High Capacity Communications from Martian Distances:
Part 1 – Spacecraft Link Design Analysis

Hemali Vyas, Jet Propulsion Lab, USA, 818-354-39287, 818-354--, Hemali.N.Vyas@nasa.gov
Leonard Schuchman, SATEL, USA, len.schuchman@sa-tel.com
Richard Orr, Affiliation, SATEL, USA, richard.orr@sa-tel.com
Dan Williams, NASA GRC, USA, 202-358-1694, 202-358-2830, Wallace.D.Williams-1@nasa.gov
Michael Collins, ASRC Services, USA, 571-262-3136, 571-203-1346, Michael.Collins@asrms.com

Abstract

High capacity space communications has been a desire for Human Exploration and Science missions. Current Mars missions operate at data rates of 120 kbps for telemetry downlink and it is desirable to study high rate communication links in the range of 100 Mbps to 1 Gbps data rates from Martian distances. This paper will present some assumed scenarios along with link design assumptions and link analysis for high capacity communications from Mars. The paper will focus on RF subsystems namely antenna and power for the downlink communication from a relay orbiter at Mars. The relay orbiter will communicate with the low orbit spacecrafts at Mars or any Martian surface elements such as robots, and relay the data back to the ground networks on Earth. The study will dive into the spacecraft downlink system design and communication link analysis between the relay orbiter and ground network on Earth for data rates ranging from 100 Mbps to 1 Gbps based on the assumed scenarios and link assumptions. With high rate links at larger distances, there will be a significant impact on the antenna and power requirements and the link design will make an attempt to minimize the mass of the RF subsystem on the spacecraft. The results of this study will be presented for three data rates 1 Gbps, 500 Mbps and 100 Mbps at maximum Mars to Earth distance of 2.67AU. The design will use a Ka-band downlink with 90% link availability, along with various ground network G/T assumptions and possible bandwidth efficient modulations. The paper will conclude with what types of high rate communication links are feasible from Martian distances and also identify a range of requirements for antenna and power technologies for these high capacity communications from Mars.

1. Introduction

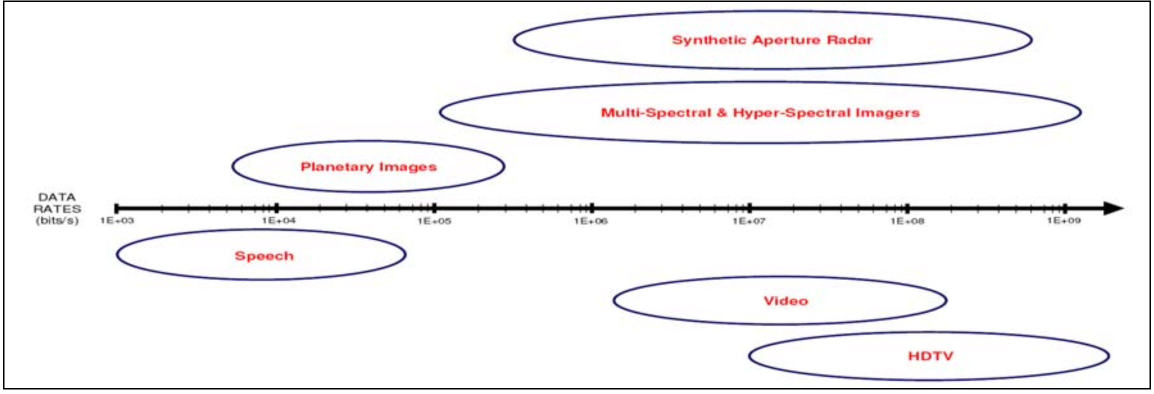
High rate communications from Mars during the timeline of 2020-2030 has significant but manageable challenges. In the past Mars missions have operated with downlink data rates of 120kbps and the Mars Reconnaissance Orbiter (MRO) which has just arrived at Mars is planned to send data on X-band at data rates of upto 5.3Mbps. MRO could have been designed to send data at a much higher data rate if it were not for the bandwidth limitations at X-band. Ka-band offers a 500MHz bandwidth as compared to 50MHz bandwidth at X-band, thus the need to review Ka-band communication links for high rate communications. The other advantage of Ka-band over X-band is increase gain in the link of 11dB on the basis of free-space link (assuming equal antennas and transmitted power), though this advantage reduces down to 5-7dB of gain with atmospheric and weather impacts. The paper focuses on the link design, analysis and trades space for high rate Ka-band downlink communications from Mars. The focus of the paper is only on the downlink high rate communications for Ka-band link between Mars Telecom Relay Orbiter to ground network on Earth. It is assumed that the communications for local elements at Mars to Earth will be thru this Orbiter.

