss with policy planners the potential of the LC3 communications architecture, a summary is provided in Table 12 and a preliminary Space Mission Concept Summary is provided in Table 13.

IV. Defining the Space Mission Concept

Table 12. Linear-Circular Chain Solution Summary

Segment	Location	Description
A	Areostationary Orbit	Fleet of MIR/G spacecraft communicating with MIR/R spacecraft of Segment B and Mars orbiters, landers, rovers, other terminals of Mars network.
B	Deep space orbits between Earth and Mars orbital tracks	Fleet of MIR/R spacecraft (N1) following Mars but placed at various distances in deep space between the orbital track of Mars and Earth in a roughly linear chain. The orbits of the N1 group will vary with the position of Mars around the Sun but will never come into the sphere of influence of either Mars or Earth. The outer edge of the group will remain in contact with Segment A, the inner edge of the group will be located within Earth orbit, and will connect to the nearest neighbor of the N2 Group.
C	Heliocentric orbit	Fleet of MIR/R spacecraft (N2) in a single orbital track within Earth’s own orbit and connecting to Segment D, Segment B at all times.
D	Geostationary Orbit	Fleet of MIR/G spacecraft communicating with Earth based fixed, mobile, GEO and LEO facilities.
NOTE	Assumption: Distances between Earth orbit and Mars orbit vary from 0.67 AU (max) to 0.38 AU (min); orbits are skewed by respective longitude of perihelion.	

Table 13. Prelminary Space Mission Concept Summary

A Broadband Multi-hop Network for Earth-Mars Communication using Multipurpose Interplanetary Relay Satellites and Linear-Circular Chain Topology			
Primary Objectives	[1] To establish a 1 Gbps full duplex interplanetary network between Earth and Mars on a permanent basis [2] To establish the required engineering practices and administrative procedures for manufacturing numerous relay satellites for use in deep space that will last > 50 years in service life [3] To establish new design paradigm to manufacture spacecraft that can be repaired by remotely piloted missions while in deep space		
Secondary Objectives	[1] To provide support to the programs of the Deep Space Network by allowing deep space missions to connect through the network using reduced transmission power and higher data rates [2] To expand the network to support Human spaceflight operations and activities [3] To establish a radio/optical navigation network infrastructure in deep space for future spacecraft		
Requirements	MIR/G Satellites for planetary gateways (6 estd.) MIR/R Satellites for interplanetary relay functions (365 estd.) Robotic/Mechatronic/Remotely Piloted Service missions for maintenance in deep space. All nodes in a Linear-Circular Chain topology: N1 group (Linear, Mars affinity, heliocentric); N2 group (Circular, heliocentric)		
Orbit Description	Areostationary orbit for MIR/G – Mars gateway Heliocentric orbit (Mars affinity) for MIR/R group, Heliocentric orbit (Earth affinity) for MIR/R group, Geostationary orbit for MIR/G – Earth gateway		
Mission Constraints	Total number of satellites to be constructed cannot exceed in first phase 365 (MIR/R), 10 (MIR/G) type spacecraft, for a grand total of: 375. Service life of all systems > 50 years Deadline to establish network 2020		
Issue Date	December 13, 2010	**Version**	PRELIMINARY

V. Conclusion

In light of the analysis performed, the following conclusions are offered:

1. A broadband network can, most likely, be able to be developed using numerous instances of Multi-purpose Interplanetary Relay satellites and provide 1 Gbps full duplex service between Earth and Mars using technology readily available, using the Linear-Circular Commutating Chain network architecture.
2. The network will most likely be able to be deployed adjacent to the path of regular spacecraft plying between the two planets by either a automated mechanism or human crew and will have a definite potential to stay in service for many decades, with servicing being performed in deep space.
3. The network will most likely be available for use regardless of the orbital positions of Earth, Mars and Sun.
4. A preliminary estimate of the communications payload for a MIR/R satellite with four antennas and eight Ka-band sub-systems has been calculated at approximately 601.50 Kg.
5. The first complete network will be able to be deployed with a total of 375 satellites.
6. 2-D analysis has shown initial positive viability. However, rigorous 3-D analysis of orbit determination needs to be done, in addition to extensive perturbation modeling for all near earth objects.

As this study was a preliminary treatment of a new concept, there is much room to investigate further into the makeup of an LC3 communications network. In particular it will be important to develop more network sizing models based upon accurate industry-driven specifications of flight ready hardware and performance characteristics. The issue of propulsion has not been given much attention in this treatise, and it is recommended that a in-depth program should be started to build up a body of knowledge to improve this concept's suitability for adoption by industry and deep space mission users. Another issue that could not be covered in this short time frame is the issue of mass budget for the carrier spacecraft which will deploy the nodes in space, and how to actually conduct on-orbit service in deep space.

Abbreviations

AU	Astronomical Unit
CCSDS	Consultative Committee for Space Data System
CFDP	CCSDS File Delivery Protocol
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Camera
DSN	Deep Space Network
Gbps	Gigabit/s or 1E9 bits/second
HiRISE	High Resolution Imaging Science Experiment
HGA	High Gain Antenna
LDPC	Low Density Parity Check
MARCI	Mars Color Imager
Mbps	Megabit/s or 1E6 bits/second
MCS	Mars Climate Sounder
MER-A	Mars Exploration Rover – A aka *SPIRIT*
MER-B	Mars Exploration Rover – B aka *OPPORTUNITY*
MGS	Mars Global Surveyor
MHO	Mars High Energy Orbit
MLO	Mars Low Energy Orbit
MRO	Mars Reconnaissance Orbiter
MSO	Mars Synchronous Orbit
MTO	Mars Telecommunication Orbiter
NASA	National Aeronautics and Space Administration
S/C	Spacecraft
SHARAD	Shallow (Subsurface) Radar
SNR	Signal to Noise Ratio
TWTA	Travelling Wave Tube Amplifier

Acknowledgments

This study was initially conducted from July to October, 2009 under the supervision of Professor Robert S. Thrower for the author's capstone thesis research project in fulfillment of the requirements for MS with Honors degree in Space Studies, at American Military University (American Public University System), Charles Town, WV. The author would like to thank Julian Breidenthal of NASA/JPL, Dr. Michael Keidar of George Washington University, for their deep insight, and express appreciation for the help in link budget modeling from AMSAT colleagues Domenico *I8CVS*, Tony *AA2TX*, Achim *DH2VA*, Arthur *W4ART*.

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