Performance Evaluation of Earth-Mars Links for Interplanetary Internet

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Abstract – This study explores Earth's network architecture, functionality, challenges of interplanetary networks, and evaluates link-level performance for an Earth–Mars interplanetary network. Performance evaluation is done by modeling three RF hops: Starlink gateway to LEO Starlink satellite, Starlink satellite to Mars Reconnaissance Orbiter, and orbiter to Mars surface, using Starlink and MRO antenna and power parameters. Key metrics like latency, free-space path loss, SNR, and Shannon capacity were computed in a MATLAB simulation across distances of 56–401 million km. Investigation results demonstrate that the main issues of interplanetary internet are latency, relay bottlenecks, interruption by weather, lack of terminals, and high cost of equipment. MATLAB simulation results show high theoretical capacity for LEO links measuring at Gbps speeds, but less than 1 kbps rates at maximum Mars separation, demonstrating the overwhelming impact of path loss on deep-space throughput. The work showcases the gap between ideal Shannon capacity values and operational link rates and recommends extending the framework to alternative RF constellations and high-rate optical laser links for future interplanetary Internet applications.

Introduction

The Internet functions as a global network infrastructure, enabling data exchange between computational devices through standardized communication protocols. The majority of the Earth-based networks implement the TCP/IP protocol suite [5][6], which operates across a five-layer architectural framework: At the foundation, the physical layer manages signal transmission through media including fiber-optic cables, copper lines, and RF-based wireless technologies. Above this, the data link layer handles frame synchronization and error control, while the network layer provides IP-based routing across heterogeneous subnets. The transport layer implements TCP for connection-oriented reliability or UDP for lightweight datagram services, culminating in the application layer where protocols like HTTP and FTP execute user services [29]. This layered model supports connectivity variations ranging from broadband fiber backbones to RF-based satellite constellations like Starlink across the planet[1].

When attempting to extend the internet functionality to interplanetary distances, the architecture of the network must adapt to the following three challenges. First, extreme

propagation latency induced by planetary distances creates long signal delays. Earth-Mars communications experience 3-22 minute one-way light-time lags, exceeding Earth-based protocols' time-out timers and making them unusable. Similarly, periodic connectivity from the motion of the planets and environmental disruptions like solar conjunctions and Martian dust storms break down the terrestrial protocols' expectations of constant connectivity [30]. These protocol incompatibilities can be demonstrated through TCP's acknowledgment-based flow control failing during extended delays, while IP lacks mechanisms for disruption-tolerant routing [6].

Consequently, space networks employ specialized protocols operating across adapted stack layers. The Delay-Tolerant Networking (DTN) framework implements store-and-forward bundle services at the application layer, utilizing custody-based retransmission to overcome disruptions [7]. The CCSDS File Delivery Protocol (CFDP) provides reliable asynchronous file transfer at the transport layer [8], while Space Communications Protocol Specifications (SCPS) optimize security and network services for resource-constrained links [9]. For proximity operations, the Proximity-1 protocol mediates MAC-layer coordination between Martian rovers and orbiters.

Earth-Mars internet implementations face additional physical constraints beyond protocol limitations. Bandwidth asymmetry restricts uplinks to 5-500 kbps versus downlinks at 2-6 Mbps, which is orders below terrestrial Gbps capabilities [22]. Path loss exceeding 250 dB at maximum range combined with limited spectral allocations in X-band (8.4 GHz) and Ka-band (32 GHz) , degrades channel capacity [31]. Relay architecture vulnerabilities further create single-point failure risks during critical mission phases [22]. This study evaluates the physical-layer feasibility of bridging these gaps through channel modeling and Shannon capacity analysis of the modern RF infrastructure.

Methodology

This research aims to evaluate the link-level performance of Earth-Mars links for future interplanetary internet applications. To achieve this goal, a literature review and simulation-based calculations were chosen as research methods.

The objectives of the study are to:

1. **Define "the internet" and its functionality**

Investigate articles on how the internet functions on Earth, types of layers, and their functions, define the terms "Latency", "Data Rate", "Bandwidth", "Signal-to-Noise Ratio", and "Shannon Capacity".

2. **Summarize the challenges of the satellite-to-satellite Earth-Mars links**

Investigate the difficulties of applying Earth networking techniques in interplanetary networks.