The paper will first evaluate possible user scenario assumptions provided in section 2. These user scenarios are assumptions at this moment and the actual scenario may vary for real missions, but the goal for this user scenarios is to assist in identifying the data rates and thus bandwidth requirements for future communication from Mars. Following the user scenarios, various link assumptions is provided in section 3 which identifies the constraints and limits to be applied to the link analysis. This would involve assumptions for the spacecraft, ground network, atmospheric and weather implications at Ka-band, solar conjunction and finally the link margin variations related to the distance variations of 2.67AU down to 0.38AU between Mars and Earth. Section 4 will dive into the link design and analysis for the user data rates scenarios that have been derived in section 2 for various ground network options. The link design and analysis will provide the approach used for the link budgets for the scenarios defined along with the link assumptions provided in section 3. This section will also dive into the trade space and provide the results for various user data rate scenarios. The link design for each data rate is initiated with the worst case scenario from the farthest distance between Mars and Earth at 2.67 AU followed by reviewing possible options when the link margin increases as the distance between Mars and Earth reduces from 2.67 AU down to 0.38AU. The paper then concludes in section 5, which will provide key observation from the link design, analysis and trade space. This section will identify possible range of the RF subsystem namely antenna and power requirements that are applicable for this high rate communications from Mars.

2. User Scenario Assumptions

Mars exploration communication scenario has been derived from a strawman set of requirements for human and robotic missions in 2020 to 2030 time frame as in [2,3]. Many applications are envisioned such as audio, video, HDTV, and science applications for which the span of data rates are shown in Figure 1:

Figure 1 - Range of Data Rates for Various Applications



A user scenario is assumed as shown in Table 1 for each application along with associated data rate. The Design Reference Mission (DRM) [3] assumes, human mission with possibly four science orbiters and eight robotic surface vehicles (landers, rovers, etc.) and the communication to and from the Earth is assumed to be via a telecom orbiter. The DRM presumes six astronauts on surface, two active in a base station and four roving away from base station in two human transports. The data rates assumed for the trade space are 100Mbps for Basic Operational Activities, 500Mbps for inclusion of robotic exploration and finally 1Gpbs to include the science orbiters.

Table 1 - Mars-Earth Communication Scenario

	User	Channel Content	Latency	No. of Channels	Bit rate per channel	Total Bit Rate
Operational	Base	Speech	NRT	2	10 kbps	20 kbps
		Engineering	NRT	1	100 kbps	100 kbps
	Astronauts	Speech	NRT	4	10 kbps	40 kbps
		Helmet camera	NRT	4	100 kbps	400 kbps
		Engineering	NRT	4	20 kbps	80 kbps
	Human Transports	Video	NRT	2	1.5 Mbps	3 Mbps
		Engineering	NRT	2	20 kbps	40 kbps
	Robotic Rovers	Video	NRT	8	1.5 Mbps	12 Mbps
		Engineering	NRT	8	20 kbps	160 kbps
	Science Orbiters	Quick Look	NRT	4	1 Mbps	4 Mbps
		Engineering	NRT	4	20 kbps	80 kpbs
High Rate	Human Transports	HDTV (medical, PIO)	NRT	2	20 Mbps	40 Mbps
		Hyperspectral imaging	1 day	1	150 Mbps	150 Mbps
	Base	HDTV	1 day	1	20 Mbps	20 Mbps
	Robotic Rovers	Surface Radar	1 day	1	100 Mbps	100 Mbps
		Hyperspectral imaging	1 day	1	150 Mbps	150 Mbps
	Science Orbiters	Orbiting Radar	1 day	2	100 Mbps	200 Mbps
		Hyperspectral imaging	1 day	2	150 Mbps	300 Mbps
Total	Design Reference Mission (DRM) and HDTV - operational					**80** Mbps
	Add robotic operations and DRM hyperspectral imaging					**480** Mbps
	Add science orbiters					**980** Mbps

