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BUILDING RESILIENT NETWORKS ON MARS: STRATEGIES FOR ENHANCED INTRA-PLANETARY AND INTERPLANETARY CONNECTIVITY

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Abstract

As the number of research instruments on the surface of Mars increases, the lack of communication between independent instruments may cause some limitations and problems in space exploration. If we consider the idea of colonizing Mars in the coming decades, the lack of an established network means that the colony we will establish on Mars will not develop as rapidly. In the past century, information sharing has become crucial for all disciplines, and it will be beneficial for humanity to not limit this information sharing only to the earth but extend it beyond our borders. The aim of this research is to investigate the network that we can establish on the surface of Mars and to examine the potential factors of DTN (Delay-Tolerance networking) systems, which were developed especially for interplanetary data transfer, as well as protocols such as TCP/IP, and UDP/IP that we use now. Within the scope of our paper, we will delve into two main topics: the Mars surface network and the Mars-Earth network. While discussing the steps that can be taken regarding the Mars surface network, its potential difficulties, and its advantages, we will delve deeper into the challenges we encounter in the Mars-Earth network connection, such as distance and location. Therefore, it is apparent that using these protocols for communication between Mars and Earth will cause problems in terms of proximity and delays, hence it can be established using DTN. By doing so, we can provide efficient, reliable communications which preserve the data integrity. Furthermore, our research suggests that sending rovers dedicated to data transmission to Mars will shoulder the responsibility of sending data to Earth. The method used in our research consists of standard literature review practices and an investigation into technical documents, such as Requests for Comments (RFCs). In our research, we will describe the communications rovers' specifications and explain how space missions could be adjusted to account for it. Moreover, our research will propose a plan for the transition period between our current situation and the desired outcome, and how we will synchronize it with the existing frameworks established by major space organizations. In conclusion, while interplanetary communication allows many devices on the same planet to instantly share their findings with each other, using interplanetary communication to promptly send them to Earth will expand our understanding of the universe and will help us to take one step in our colonization goal.

Keywords: *Mars Surface Network, Mars-Earth Communication, Delay Tolerant Networking (DTN), Optical Communication, Data transmission, Mars Communication Challenges*

Acronyms/ Abbreviations	Definition
AMO	*Areosynchronous Mars Orbit*
AU	*Astronomical Unit*
Bps	*Bits per second*
BPSK	*Binary Phase Shift Keying*
DSOC	*Deep Space Optical Communication*
DTN	*Delay/Disruption Tolerant Networking*
EMI	*Electromagnetic Interference*
GEO	*Geostationary Orbit*
GHz	*Gigahertz*
HTS	*High Throughput Satellites*
ISS	*International Space Station*
ITU	*International Telecommunication Union*
JIMO	*Jupiter Icy Moons Orbiter*

K-band	*18-27 GHz microwave*
kbps	*Kilobits per second*
LADEE	*Lunar Atmosphere and Dust Environment Explorer*
LLCD	*Lunar Laser Communication Demonstration*
Mbps	*Megabits per second*
NASA	*National Aeronautics and Space Administration*
NTIA	*National Telecommunication and Information Administration*
OCTL	*Optical Communication Telescope Laboratory*
QAM	*Quadrature Amplitude Modulation*
RF	*Radio Frequency*
SCaN	*Space Communications and Navigation*
SEL	*Single-Event Latch-up*
SEU	*Single-Event Upsets*
SEE	*Single Event Effects*
STPSat-6	*Space Test Program Satellite-6*
TCP	*Transmission Control Protocol*
TID	*Total Ionizing Dose*
UDP	*User Datagram Protocol*
X-band	*8-12 GHz microwave band*

1. Introduction

The reason why the colonization of the Moon is not possible is because there is no hope of finding liquid water. Life on the surface of the Moon would not differ from a life in an abandoned desert. Mars, in comparison to the other planets in our solar system, is not exceedingly hot, nor is it wholly gaseous, thus provides a far more hospitable environment for human habitation, given the prospect of finding liquid water and vital mineral resources beneath its surface layer. Despite challenges like low air pressure, carbon dioxide-rich atmosphere, and magnetic field for protection, Mars is set to be explored through a collaborative effort between humans and robots. Humans would conduct scientific exploration of Mars in cooperation with robotic probes controlled by human explorers on the planet's surface. Under human direction, robotic probes may go long distances from the human habitat, returning rock and dust samples and covering lengths that were too dangerous for human investigation.

One of the primary reasons for exploring Mars is for the scientific insights that can be gained in the process. The surface of Mars can teach us about the formation of the universe, planets, and Earth (Gayon, 2023). We can learn more about our home planet by studying another.

Furthermore, space exploration drives technological advancements that not only aid in extraterrestrial missions but also transform our everyday lives. As highlighted by Levchenko et al. (2018), an image analysis algorithm originally developed to interpret the blurry images from the Hubble Telescope has been repurposed in medicine. It now enables more precise visualization of cancer-affected breast tissues in X-ray images, which has led to the development of minimally invasive stereotactic large-core needle biopsy.

The possibility of resource extraction is another advantage of colonizing Mars. Mars is rich in minerals and other resources, such as water, which could support future space missions and even supply Earth with valuable materials. For instance, the abundant iron and aluminum on the Red Planet could be used to construct a spacecraft and other infrastructure. Water on Mars, besides being utilized by humans, can also be turned into rocket fuel in the future (Gayon, 2023).