3. **Explore existing Deep Space Networks**

Investigate the solutions for making interplanetary networks.

4. **Define use cases for the Earth-Mars interplanetary network**

Investigate scientific and civilian use cases for the Earth-Mars interplanetary network.

5. **Calculate the network characteristics for the Earth-Mars interplanetary network**

Calculate the possible latency, data rate, received power, and Shannon capacity based on existing ground stations and satellites for the Earth-Mars Interplanetary network

Research

1.**“The internet” and its functionality**

The architecture of the Internet is described using the TCP/IP model, where information must pass through all four levels to reach its destination. This is how this system ensures quality, mobility, and stability. The first of them is the data link layer, which contains all the physical components necessary for transmitting information and connecting to the network. Thus, at this first level, information transmission reaches those device components that provide Internet access. The second one is the Internet layer. This is the layer that is responsible for traffic routing and traffic flow management; therefore, some people also call it the Internet layer. Thus, it is the Internet layer that is responsible for ensuring that the files sent are not corrupted. Third is the Transport layer. This is the layer that is responsible for dividing information into several packets so that communication is efficient and everything is received properly. The final layer is the Application layer. This is the level at which information enters programs, at which we can read it [10].

Latency is the time it takes for data to pass from one point on a network to another.

This “end-to-end delay” is calculated by summing up the following delays:

- Propagation delay (distance/speed of light in medium)
- Transmission delay (packet size/link bandwidth)
- Processing delay (router/switch/frame-assembly time)
- Queuing delay (time waiting in buffers under congestion)[11]

Bandwidth is a measurement indicating the maximum capacity of a wired or wireless communications link to transmit data over a network connection in a given time. Bandwidth, being 100Mbps as an example, does not guarantee constant speed at the maximum capacity, as it requires ideal conditions like a strong signal, low traffic, and high-end routers [12].

Physical-layer limits of bandwidth are determined by:

Channel bandwidth (Hz) set by antenna size(bigger size, more bits per Hz), RF design(filters and mixers’ passband limits the usable bandwidth), allocated spectrum(higher Hz, higher bandwidth) [12].

Modulation type is a specific scheme by which information is imposed onto a carrier wave so it can be transmitted over radio waves or optic fibers. QPSK (Quadrature Phase-Shift Keying), 16-QAM, and 64-QAM encode 2, 4, and 6 bits per symbol, respectively. As the modulation type shifts from QPSK to 64-QAM, spectral efficiency (bits/Hz) rises, but the constellation points draw closer together, so the minimum required signal-to-noise ratio at the receiver increases. In practice, higher-order schemes (16-QAM, 64-QAM) achieve greater data throughput but demand cleaner channels and more precise demodulation, making them less robust than QPSK under identical noise conditions [13].

Coding rate (Forward Error Correction overhead reduces net throughput) - FEC adds redundant or extra bits so the receiver can detect and correct errors without retransmission. The higher the coding rate, the more extra bits are sent, resulting in less new data transmission but higher reliability. For example, a 0.5 coding rate for a 1 Mbps raw X-band channel makes only 500kbps usable data rate [14].

SNR(Signal-to-noise ratio) is the difference between the received wireless signal and the noise floor. The noise floor is simply erroneous background transmissions that are emitted from either other devices that are too far away for the signal to be intelligible, or by devices that are creating interference on the same frequency [15].

Shannon’s channel capacity theorem states that the maximum rate at which information can be transmitted over a communication channel of a specified bandwidth in the presence of noise [4].

The Shannon capacity provides a theoretical upper bound on error-free rate and guides link-budget and spectrum allocation decisions.

2. Summary of the challenges of the satellite-to-satellite Earth-Mars links

- **Extreme Latency & DTN**

Mars–Earth one-way delays vary from ~3 to 22 minutes, making interactive protocols unusable. Delay/Disruption-Tolerant Networking solves this by "store-and-forward" bundles: each node holds data until a link opens, then sends large packets in a single shot, maximizing each Martian visibility window [7].