3. Link Assumptions

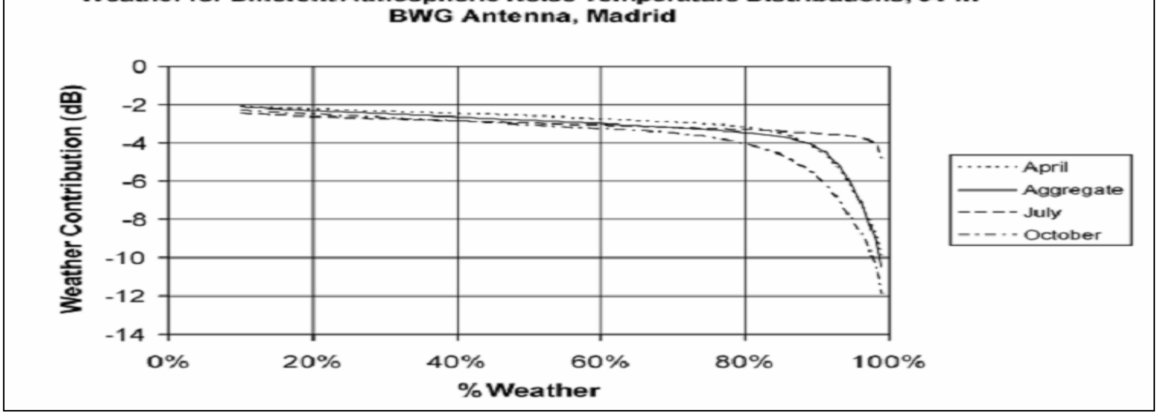
This section discusses various assumptions and challenges foreseen for a high rate Ka-band downlink communications from Mars which are necessary for the communication link design and analysis discussed in section 4. The link assumption and also challenges include spacecraft constraints, ground station configuration, weather and atmospheric implications, solar conjunction, spectrum constraints and the extreme distance variations between Earth and Mars which will be presented here in the same order.

The first thing that high rate communications from Mars require is developing RF capability with high availability and reliability along with increased bandwidth. This would require large spacecraft antennas and high power transmitters. For the link analysis, the antenna size to be assumed would be 4m to 25m diameter while the power amplifier assumed would be within 0.2kW to 10kW. A worst case spacecraft antenna pointing accuracy to be assumed would be 14mdeg for a body mounted High Gain Antenna using spacecraft Attitude Control System (ACS) and accuracy less than 14mdeg would require Fine Beam Pointing System.

The next aspect is the ground network which is assumed to be Deep Space Network (DSN) in this study. As compared to the current DSN ground network which includes 34m and 70m antenna a performance improvement by a factor of upto 1000 would be required to achieve high rate communication from Martian distances. This is assumed with upgrades to the DSN ground network with array of 12m antennas for all three DSN sites [5, 6]. For the link design in this study, three array scenarios for 12m-DSN array are assumed which involves an array with 180elements, an array with 45 elements and an array with 12 elements. The study will be performed for all these ground options for each user data rate scenario.

Ka-band communication links are affected by atmosphere and weather [7, 8, 9]. A Ka-band link provides ideal advantage of about 11dB over a X-band assuming equal antennas and equal transmitted power. This gain is reduced due to atmospheric and weather impacts to actual Ka-band advantage of about 5-7dB. This is primarily because of greater variability at Ka-band in the system noise temperature associated with atmospheric moisture. Atmospheric noise temperature and attenuation affect link reliability since an outage occurs whenever an elevated noise temperature and increased attenuation cause the signal-to-noise ratio to fall below the threshold. The main challenge Ka-band presents in determining an appropriate link margin due to the large noise temperature variability caused by the weather as shown in Figure 2 [7]. The figure indicates that the variability can vary depending on the month for given link availability. The link design assumes minimum impact due to atmospheric attenuation and it would be important to evaluate the actual this impact when designing for actual missions. It is also important to determine and apply various solutions such as accurate statistical weather forecasting along with optimized and multi-data-rate systems to optimize the data return at Ka-band [10, 11].

Figure 2 - Ka-band Downlink Degradation as a Function of Percent Weather



The next thing to review is the effect of solar conjunction on the Ka-band communication links. Radio signals passing near the Sun are affected by solar conjunction due to increased numbers of intervening charge particles causing intensity scintillation (fades) and phase scintillation of the spacecraft signals leading to significant degradation [12]. Solar conjunction causes spectral broadening which leads to increase in signal bandwidth and scintillation which leads to fading and Doppler noise. Solar effects on communication are often expressed in terms of Sun-Earth-Mars (SEM) angle which is nearly the angular separation between the direction from the station to the center of the Sun and the direction to the spacecraft around Mars. As the SEM angle decreases, carrier locking and data detection issues become more stringent.