There are many perspectives on the matter, but the truth is that we don't know. Should we focus on solving the pressing problems on our planet, rather than investing vast financial resources and time in colonizing another one? Or could the colonization of Mars actually save us by providing access to new resources that could be sent back to Earth? And even if that's possible, how ethical would it be? There are too many sides to this debate. J.F. Kennedy in his speech "We Choose to Go to the Moon" quoted the great British explorer George Mallory, who died on Mount Everest. When asked why he wanted to climb it, he replied: "Because it is there." Space draws us by its uncertainty and vastness. Humanity has always been compelled to explore and embark on new adventures. One way or another, this journey will happen. If we believe we are capable of caring for Earth, taking responsibility for our actions, and acting ethically on the Red Planet, toward any potential inhabitants, and to embark on this new frontier, then perhaps it's a journey worth taking.

One of the most daunting challenges of space travel and human habitation on Mars is the lack of real-time communication. It's crucial to address this issue before embarking on such missions. To travel to a distant planet and establish a colony there, we must ensure a reliable and effective communication system with Mars.

2. Enhancing Mars-Earth Communication: Frequency Bands, Modulation Techniques, and Optical Innovations

Thus, as we have already established, a communication link between Mars and Earth is important, however, it cannot be achieved via a physical medium. Therefore, it is crucial to consider the frequency band used for this link. In today's world, there are dedicated frequency bands for space missions. Selecting the appropriate band is essential for reliable communication due to potential issues such as propagation, interference, distance, and data transfer capabilities. To address these challenges when establishing a network on Mars, especially for communication between Mars and Earth, data transmission should be carefully tailored.

Even though some missions still use low-frequency bands, such as the Mars Reconnaissance Orbiter (X-band 8-12 GHz), low-frequency bands (below 20 GHz) have insufficient data transfer capabilities for high-speed deep space communication (Taylor et al., 2006). Although lower frequency bands offer advantages like reduced power usage, better obstacle penetration, and longer range, they cannot provide the high data rates needed for effective communication. Additionally, they require larger antenna sizes, which can be problematic when deployed in alien worlds. On the other hand, higher frequency bands offer more data-carrying capacity than lower frequencies. However, they need more power, a direct line of sight, and have more atmospheric propagation. Despite these disadvantages, it still does not disqualify them from being used in the space industry. Higher data rates, less congestion, and smaller antenna sizes make higher frequency channels crucial for space communication.

2.1 Why do higher frequencies usually mean higher data transfer?

According to the Shannon-Hartley theorem, bandwidth is proportional to the bit rate, and more specifically, the equation states that the channel capacity in bps (C), is equal to the bandwidth of the channel in Hz (B), multiplied by the base 2 logarithm of 1 plus the average signal power (S) divided by the average noise power (N) (Shannon, 1948).

$$C = B\, log_2(1 + \frac{S}{N})$$

Because traditionally, lower frequencies have been used, there are fewer allocations for higher frequencies, meaning that using higher frequencies means that more spectrum is available, and therefore there is a higher bandwidth, so more data can be transmitted at the same time. Therefore, higher frequencies allow for more efficient modulation algorithms to be used, which enables a higher bit rate. For example, because of the greater number of oscillations of higher frequency waves, it is possible to modulate them to carry more data per second, as each oscillation of the data can be used to represent one bit or symbol. The process of modulation involves encoding data by controlling a part of the wave, such as its amplitude or phase. Quadrature Amplitude Modulation (QAM) is a technique suitable for higher frequencies and combines amplitude and phase modulation, thus allowing for an oscillation to represent multiple symbols. Each amplitude-phase combination is used to encode a separate symbol and can be shown as a point on the constellation diagram.

More complex modulation techniques, however, have disadvantages such as the need for more complex equipment and a higher signal-to-noise ratio, meaning that it is less robust than simpler modulations such as Binary Phase Shift Keying (BPSK). Higher frequencies are more suitable for complex modulation schemes because it is easier to distinguish the differences in the variables used for encoding (such as the frequency and phase in QAM), leading to higher levels of precision when decoding. The lack of congestion in higher frequencies compared to lower frequencies facilitates more complex modulation schemes since there is less interference and therefore a higher signal-to-noise ratio.

In 2019, NASA increased the data rate on the International Space Station by a factor of two, now making it 600 Mbps (Schauer, 2023). This data rate requirement would be even greater in a Martian environment due to the numerous research instruments that future colonizing scientists will use. Therefore, relying on lower frequency bands with limited data capabilities would not be practical for Mars communication.

2.2 High Radio Frequency (RF) Data Transferring Missions

2.2.1 The Mars Reconnaissance Orbiter

The Mars Reconnaissance Orbiter (Figure 1) is a mission that aims to find evidence of water existence on Mars and tries to communicate via Radio frequency waves in higher data capacities. The satellite uses both X-band and K-band by prioritizing the X-band. The Ma**rs** Reconnaissance Orbiter can provide data rates of up to 500 kbps at the maximum distance from Earth (400 million km [250 million miles]) while achieving 3-4 Mbps (with a 34-m Deep Space Station) and 6 Mbps (with 70-m Deep Space antennas) (Taylor et al., 2006). These data rates are 10 to 20 times faster than those of previous Deep Space missions (Taylor et al., 2006). While transmitting at these high data rates, the satellite uses a 3-meter-diameter (10-foot) high-gain antenna and a 100-watt X-band traveling wave tube amplifier (Taylor et al., 2006).