- **Relay Bottlenecks & Adaptive Scheduling**

Rovers share a handful of orbiters with only minutes of daily passes and sub-MHz deep-space channels. Time-Division Multiple Access plus traffic prioritization ensures high-value science data goes first. On the physical layer, Adaptive Modulation and Coding, which switches between BPSK, QPSK, and 16-QAM, lets the link squeeze more bits/Hz whenever SNR allows [17].

- **Atmospheric Fading & Robust Links**

Martian dust storms can suddenly attenuate X-band signals. By designing link margins of 5–10 dB above the minimum and falling back to lower-order modulation (BPSK) with stronger FEC (rate ½), the system trades peak throughput for reliability until conditions improve [18].

- **Earth-Side Constraints & Optical Alternatives**

NASA's Deep Space Network's 34 m/70 m dishes are heavily booked, so supplementing with ESA/CSRIO ground stations or even laser-optical terminals adds extra capacity. Optical links can offer hundreds of MHz (or Gbps) but demand precise pointing and clear line-of-sight [19][20].

- **Power/Mass Trade-offs & Smart Radios**

Higher transmit power and large dishes cost mass. Software-Defined Radios that hop between UHF (rover→orbiter) and X-band (orbiter→Earth), plus onboard compression of images/telemetry, let missions hit data targets within strict spacecraft power/mass budgets [21].

3. Existing deep space networks

Deep Space Network-the largest and most sensitive scientific telecommunication system in the world. DSN is a powerful system for commanding, tracking, and monitoring the health and safety of spacecraft at many distant planetary locales. DSN also enables powerful science investigations that probe the nature of asteroids and the interiors of planets and moons. The three DSN complexes are located in Barstow, California; Madrid, Spain; and Canberra, Australia. Strategic placement of these complexes supports constant communication with a spacecraft [19].

Mars Relay Network-it is a group of five artificial satellites of Mars, such as Odyssey, Mars Express, Mars Reconnaissance Orbiter(MRO), MAVEN, and ExoMars Trace Gas Orbiter(TGO) that sends information about Mars collected from surface rovers like Curiosity and Perseverance. In order to wrap the information that will be transmitted, it is divided into active satellites in order to deliver information faster and more reliably. The MRN spacecraft can transmit its data to one of three antenna complexes on Earth serviced by ESA, NASA, and Roscosmos [22].

These two networks play an important role in building interplanetary communication. Because now they are the ones who can connect Mars and Earth together, while maintaining the fastest and highest quality communication. Since both have already been tested by time, it remains only to improve the existing connections.

4. Use cases for the Earth-Mars interplanetary network

High-resolution imagery, spectroscopic readings, and environmental measurements collected by Mars orbiters and rovers require reliable, high-throughput downlinks to Earth for analysis. For example, NASA's Mars Reconnaissance Orbiter routinely relays gigabytes of raw science data consisting of surface mineralogy and climate observations through near-Mars links to deep-space antennas on Earth. An interplanetary network would create a near-constant flow, enabling near-real-time monitoring of surface changes such as dust storms, seasonal CO_2 ice shifts, and more rapid iteration of mission plans [23].

Beyond science, an interplanetary network could support future civilian communication services for Mars inhabitants. Mobile-network experiments in lunar orbit have shown that personal devices, including smartphones, tablets, and wearables, can connect via satellite links to distant habitats. On Mars, colonists could use similar infrastructure for voice calls, messaging, and Internet-style browsing. Telemedicine consultations, live video links between Martian patients and Earth-based specialists, would become feasible, ensuring timely medical care despite the ~20-minute one-way delay. Access to the internet would also enable the Mars inhabitants to access Earth-based entertainment or stream the developments on Mars when they desire [24].

5. The network characteristics for the Earth-Mars interplanetary network

The maximum and minimum distances between Earth and Mars are 56 million km and 401 million km, respectively[16]. The one-way latency of data transmission is calculated using the distance between planets and the speed of light, 300,000m/s², at which the data travels. Assuming that communicating satellites are on a geosynchronous orbit, where a satellite is on a fixed point in space and 35,786km above Earth's surface, and an areostationary orbit, similar to geosynchronous but used for Mars, 17,032km above the surface, the total distance between satellites and the surfaces of their planets approximates to ~50,000km .

$$t_{one-way} \geq \frac{distance}{3*10^5 km/s}$$

$$t_{max} = \frac{401.05*10^6 km}{3*10^5 km/s} \approx 22.28\, min$$

$$t_{min} = \frac{56.05*10^6 km}{3*10^5 km/s} \approx 3.11\, min$$

$$t_{avg} = \frac{228.55*10^6 km}{3*10^5 km/s} \approx 12.70\, min$$

Based on the calculations above, the latency between Earth and Mars data transmission ranges from 3.11 minutes at the closest point to 22.28 minutes at the farthest point, with an average latency of 12.7 minutes.