Table 1 [12] shows the number of days of Mars solar conjunctions from 2010 to 2030 within bounds of 3, 2, 1, 0.5 and 0.4 deg Sun-Earth-Mars (SEM) angle. This table defines Ka-band in terms of a 1-deg SEM angle limit and X-band in terms of a 2-deg SEM angle limit for BPSK modulation. As described in [12], it becomes harder and harder at Ka-band to maintain telemetry lock using PSK modulation as the SEM angle decreases from 1 to 0.4 deg, the transition region between weak and strong scintillation. For the actual mission, the link design must take into account the impact of solar conjunction and provide various options such as use of a different schemes such as using FSK modulation, semaphore based communication or if need be to plan out communication outage during the moments of solar conjunction. This is not applied for the link design presented in this paper, but these issues must be looked at for the real mission scenarios.

Table 2 - Durations of Outages during Solar Conjunctions from 2010-2030

	Days in which Sun-Earth-Mars angle is under:				
Year	3° (Optical)	2° (X-Band BPSK)	1° (Ka-Band BPSK)	0.5° (X/Ka-Band FSK)	0.4° (Ka-Band FSK)
2011	24.83	14.93			
2013	26.34	17.37	8.13	2.69	0.37
2015	21.42	13.88	5.73		
2017	17.9	10.71			
2019	16.92	10.17			
2021	17.8	11.49	4.61		
2023	19.85	13.22	6.57	3.22	2.53
2025	23.07	14.29	2.74		
2028	26.93	17.05	5.47		
2030	23.45	15.55	7.55	3.27	2.27
Total	**218.5**	**138.7**	**40.8**	**9.2**	**5.2**

With many other assumptions, reviewing spectrum allocation for Ka-band is critical for the link analysis. The spectrum allocation assumed in the link budget is 37.25GHz. But for actual Mars missions, the Ka-band spectrum allocation for Deep Space missions for human and robotic missions as recommended by the Space Frequency Coordination Group (SFCG) is [1]:

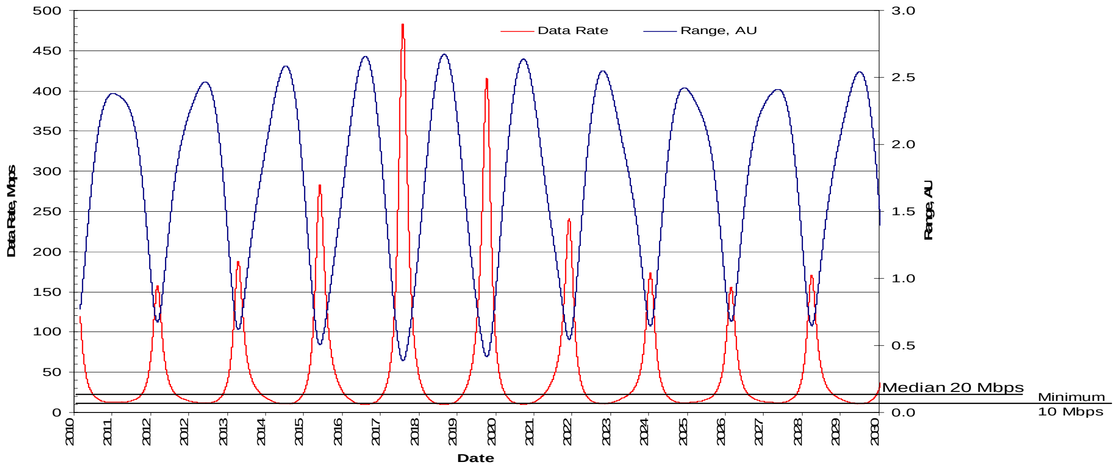
Mission Category	Mission	Uplink (forward) band (GHz)	Downlink (return) band (GHz)
A	TDRSS	None	25.5 to 27.0
A	Lunar, L2; human and robotic (SFCG)	None	37.5 to 38.0
B	Deep space robotic exploration	34.2 to 34.7	31.8 to 32.3
B	Deep space human and robotic exploration (SFCG)*.	40.0 to 40.5	37.0 to 37.5

* Includes deep-space technology demonstration in near-Earth regions.