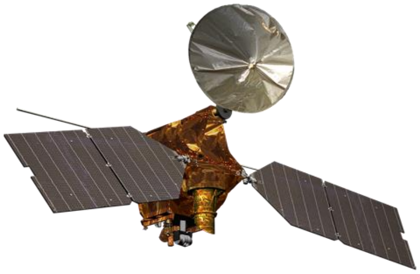

Figure 1 The Mars Reconnaissance Orbiter (NASA/JPL-Caltech, n.d.)

2.2.2 NASA's Jupiter Icy Moons Orbiter

NASA's Jupiter Icy Moons Orbiter (JIMO) is a mission that will explore the icy moons of Jupiter (Callisto, Ganymede, and Europa). This orbiter will use nuclear power for a sustainable exploration duration. For communication, it will use a 32 GHz band, a 3-meter high-gain antenna, and a 1 kW 32 GHz band transmitter. These instruments will allow data transmissions of up to 10 Mbit/s at a distance of 6.5 Astronomical Units (AU). According to calculations in the International Telecommunication Union (ITU) Report ITU-R SA.2167, if these communication instruments were used for Mars communications at a range of 2.6 AU, it would significantly increase data transfer capabilities to up to 62 Mbit/s (2009).

2.3 Optical Communications

Another high data rate communication technology being developed by Space Communications and Navigation (SCaN) program is optical communication. This technology is still in development and is currently being tested on several space missions. Optical telecommunication provides faster, more secure, lighter, and more flexible communication.

Faster - Increasing operational frequencies into the visible and ultraviolet spectrum allows for extremely high data rates, which is crucial for space communication. This is not related to the speed of travel; the speed of light in a vacuum remains constant. Instead, optical communication can send more data in a fraction of the time compared to radio frequency communication (See Figure 2).

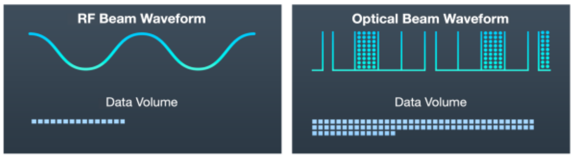

Figure 2 Left: RF Beam Waveform - The RF signal demonstrates a continuous, sinusoidal waveform capable of transmitting a moderate volume of data over time. Right: Optical Beam Waveform - The optical signal is represented with pulsed, high-density data (Source: NASA)

Spectrum Occupying: While RF signals are commonly used for terrestrial data transfer and space exploration, obtaining a license for a unique frequency band that is appropriate for a specific mission can be challenging (Figure 3). However, optical communications use the light spectrum, which is not widely used in terrestrial applications. Additionally, optical communication systems focus on their target, resulting in a narrow beam that is less likely to interfere with other optical communications compared to radio frequencies.

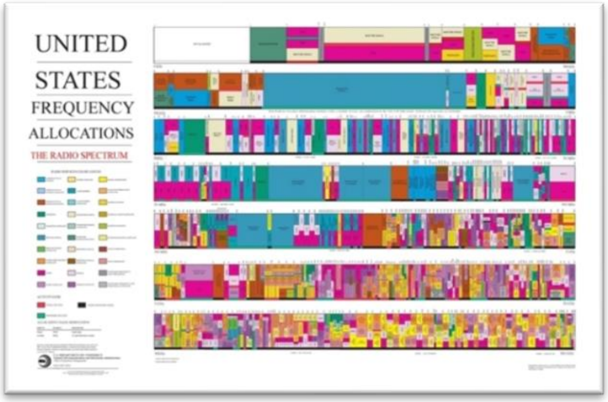

Figure 3 United States Frequency Allocation Chart (National Telecommunications and Information Administration, 2016)

Higher Security: Optical communication can provide a more secure communication environment because it uses a narrow beam of light that does not spread over the atmosphere (Figure 4). The direct line-of-sight communication makes it difficult to intercept or jam without being detected.

Figure 4 RF beam vs Laser beam width comparison (Source: NASA)

Compact and Lightweight Equipment: The use of optical communications eliminates the need for large and heavy antennas, particularly on a spacecraft. This reduction in equipment size and weight is critical for creating more compact and reliable space missions.

However, optical communication also has some challenges. Because of its narrow beam, both communication nodes must maintain a direct line of sight and must be precise enough to hit each other's sensors. Space Communications and Navigation (SCaN) is developing a beacon system to help spacecraft hit their target while establishing an optical connection.

Another challenge is the Earth's atmosphere. Even though it is crucial for life on Earth, clouds and mist can interrupt the laser and cause communication loss between spacecraft and ground stations. Establishing multiple ground stations or locating them at higher altitudes can help ensure more reliable communication. SCaN is currently working on multiple different solutions, such as Delay/Disruption Tolerant Networking (DTN).