To calculate the Shannon Capacity for the Earth-Mars interplanetary network, 3 notable links were chosen. The first link is the link between a Starlink Gateway ground station and a Starlink satellite. The second link is the link between a Starlink satellite and a Mars Reconnaissance Orbiter. The third link is the link between the Mars Reconnaissance Orbiter and Mars' surface ground station, which we assume to have the same parameters as Starlink Gateway for the sake of calculations. Starlink's and Mars Reconnaissance Orbiter's approximate parameters were chosen to base calculations on real parameters used for networks by citizens and scientists.

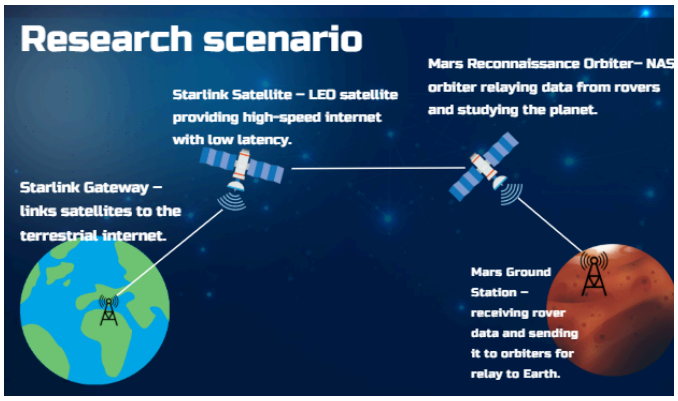


Figure 1. Illustration of the scenario.

For calculations, MATLAB is used. MATLAB is a high-level numerical computing environment and programming language designed for matrix-based data analysis, algorithm development, and simulation. It is widely used in engineering and scientific research for tasks such as signal processing, control system design, and visualization, thanks to its extensive built-in function libraries and toolboxes [3].

The initial parameters for the first, second, and third links can be found in Appendices 1, 2, and 3, respectively.

The calculations are made with the assumptions of no atmospheric disruptions such as rain, snow, or dust storms on Earth and Mars, as it would be difficult to quantify the impact of the weather on network characteristics and calculate a probable range.

In the MATLAB calculations, the following formulas are applied:

$$P_{td}(dBm) = 10 * log_{10}(P_W * 10^3)$$

In the formula above, power transmitted is converted from Watts to dBm(log scale milliwatts) to make large ratios more manageable in calculations.

$$FSPL = 20log_{10}(d) + 20log_{10}(f) + \\ + 32.44$$

In the formula above, the Free-Space Path radio signal Loss is calculated, where d is the distance between the transmitter and receiver, f is the carrier frequency, and 32.44 dB is a constant that adjusts units [25].

$$P_{rd}(dBm) = P_{td}(dBm) + G_{td} + G_{rd} - \\ - FSPL - margin(dB)$$

In the formula above, the power received is calculated by summing up the power transmitted in dBm with the transmitting and receiving antenna gain, and subtracting the Free-Space Path Loss and link margin [25].

$$N(W) = k * T_{sys} * B(Hz)$$

$$N(dBm) = 10 * log_{10}(N(W) * 10^3)$$

In the formulas above, the Noise Floor is calculated using Boltzmann's constant, System Noise Temperature, and Bandwidth in Hz and converted to dBm [26].

$$SNR(dB) = P_{received}(dBm) - \\ - N(dBm)$$

$$SNR(linear) = 10^{(\frac{SNR(dB)}{10})}$$

In the formulas above, the Signal-to-Noise ratio is calculated and then converted into a linear, unitless form [28].

$$C(bps) = B(Hz) * log_2(1 + \\ + SNR(linear))$$

In the formula above, Shannon Capacity is calculated using Bandwidth and linear Signal-to-Noise ratio [4].