Note: Category A – Missions within Lunar Vicinity (< 2million km), Category B – Deep Space Missions (> 2million km)

The final aspect for link assumption is the big distance variation between Mars and Earth ranging from 2.67 AU down to 0.38AU. The data rate that can be supported from Mars is a function of, among other things, this distance between Earth and Mars. The effect of Mars-Earth distance variation between 2010 and 2030 on the possible data rate is shown in Figure 3 [1] which is normalized for a minimum required rate of 10Mbps at maximum distance. The resulting median data rate is 20Mbps but the data rates can be upto 480Mbps at minimum distances indicating a gain of about 16.5dB. This variation and link margins must be taken into consideration when designing the link.

Figure 3 - Required Power and Mars-Earth Range Variations during 2010-2030



4. Link Design Approach and Trade Study

The Ka-band communication link design for telecom system for Mars to Earth communication downlink for Mars telecom relay Orbiter is planned for three data rates capabilities of 1Gbps, 500Mbps and 100Mbps per user scenario identified in section 2. In designing for the link scenarios, there is a three dimensional trade space namely ground G/T, size of the spacecraft antenna and spacecraft RF power. The approach to the link budget for a Ka-band will require using link assumptions presented in section 3 and summarized here as 90% link availability for the maximum distance of 2.67AU (furthest point from Earth to the Mars), use 3 options for ground network array, BPSK/QPSK modulation, LDPC coding and 1dB spacecraft antenna pointing losses. The maximum bandwidth available for Ka-band downlink is 500MHz and dual polarization is assumed in the cases where the data rate exceeds the bandwidth available. Other options such as Bandwidth Efficient Modulations will also be reviewed for high data rate scenarios which exceed available bandwidth especially in the case of increased link margins during shorter distance between Earth and Mars of 0.38AU.

On the spacecraft, for a given EIRP requirement, the spacecraft parameters can be optimized to minimize the RF mass of the spacecraft [1]. To optimize and minimize RF mass of the spacecraft, the mass of the antenna system and power system must be equal as shown in the following equation [1].

$$m_{a+p} = 2m_a = 2m_p = \lambda\sqrt{\frac{EIRPd_a d_p}{L_t \eta_{ap} \pi}}$$

A link budget [4] is created for each of the data rate scenario and ground network option along with other assumptions and mass minimization concepts. This link budget analysis would determine the spacecraft parameters for each ground option and for each data rate design point at maximum Earth-Mars distance, 2.67 AU. Further, when the distance between Earth and Mars reduces to its minimum (0.38 AU), there is an increase in the link margin to about 14-17 dB that allows one to trade among the given trade space as: (1) increasing the downlink data rate; (2) reducing the number of antenna elements in the ground network; and (3) applying power conservation methods on the spacecraft.
A summary of results for three data rate design points (1 Gbps, 500 Mbps, 100 Mbps) and three ground network options (180, 45, 12 element array) are provided in Table 3. The results [1] indicate that EIRP for the spacecraft increases as the ground element decreases thus requiring larger antennas and power amplifiers. The antenna expected is within the range of 3m to 9m while the power amplifier is within the range of 0.26kW to 2.2kW. It is also seen that the bandwidth-efficient modulation does not provide much increase in the data rate for the increased link margin seen as the distance between Mars-Earth reduces down from 2.67AU to 0.38AU.