Despite these challenges, researchers recognize the potential of high-speed deep space communications and the possibilities for its development. While these benefits are well-known, some space industry organizations have already begun developing their optical communication technologies. NASA is currently working on multiple projects, and despite the experiments only starting in 2013, they have already achieved significant milestones in optical laser communication.

2.3.1 The Lunar Laser Communication Demonstration (LLCD)

The Lunar Laser Communication Demonstration (LLCD) was the first attempt at optical communication as part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. The satellite was launched on September 6, 2013, aboard a Minotaur V spacecraft, and it impacted the Moon on April 14, 2014, as part of the mission (NASA, n.d.). Before the impact, LLCD successfully transmitted optical data to Earth, testing optical communications for the first time. The LLCD mission achieved a downlink speed of 622 Mbps and an uplink speed of 20 Mbps from the Moon to Earth (NASA, n.d.). Achieving such high data transfer rates while occupying less weight and space compared to traditional RF systems was a significant milestone for the space industry.

2.3.2 Deep Space Optical Communications (DSOC)

The Deep Space Optical Communications (DSOC) system is another experimental optical communications attempt, now part of the Psyche spacecraft, which launched on October 13, 2023 (NASA Jet Propulsion Laboratory, n.d.). The primary mission of Psyche is to explore a unique metal-rich asteroid located in the asteroid belt between Mars and Jupiter. During its two-year journey to its destination, Psyche will test DSOC by sending optical signals to the Palomar Observatory's Hale Telescope. Meanwhile, the Optical Communication Telescope Laboratory (OCTL) at NASA's Table Mountain Facility near Wrightwood, California, uses a modulated laser to transmit low-rate data to the transceiver aboard the spacecraft. One of the most popular demonstrations of this mission was the transmission of a 15-second cat video featuring a cat named Taters chasing a laser (See Figure 5). This video was transmitted back to Earth on December 11, 2023, as part of the DSOC mission. It took 101 seconds for the light to travel from 19 million miles (31 million kilometers) to Earth. The transmission used the system's maximum data rate capacity of 267 megabits per second (NASA Jet Propulsion Laboratory, n.d)

Figure 5 A cat is seen in the video 'The Video NASA's Laser Communications Experiment Streamed From Deep Space' (JPLraw, 2024).

2.3.3 Laser Communications Relay Demonstration (LCRD)

Laser Communications Relay Demonstration (LCRD) is an optical communication system that was launched on Satellite-6 (STPSat-6) 7 December 2021 along with the Atlas V rocket (NASA, n.d.). This mission aims to establish high-speed data communication with Earth and the International Space

Station (ISS). It will test areas with different cloud coverage in order to gather data about the robustness and reliability of high-speed optical communications methods in space missions. The data will be transmitted between Table Mountain, California, and Haleakalā, Hawaii, both areas which tend to have variable weather (NASA, 2023). This mission is important because optical systems are up to 100 times faster than radio frequency systems, but they require a line of sight, so obstacles may prevent data transmission. This mission will be pivotal for future missions such as the Artemis program and the Mars Sample Return mission. Furthermore, the LCDR will be used as a relay system, which can improve the effectiveness and speed of communication.

3. Network Architecture

Network protocols are one of the most important components of computer networks. Ensuring robust and reliable data transmission between spacecraft and Earth requires the proper usage and optimization of network protocols. In terrestrial applications, devices must establish an end-to-end communication link between each other. Over the years, the structure of the internet has devolved accordingly. However, this type of connection between spacecraft or planets is not feasible due to their constant movement. The movement of planets and spacecraft makes it harder to track them and establish an end-to-end connection, especially when these devices are obstructed by other celestial bodies. All these almost make the usage of terrestrial network protocols such as TCP or UDP impossible. Specifically, it is impossible to establish an environment that satisfies the TCP's handshake requirement. Due to these reasons, NASA developed Delay Tolerant Networking (RFC 4838) with multiple implementations to establish reliable data transmission for space missions. As can be seen from it is name DTN it has robustness to vast distances and connectivity losses. This networking type uses the store-and-send method to store received data until establishing communication with other destination nodes. Another aspect of DTN is that expired satellites can be used as a DTN node to help overall space networking. This technology is currently in use with the implementation of the Interplanetary Overlay Network (ION).

Currently, rovers like Perseverance and Curiosity are actively continuing their missions, gathering more data each day. To send this data to Earth and receive commands, these rovers utilize multiple communication methods. The Perseverance rover uses an Ultra-High Frequency (UHF) antenna to communicate with Mars orbiters such as the Mars Reconnaissance Orbiter and Odyssey (NASA Science, 2024). The communication speed between the rover and the orbiter can reach up to 2 Mbps, while the orbiter can transmit data to Earth at speeds of up to 6 Mbps, depending on the specific orbiter (NASA Science, 2024; Taylor et al., 2006). Additionally, the Perseverance rover can communicate directly with Earth via its X-band High-Gain Antenna at speeds of 160/500 bits per second to/from a 34-meter diameter Deep Space Network antenna or 800/3000 bits per second to/from a 70-meter diameter Deep Space Network antenna (NASA Science, 2024).