Results

The calculations using MATLAB yielded the following results:

Table 1. The network characteristics of the Starlink Gateway and the Starlink satellite link

Parameter	Value
Transmit Power(dBm)	47.0
Free-Space Path Loss(dB)	168.8
Received Power(dBm)	-38.3
Noise Floor(dBm)	-92.2
Signal-to–Noise ratio(dB)	53.9
Shannon Capacity(Mbps)	2076.41

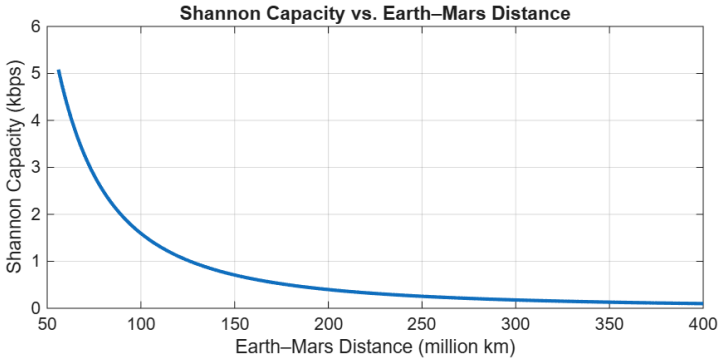
For the calculation of the 2nd link between the Starlink satellite and the Mars Reconnaissance Orbiter, it's not possible to derive a constant value since the distance between Earth and Mars varies. For calculating the Free-Space Path Loss, Received Power, Noise Floor, Signal-to-Noise ratio, and Shannon capacity, the average distance between Earth and Mars was chosen.

Table 2. The network characteristics of the Starlink Satellite and the Mars Reconnaissance Orbiter link

Parameter	Value
Transmit Power(dBm)	40.0
Free-Space Path Loss(dB)	278.0
Received Power(dBm)	-159.8
Noise Floor(dBm)	-102.5
Signal-to–Noise ratio(dB)	-57.3
Shannon Capacity(kbps)	0.32

To give a more accurate representation of the network characteristics for the 2nd link, Graph 1 of Shannon Capacity against varying distance from Earth to Mars was plotted, as Shannon Capacity's calculation encompasses all of the network characteristics.

Graph 1. Shannon Capacity against varying distance from Earth to Mars.



In Graph 1, it can be seen that the Shannon capacity varies from approximately 5 kbps at the closest point between Earth and Mars to below 1 kbps at the farthest point.

Table 3. The network characteristics of the Mars Reconnaissance Orbiter link and the Mars ground station

Parameter	Value
Transmit Power(dBm)	50.0
Free-Space Path Loss(dB)	160.5
Received Power(dBm)	-17.3
Noise Floor(dBm)	-98
Signal-to–Noise ratio(dB)	80.7
Shannon Capacity(Mbps)	3109.21

Discussion

The theoretical Starlink Gateway and Starlink satellite link between a 50 W, 49.5 dBi gateway and a 10 W, 36 dBi LEO satellite produces a one‑way FSPL of 168.8 dB at 550 km, yielding a received power of –38.3 dBm, noise floor –92.2 dBm (assuming 35 K system noise and 116 MHz bandwidth), and an SNR of 53.9 dB. Applying the Shannon capacity theorem gives a theoretical maximum throughput of 2,076 Mbps.

Commercial Starlink user terminals deliver on the order of 100–200 Mbps per user beam, with aggregate spot-beam capacity up to ~1 Gbps over a 100 MHz channel [27].

Achieved result exceeds practical rates by an order of magnitude because it represents an upper bound; real systems must back off for modulation/coding overhead, rain fade margins, and multiple-access sharing.

Using the same 10 W, 36 dBi Starlink satellite and a 100 W, 45.2 dBi MRO HGA across the average Earth–Mars distance yields FSPL ≈ 278 dB, received power –159.8 dBm, noise floor –102.5 dBm, and SNR ≈ –57.3 dB. The computed Shannon capacity is 0.32 kbps, effectively zero under these assumptions.