Table 3 - Summary of Link Results for User Data Rates of 1Gbps, 500Mbps, 100Mbps

User Scenario	DataRate (Mbps)	Range (AU)	SCAnt (m)	SAntPtgEr (mdeg)	SCRFOut (kW)	SC-EIRP (dB)	Ground Network	GndGain (dB)	T_Gain (dB)	Comments
1Gbps	**1000**	**2.67**	**4.5**	30	**0.6**	119.02	**Array-180**	92.95	211.97	Dual Polarization (500Mbps)
w/ Array of	**1000**	**0.38**	4.5	30	0.6	119.02	**Array-4**	76.42	195.44	Dual Polarization (500Mbps)
180 elements	**2000**	**0.38**	4.5	30	0.6	119.02	**Array-35**	85.84	204.86	BEM - 8PSK Dual Polarization (1Gbps)
1Gbps	**1000**	**2.67**	**6.2**	20	**1.1**	124.58	**Array-45**	86.93	211.51	Dual Polarization (500Mbps)
w/ Array of	**1000**	**0.38**	6.2	20	1.1	124.58	**Array-1**	70.4	194.98	Dual Polarization (500Mbps)
45 elements	**2000**	**0.38**	6.2	20	1.1	124.58	**Array-8**	79.43	204.01	BEM - 8PSK Dual Polarization (1Gbps)
1Gbps	**1000**	**2.67**	**8.7**	14	**2.2**	130.56	**Array-12**	81.19	211.75	Dual Polarization (500Mbps)
w/ Array of	**2000**	**0.38**	8.7	14	2.2	130.56	**Array-1**	70.4	200.96	Link Capability only (single polarization)
12 elements	**2000**	**0.38**	8.7	14	2.2	130.56	**Array-2**	73.41	203.97	BEM - 8PSK Dual Polarization (1Gbps)
500Mbps	**500**	**2.67**	**3.9**	40	**0.45**	115.69	**Array-180**	92.95	208.64	Dual Polarization (250Mbps)
w/ Array of	**1000**	**0.38**	3.9	40	0.45	115.69	**Array-8**	79.43	195.12	Dual Polarization (500Mbps)
180 elements	**2000**	**0.38**	3.9	40	0.45	115.69	**Array-180**	92.95	208.64	BEM - 8PSK Dual Polarization (1Gbps)
500Mbps	**500**	**2.67**	**5.3**	25	**0.8**	121.72	**Array-45**	86.93	208.65	Dual Polarization (250Mbps)
w/ Array of	**1000**	**0.38**	5.3	25	0.8	121.72	**Array-2**	73.41	195.13	Dual Polarization (500Mbps)
45 elements	**2000**	**0.38**	5.3	25	0.8	121.72	**Array-16**	82.44	204.16	BEM - 8PSK Dual Polarization (1Gbps)
500Mbps	**500**	**2.67**	**7.4**	18	**1.6**	127.62	**Array-12**	81.19	208.81	Assume Dual polarization with 500Mbps each
w/ Array of	**1000**	**0.38**	7.4	18	1.6	127.62	**Array-1**	70.4	198.02	Dual Polarization (250Mbps)
12 elements	**2000**	**0.38**	7.4	18	1.6	127.62	**Array-4**	76.42	204.04	BEM - 8PSK Dual Polarization (1Gbps)
100Mbps	**100**	**2.67**	**3**	45	**0.26**	111.86	**Array-180**	92.95	204.81	Single polarization transmit
w/ Array of	**1000**	**0.38**	3	45	0.26	111.86	**Array-23**	88.53	200.39	Dual Polarization (500Mbps)
180 elements	**1800**	**0.38**	3	45	0.26	111.86	**Array-180**	92.95	204.81	BEM - 8PSK Dual Polarization (900Mbps)
100Mbps	**100**	**2.67**	**4.2**	30	**0.5**	117.75	**Array-45**	86.93	204.68	Single polarization transmit
w/ Array of	**1000**	**0.38**	4.2	30	0.5	117.75	**Array-5**	77.39	195.14	Dual Polarization (500Mbps)
45 elements	**1800**	**0.38**	4.2	30	0.5	117.75	**Array-45**	86.93	204.68	BEM - 8PSK Dual Polarization (900Mbps)
100Mbps	**100**	**2.67**	**5.9**	20	**1**	123.58	**Array-12**	81.19	204.77	Single polarization transmit
w/ Array of	**1000**	**0.38**	5.9	20	1	123.58	**Array-1**	70.4	193.98	Dual Polarization (500Mbps)
12 elements	**2000**	**0.38**	5.9	20	1	123.58	**Array-12**	81.19	204.77	BEM - 8PSK Dual Polarization (1Gbps)