3.1 Communication Architectures

NASA uses three different communication Architecture. They designed for three phases of mars and Earth place arrangement. As can be seen from Figure 6 In Mars's near-term communication architecture rovers. Mars Near-Term Communication Architecture is designed for reasonably high-speed communication and implements X- and Ka- radio frequency technology on each individual orbiter, and the large rovers. The orbiters are the communication hubs which use a moderately high data rate RF backbone link, which in turn connects them to the DSN. The near-term communication architecture on Mars is efficient because the large rovers have a direct communication line to Earth, whilst the smaller rovers do not need these capabilities and are able to be dedicated to collecting the scientific data and communicating with the larger rovers. The smaller vehicles will have a dedicated satellite called the ASI Telesat, which will act as a data relay and ensure that all of the rovers on the surface are able to communicate with Earth through the orbiters. The low-rate proximity networks allow for communications both between the vehicles and the landers and rovers. This intra-planetary communication is necessary to enable the sharing of data between vehicles and to better coordinate the exploration mission plans for each vehicle at a given time, which will allow for better coordination. The orbiters can provide navigation information to the rovers, which will allow for better precision and awareness of surroundings.

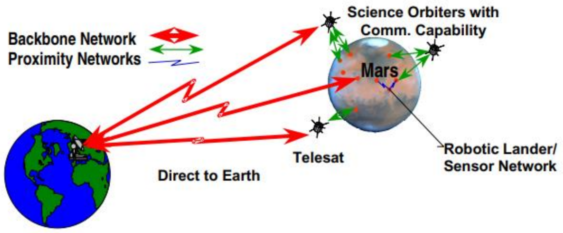

Figure 6 Mars Near-Term Communication Architecture (Source NASA)

On the other hand, the Mars mid-term communication architecture (See Figure 7) is designed for a more long-term usage on Mars and includes a robotic outpost which may be used as the first permanent Mars base. The outpost should be equipped with a network of sensors which will be used to monitor the Martian environment. It will also be used as a central hub for the surface elements, enabling them to communicate more efficiently between one another. There will be a network of micro-satellites the objective of which will be to provide a backbone connection to the DSN through their Ka-band package. Therefore, it will allow for high-speed communication links between the mars vehicles and Earth to be established. Mars Communications Satellites, will be located in the Areosynchronous Mars Orbit, and will ensure that there is a continuous line-of-sight connection possibility between it and the ground elements. It is designed to be a reliable, continuously available, and rapid communication link between Earth and the Robotic Outpost, as well as other devices on the surface of Mars. Furthermore, there will be additional relay stations added on the orbit of the Earth to use high-frequency radio waves or optical communication and to reduce bottlenecks and increase data throughput.

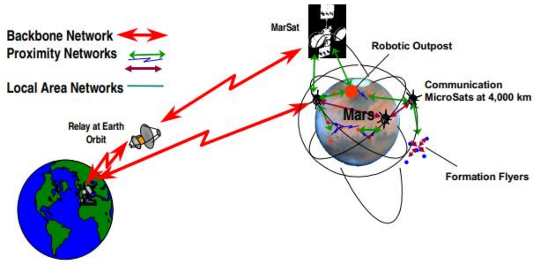

Figure 7 Mars Mid-Term Communication Architecture (Source NASA)

Mars far-term communication architecture (See Figure 8) is the most complex stage, which is intended to facilitate Human Exploration and Development of Space (HEDS). It features high-speed and high-availability communication, and transforms the one-way data transmission into two-way data transmission, and will support more complex data types including video and voice formats to enable for more natural and effective communication with humans. The architecture must fulfill the communication needs of astronauts in complex scenarios, such as those featuring telemedicine. Local Area Networks (LANs) must be established within certain areas to allow for communication between astronauts and technology such as robotic systems. An Interplanetary Internet (IPN) Hub will be established as a central node for all deep space missions and it will have the capability to relay data between spacecrafts. The relay stations will be placed on the Lagrangian points, which are points where the gravitational forces and the motion of the satellite will cancel each other to allow the satellite to remain in a stable position with as little fuel as possible. Moreover, the relay stations will ensure continuous communication, even during solar conjunctions. This will be essential for creating the network backbone for the intra-solar system communication network. Mars Communications Satellites must be placed in Areosynchronous Mars Orbit (AMO) to ensure communication consistency and to tolerate higher data rates. They will be able to communicate directly with either Earth or its relay satellites. Furthermore, supplementary relay stations will be established on the Earth orbit, which will use optical communication methods to improve the DSN.

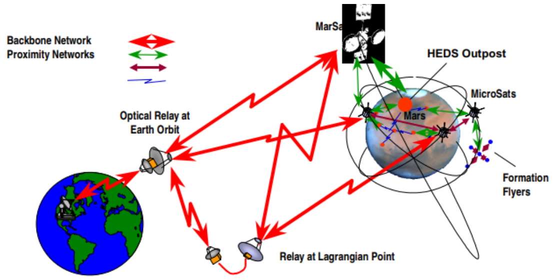

Figure 8 Mars Far-Term Communication Architecture (Source NASA)