NASA reports 2–6 Mbps X-band downlinks from Mars Reconnaissance Orbiter via the DSN's 34 m dishes using ~100 W SSPAs and cross-strapped coding for ~4 dB link margin. The negative SNR in results indicates that the assumed Starlink Satellite to Mars Reconnaissance Orbiter parameters, particularly the low transmit power and moderate gains, are insufficient; real deep-space links require much higher power and larger receive apertures to overcome ~250 dB of path loss [23].

Assuming a 100 W, 46.7 dBi MRO HGA communicating with a 50 W, 49.5 dBi "Mars‑Starlink" ground terminal at 300 km yields FSPL 160.5 dB, Pr –17.3 dBm, noise floor –98 dBm, SNR 80.7 dB, and a Shannon capacity of 3 109 Mbps

Actual UHF/XS-band Mars surface relays, such as the Mars Perseverance Rover to Mars Reconnaissance Orbiter, operate at a few hundred kbps to a few Mbps due to low‑power lander transmitters and narrow UHF channels. It can be stated that the achieved result values reflect a theoretical max with optimistic hardware.

The Shannon capacity curve seen in Graph 1, from ~5 kbps at 56 Mkm down to <1 kbps at 401 Mkm, follows the loss profile of FSPL $1/d^2$.

The fall of Shannon capacity as distance increases demonstrates that distance dominates interplanetary link performance, as multi-GHz antennae and large apertures cannot sustain high data rates across vast space distances between Earth and Mars.

Conclusion

MATLAB‑based analysis of interplanetary network links between Earth and Mars showcases the gap between theoretical Shannon bounds and operational link rates for communications between the two planets. While Starlink‑style hardware could in principle support multi-Gbps across short LEO/Mars‑LEO hops, the extreme path loss to Mars orbit demands higher power sources and antennas, or the adoption of optical links. Deep‑space assets like Mars Reconnaissance Orbiter rely on highly optimized X-band transponders and the Deep Space Network's 34/70 m dishes to achieve a speed of a few Mbps, orders of magnitude below Shannon limits over those ranges.

Further Research

A logical extension of RF‑based interplanetary communication studies is a focused investigation into laser‑optical links for Mars–Earth data exchange. Optical terminals promise multi‑gigabit throughput and superior spectral efficiency compared to X- and Ka-band systems, yet they demand ultra-precise beam pointing, complex adaptive optics to mitigate atmospheric turbulence, and strategies for weather‑induced outages [32]. Future work could develop a simulation framework that models spacecraft laser transceivers, ground-station optical subsystems, and planetary weather patterns to evaluate link availability and performance. The simulation would quantify end-to-end capacity gains, assess reliability under variable conditions, and determine the terminal aperture and pointing-accuracy specifications necessary to enable sustained gigabit-class interplanetary service.

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Figure 1. Illustration of the scenario. Made by using Canva graphics elements.

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Appendix List

Appendix 1. Initial parameters for the Starlink Gateway and Starlink Satellite link

Parameter	Value
Transmit Power(W)	50
Ground Terminal Gain(dBi)	49.5
Starlink Satellite Gain(dBi)	36
Link Margin(dB)	2
Low Earth Orbit Distance(km)	550
Ku-band Frequency(MHz)	12000
System Noise Temperature(K)	374
Boltzmann constant [J/K]	1.380649e-23
Bandwidth(MHz)	116

Appendix 2. Initial parameters for the Starlink Satellite and Mars Reconnaissance Orbiter link

Parameter	Value
Transmit Power(W)	10
Starlink Satellite Gain(dBi)	36
Mars Reconnaissance Orbiter Gain(dBi)	45.2
Link Margin(dB)	2
Average distance(km)	228.5e6
Minimum Distance(km)	56e6
Maximum Distance(km)	401e6
X-band Frequency(MHz)	8400
System Noise Temperature(K)	35
Boltzmann constant [J/K]	1.380649e-23
Bandwidth(MHz)	116

Appendix 3. Initial parameters for the Mars Reconnaissance Orbiter and the Mars Ground Station link

Parameter	**Value**
Transmit Power(W)	100
Mars Reconnaissance Orbiter Gain(dBi)	46.7
Ground Terminal Gain(dBi)	49.5
Link Margin(dB)	2
Distance from surface(km)	300
Ku-band Frequency(MHz)	12000
System Noise Temperature(K)	374
Boltzmann constant [J/K]	1.380649e-23
Bandwidth(MHz)	116