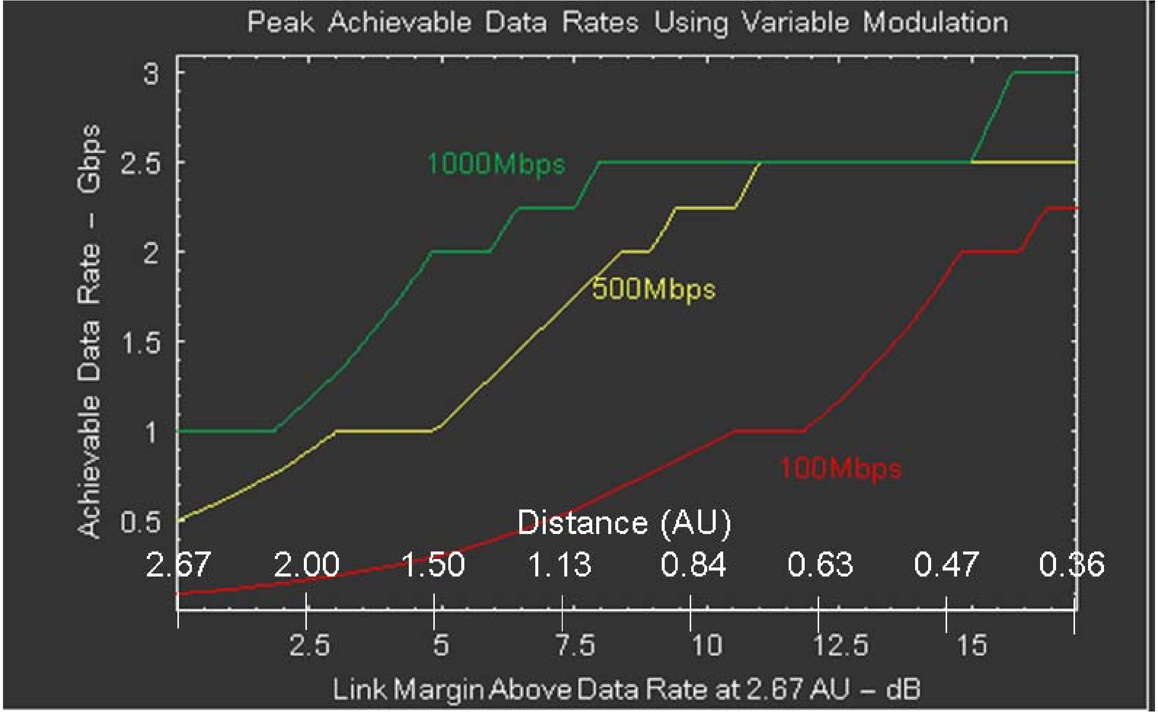
Further studies reviewed various modulation schemes as shown in Table 4 [1] so that the spacecraft may allocate its additional link margin to increase the data rate. These results assume that: (1) the exploration bandwidth allocated for the Mars satellite relay transmission to Earth is fixed at 500 MHz; (2) the EIRP has been designed for the maximum distance to Earth; and (3) all of this available EIRP is utilized to maximize the data rate when the range is less than the maximum.

Table 4 - Modulation Types for Maximum Achievable Data Rates vs Distance (or Equivalent Margin)

Number	Modulation	Coded Bits/Symbol	Code Rate	Spectral Efficiency (Info. Bits/Symbol)	Eb/No (dB)
1	QPSK	2	1/2	1	2.2
2	8PSK	3	3/4	9/4	6.4
3	8PSK TCM	3	2/3	2	4.0
4	8PSK TCM	3	3/4	9/4	5.1
5	8PSK TCM	3	5/6	5/2	6.2
6	QPSK	2	1	2	9.6
7	8PSK	3	1	3	13.2

The results for are presented in Figure 4 [1]. The figure indicates that even though the gain in link margin at closer distances is within the range of 14-17dB, the actual gain in the data rates is not more than 3Gbps for the link that is designed at the maximum of 1Gbps, 500Mbps or 100Mbps at maximum distance of 2.67 AU.

Figure 4 - Peak Data Rates Achievable with Best Modulation Technicques for Each Margin Value



5. Conclusion

A high rate Ka-band downlink is feasible between Earth and Mars at a maximum distance of 2.67 AU. The trade study considers Mars-Earth communication links of 1 Gbps, 500 Mbps and 100 Mbps for 3 DSN-array ground options of 180-element, 45-element and 12-elements. As the numbers of ground elements are reduced, spacecraft EIRP requirement increases leading to an increase in antenna size, and amplifier size thus resulting in an increase of the spacecraft RF mass. From the results presented before to support the data rates of 1Gbps requires the antenna within the range of 4.5m to 8.7m with power amplifier of 0.6kW to 2.2 kW (respectively), depending on the ground array network configuration. Similarly, 500Mbps and 100Mbps require antenna size within the range of 3.9m to 7.4m and 3m to 4.9m respectively. The power amplifier required for 500Mbps and 100Mbps would be within the range of 0.45kW to 1.6kW and 0.26kW and 1kW respectively.