4. The Challenges of Establishing Adequate Networks on Mars

4.1 Radiation

Radiation on mars presents a serious concern for technology, as the planet's thin atmosphere offers inadequate shielding, and without Earth's protective magnetosphere, objects on Mars can experience radiation doses up to "700 times higher than on our planet” (The European Space Agency, 2019). Radiation can cause significant damage to technology through various ways including but not limited to Single Event Effects (SEE), the Total Ionizing Dose (TID), and Electromagnetic Interference (EMI). SEEs have many possible variations and are a result of charged particles colliding with an electronic component. Protons coming from solar flares are an example of a charged particle which may result in an SEE. According to a recent article published by NASA’s Jet Propulsion Laboratory, the Sun experiences an 11-year cycle during which solar activity peaks, unleashing higher levels of radiation. As NASA explains, “During solar maximum, the Sun is especially prone to throwing fiery tantrums in a variety of forms — including solar flares and coronal mass ejections — that launch radiation deep into space." The year 2024 marks the next phase of solar maximum, expected to be one of the most intense periods for solar radiation. This year, researchers are planning to intensively study radiation conditions on Mars during this peak, which will provide valuable insights into the planet's most extreme conditions. This research is critical for preparing the protective measures and technology that astronauts will need for future missions to Mars. Understanding the risks during the solar maximum will be a key factor in ensuring the safety of astronauts as we venture further into deep space.

In terms of technology, there is a growing emphasis on using software fault-tolerance techniques to enable commodity hardware to achieve radiation resilience comparable to, or nearly as effective as, expensive radiation-hardened hardware.

To address this challenge, Wang et al. (2023) proposed focusing on two critical issues: hardware overheating and silent data corruption.

Cosmic rays, solar radiation, and trapped particles can introduce errors in chips, as most modern commodity chips are not designed with radiation hardening. Several factors, including chip shielding, materials used in the die, and the type of ionizing radiation in the environment, influence the likelihood of radiation errors.

On Earth, most radiation is absorbed or deflected by the atmosphere and magnetic field, so radiation hardening is generally not a concern for terrestrial computers, though occasional errors from cosmic rays or solar events do occur. In contrast, satellites in orbit, with less atmospheric protection, are more vulnerable to radiation, especially from trapped protons. Beyond Earth's orbit, computers face an inordinate radiation exposure and require protection from cosmic rays and solar radiation.

High-energy charged particles can cause a single-event latch-up (SEL), a fault that acts like a short circuit in the device. SELs generate excessive heat, which cannot dissipate in space, potentially destroying the chip in minutes. While this can be resolved by power cycling the device, detecting SELs in time is challenging and has led to the loss of many commercial SmallSats (Wang et al., 2023). Moreover, detecting SELs based on the current draw is problematic, as modern CPUs exhibit significant current variations. Therefore, using system-level metrics like CPU utilization or memory bandwidth can offer better insights into the SEL detection process. Single-event upsets (SEUs) are temporary changes in a circuit's logic state caused by ionizing radiation, often leading to a bit flip or spurious signal in the compute pipeline. SEUs can affect different parts of the system, potentially causing silent data corruption, crashes, or other errors. For non-hardened spacecraft computers, components like the compute pipeline, cache, and main memory are the most vulnerable. While some memory, like flash chips, includes error correction (ECC) to handle SEUs, other components lack such mechanisms (Wang et al., 2023). The key observation is that fine-grained program behaviors, like control and data flow, can be used to detect SEUs. This approach introduces a tunable form of dual modular redundancy (DMR), which ensures control and data flow integrity with various trade-offs between overhead and accuracy. A software-based memory ECC mechanism running on underused accelerators also protects in-memory data. These methods offer significant protection with lower overhead than current state-of-the-art solutions.

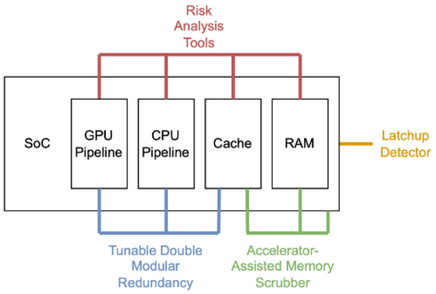

Figure 9 (Wang et al., 2023) illustrates the components of the processor protected by each suggested system

The figure above, as emphasized by Wang et al. (2023), illustrates how these proposed software-based methods protect different processor components. As low-Earth orbit (LEO) satellite operators increasingly adopt low-cost commodity computers, which are vulnerable to radiation errors, the proposed system offers a means of mitigating and detecting those errors. This system is being tested both on Earth and in space.

4.2 Propagation

The atmosphere on Mars consists of 95.32% carbon dioxide, 2.7% nitrogen, 1.6% argon, is significantly dusty, and includes trace amounts of other gases such as oxygen, water, methane, and carbon monoxide (Dobrijevic et al., 2023; Mars Space Flight Facility, n.d.). Compared to the Earth's atmosphere, the Martian atmosphere is thin, and has 100 times less atmospheric pressure than Earth (European Space Agency, n.d.)

The most common place where signal degradation could occur in the Martian atmosphere is the troposphere and like signal propagation on Earth, signals which are propagated on Mars experience attenuation, absorption, scattering, and other such phenomena. There are multiple types of signal attenuation, some of which are ray bending, fading, depolarization, and frequency broadening (NASA Jet Propulsion Laboratory, 2004).