Besides the impact on the RF technologies, an important aspect to note is that designing the link for maximum Mars-Earth distance of 2.67AU, leads to increased link margin within the range of 14-17dB as this distance decreases to 0.38AU which provides various possibilities such as increasing the link data rate, reducing the number of array elements on the ground network as this margin increases or provide low-power modes on the spacecraft. In the case of increasing the data rate with increased margin, the ultimate data rate that may be achieved is rather a weak function of the initial rate designed for 2.67 AU. The data rate achieved with this increased margin of 17dB is only upto 3Gbps. In a bandwidth constrained environment, it is not easy to convert new-found link margin into a corresponding data rate increase. This is because the margin must be used to support both the rate increase as well as the SNR inefficiency encountered in transitioning to a more bandwidth-efficient method of modulation and coding. The lower the design rate, the more slowly the 3 Gbps asymptote is approached as can be compared between the design points of 1Gbps and 100Mbps. However for the Mars example, the 17-dB range of signal variation is not wide enough to allow the eventual introduction of any non-constant envelope modulations such as QAM. The high E_b / N_0 requirements of these highly bandwidth-efficient modulation methods preclude their use because the margin cannot support them. As an example, it takes 23 -dB margin before rate-3/4 encoded 64QAM can be used to drive the data rate to 4 Gbps. Trellis-coded PSK can achieve close to this with constant-envelope waveform ability to increase data rate as the spacecraft comes closer to Earth. This can be used to increase the average data return, or throughput, achieved on a mission, as long as a large fraction of the data is highly delay tolerant. It might be worthwhile to trading this increased data rate to reducing the number of ground elements in the array network or to provide different power modes on the spacecraft such that it can take advantage of this increased margin to reduce the power consumption on the spacecraft when operating in lower power modes. In either case, a high-rate Ka-band communication downlink is a possibility from Mars and requires looking into appropriate RF antenna and power technologies to support it.

6. References

1. W. Williams, et al., “High Capacity Communications from Martian Distances – A Report for Space Communications Architecture Working Group (SCAWG)”, December 2005

2. G. Noreen, et al., “Mars Telecommunications Orbiter Ka-Band Operations,” 9th Ka and Broadband Communications Conference, Lacco Ameno, Italy, November 2003.

3. G. Noreen, et al., “Integrated Network Architecture for Sustained Human and Robotic Exploration,” 2005 IEEE Aerospace Conference, Big Sky, Montana, March 5, 2005, updated December 28, 2004.

4. DSMS Telecommunications Link Design Handbook, TMOD No. 810-005, Rev. E, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, January 2001. [This report contains information from module 101 (70-m subnet), module 103 (34-m HEF subnet), module 104 (34-m BWG subnet), module 105 (atmospheric effects), and module 106 (solar effects).]

5. M. S. Gatti, “The Deep Space Network Array,” at the IEEE Microwaves and Theory and Techniques (MTT) Workshop on Arrays, June 17, 2005.

6. M. S. Gatti, "The Deep Space Network Large Array," IPN Progress Report, vol. 42-157, pp. 1-9, May 15, 2004

7. L. J. Harcke, et. al., “Recent Ka-Band Weather Statistics for Goldstone and Madrid,” TDA Progress Report, vol. 42-125, Jet Propulsion Laboratory, Pasadena, California, May 1996.

8. D. Morabito, “Ka-Band Atmospheric Induced Temperature Fluctuations,” IPN Progress Report, vol. 42-150, Jet Propulsion Laboratory, Pasadena California, August 2002.

9. S. Shambayati, “On the Benefits of Short-Term Weather Forecasting for Ka-Band,” Aerospace, 2004.

10. S. Shambayati, “Maximization of Data Return at X-Band and Ka-Band on the DSN’s 34-Meter Beam-Waveguide Antennas,” TMO Progress Report, vol. 42-148, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, February 2002.

11. F. Davarian, et al., “Deep Space Ka-Band Link Management and Mars Reconnaissance Orbiter: Long Term Weather Statistics Versus Forecasting,” IEEE Proceedings, Vol. 92 1879-1894, December 2004.

12. D. Morabito and R. Hastrup, “Communicating with Mars during Periods of Solar Conjunction,” IPN Progress Report, vol. 42-147, Jet Propulsion Laboratory, Pasadena California, November 2001.