Attenuation of radio waves on Mars is dependent on the conditions in its troposphere, such as dust and aerosols, however, because of the aforementioned thinness of the Martian atmosphere, the impact of signal attenuation on propagation is much less impactful than on Earth, and the average refractive index of the dust on Mars during dust storms is only around 1.59 plus or minus 0.01 (Dollfus et al., 1974). On Earth, the dry air refractive index at 1 atm and 0 degrees Celsius is on average 288.0, and the refractive index of the troposphere on Mars is approximately “two orders of magnitude smaller than that of Earth” (Bean & Dutton, 1968; NASA Jet Propulsion Laboratory, 2004). These figures are important because the difference between the refractive indexes of the troposphere on Earth and on Mars cause less bending of radio waves on Mars as opposed to Earth. Furthermore, this decreases the multipath effects of radio waves on Mars, as the waves are not as frequently scattered, trapped in atmospheric ducts, or bent (NASA Jet Propulsion Laboratory, 2004). However, the multipath effect is still significant in rocky or hilly environments, because these rough surfaces cause radio wave reflections, which causes greater signal degradation (around 2-8 dB for L-band, and losses increase with higher frequencies) (NASA Jet Propulsion Laboratory, 2004).

Moreover, there are modest attenuation losses due to the fog, dust, and clouds, which is roughly equivalent to a thin cloud cover on Earth, since the weather on Mars on average is much clearer than that on Earth (Annis, 1987). Scintillation is another phenomenon that can distort radio waves, and it occurs because of the change in refractive index as a result of atmospheric turbulence, which causes fluctuations in amplitude and phase of the radio waves (Annis, 1987). The aerosol dust on Mars causes Mie scattering, but at higher angles (Mie scattering is associated with a large amount of forward scattering).

The main propagation issues between Mars and Earth stem from the free space loss, as the minimum distance between Earth and Mars is 55 million km, whilst the maximum distance is 400 million km (NASA Jet Propulsion Laboratory, 2004). In summary, the tropospheric losses on Mars at Ka-band range from 1.4 to 2 dB on Mars and 5 dB on Earth (NASA Jet Propulsion Laboratory, 2004).

5. Results/Discussion

Our study analyzed various network topologies, data transmission methods, and successful Mars-to-Earth communication missions. This analysis provides a clear understanding of the possibilities for establishing effective communication networks both on the surface of Mars and between Mars and Earth.

5.1 Mars Surface Network

The similarities between Mars and Earth suggest that by overcoming Mars-specific challenges, such as radiation and dust storms, terrestrial-like networking can be established on Mars. By deploying dedicated network devices designed to withstand strong radiation and harsh conditions, we can create a resilient Mars surface network. Sending dedicated network nodes and data servers will enable efficient communication between Martian devices and orbiters, or even directly to Earth. This would allow for smaller, more energy-efficient communication devices to be used on Martian rovers and other equipment, significantly reducing their mass and providing room for enhancements in other onboard systems.

The resemblance between Earth and Mars also means that we could potentially apply network topologies and protocols currently used on Earth, such as TCP, UDP, or IP, with certain modifications. This would allow network devices to communicate with each other or store data for future transmission. In more advanced scenarios, establishing dedicated Mars laboratories with networking infrastructure would allow rovers and humans to thoroughly analyze Martian samples in situ, without the need to return them to Earth.

Although challenges remain, such as adapting protocols for Martian conditions and ensuring communication resilience during dust storms, we believe that establishing a seamless, reliable, and fast network on Mars would revolutionize scientific research and planetary exploration.

5.2 Mars to Earth Communication

Current Mars-to-Earth communication technologies can be utilized for future missions as well. Over time, advancements in optical laser communication will enable faster and more secure communication.

6. Conclusions

In the future, if humanity establishes a permanent presence on Mars or if the number of surface vehicles increases, the need for a robust and permanent intra-planetary network will grow significantly. The main goal of this paper is to analyze current communication technologies and propose methods for implementing communication systems on Mars. This paper explores potential Mars surface networks to support future technological advancements, such as the deployment of more advanced devices or the eventual colonization of Mars. Due to the similarities between Earth and Mars, terrestrial-style networking equipment could be used on Mars with enhancements to withstand the harsh Martian environment and ionizing radiation. These devices could include servers and network nodes that enable communication between Martian devices while allowing rovers and other equipment to avoid using large, power-hungry communication devices to transmit directly to Earth or orbiters. Smaller, less powerful network nodes would be sufficient for communication, using nodes already established on Mars to relay data to Earth. Establishing dedicated laboratories on Mars would allow scientists to analyze Martian samples on-site, reducing the need to return them to Earth. For internal communication, terrestrial networking protocols like TCP, UDP, or IP can be adapted for use on Mars.

For Mars-to-Earth communication, current technologies are sufficient, but as optical communication technology advances, it will enable faster and more secure communication. Despite these potential benefits, challenges such as ionizing radiation and dust storms need to be addressed. With proper shielding and coverage, these obstacles can be overcome. Implementing these technologies will enable more extensive planetary exploration, benefiting humanity by expanding our knowledge and presence beyond Earth.

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References

[1] Bean, B. R., & Dutton, E. J. (1968). Radio meteorology (Dover books on electronics and related areas). Dover Publications.

[2] Bhasin, K., Hayden, J., Agre, J. R., Clare, L. P., & Yan, T.-Y. (2001). *Advanced communication and networking technologies for Mars exploration* (NASA Technical Memorandum No. 20010091011). National Aeronautics and Space Administration.
https://ntrs.nasa.gov/api/citations/20010091011/downloads/20010091011.pdf

[3] Brady, J., & Brady, J. (2023, January 24). What the aliens will find of us when we're gone, and why we should colonize Mars. The Michigan Daily. https://michigandaily.com/opinion/what-the-aliens-will-find-of-us-when-were-gone-and-why-we-should-colonize-mars/

[4] Catalog page for PIA26146. (n.d.). https://photojournal.jpl.nasa.gov/catalog/PIA26146

[5] Dartnell, L. (n.d.). How astronauts can hide from radiation on Mars. BBC Sky at Night Magazine.
https://www.skyatnightmagazine.com/space-missions/astronauts-hide-radiation-mars

[6] Dobrijevic, D., Howell, E., & Sharp, T. (2023, September 17). *Mars' atmosphere: Facts about composition and climate*. Space.com. https://www.space.com/16903-mars-atmosphere-climate-weather.html

[7] Dollfus, A., Dlugach, Z. M., Morozhenko, A. V., & Ianovitskii, E. G. (1974). Optical properties of the atmosphere and surface of Mars. II. The dust storm. Astronomicheskii Vestnik, 8(Oct.-Dec.), 211-222.

[8] Facts about Mars. (n.d.).
https://www.esa.int/Science_Exploration/Space_Science/Mars_Express/Facts_about_Mars

[9] Frazier, S. (2023, July 25). Real Martians: How to Protect Astronauts from Space Radiation on Mars - NASA. NASA. https://www.nasa.gov/science-research/heliophysics/real-martians-how-to-protect-astronauts-from-space-radiation-on-mars/#:~:text=The%20risk%20of%20health%20effects,habitat%3B%20and%20ensuring%20that%20astronauts

[10] Gayon, P. (2023). Exploring the Red Frontier: The benefits and challenges of colonizing Mars. *ResearchGate*. https://www.researchgate.net/publication/371718315_Exploring_the_Red_Frontier_The_Benefits_and_Challenges_of_Colonizing_Mars

[11] *How solar storms this year will help Mars astronauts in the future (MArs Report - April 2024)*. (n.d.). NASA Jet Propulsion Laboratory (JPL). https://www.jpl.nasa.gov/videos/how-solar-storms-this-year-will-help-mars-astronauts-in-the-future-mars-report-april-2024/

[12] International Telecommunication Union. (2009). Factors affecting the choice of frequency bands for space research service deep-space (space-to-Earth) telecommunication links (Report ITU-R SA.2167). https://www.itu.int/en/publ/

[13] JPLraw [Screen name]. (2024, January 5). The Video NASA's Laser Communications Experiment Streamed From Deep Space [Video]. YouTube. Retrieved February 15, 2024, from https://www.youtube.com/watch?v=GvJtVOmFs5Q

[14] Levine, J. S., & SchildRudy. (2011, January 1). *Humans to Mars: The greatest adventure in human history*. NASA Technical Reports Server (NTRS). https://ntrs.nasa.gov/citations/20110004142

[15] Levchenko, I., Xu, S., Mazouffre, S., Keidar, M., & Bazaka, K. (2018). Mars colonization: Beyond getting there. *Global Challenges, 3*(1). https://doi.org/10.1002/gch2.201800062

[16] Mars Education | Developing the next generation of explorers. (n.d.). https://marsed.asu.edu/mep/atmosphere#:~:text=Mars' atmosphere however is 95,on Mars is extremely thin

[17] McCarthy, B. J. (2024, March 12). For first time, majority in U.S. backs human mission to Mars. Gallup.com. https://news.gallup.com/poll/260543/first-time-majority-backs-human-mission-mars.aspx

[18] NASA Jet Propulsion Laboratory. (2004). Mars exploration: Atmospheric effects on propagation. https://descanso.jpl.nasa.gov/propagation/mars/MarsPub_sec3.pdf

[19] NASA Jet Propulsion Laboratory. (n.d.). Explaining the first ultra-HD video sent from deep space via laser (PIA26146). https://photojournal.jpl.nasa.gov/catalog/PIA26146

[20] NASA Photojournal. (2023, December). Catalog Page for PIA26146. Retrieved from https://photojournal.jpl.nasa.gov/catalog/PIA26146

[21] NASA. (n.d.). Laser Communications Relay Demonstration (LCRD) overview. NASA. https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/laser-communications-relay-demonstration-lcrd-overview/

[22] NASA. (2023, November 7). NASA's Laser Communications Relay: A year of experimentation. NASA. https://www.nasa.gov/missions/tech-demonstration/nasas-laser-communications-relay-a-year-of-experimentation/

[23] NASA. (n.d.). Lunar Laser Communications Demonstration (LLCD). NASA. https://www.nasa.gov/mission/lunar-laser-communications-demonstration-llcd/

[24] NASA Jet Propulsion Laboratory. (n.d.). Psyche mission. NASA. https://www.jpl.nasa.gov/missions/psyche/

[25] National Space Society. (2023, November 23). The Case for Colonizing Mars, by Robert Zubrin. NSS. https://nss.org/the-case-for-colonizing-mars-by-robert-zubrin/

[26] Perseverance Rover Components - NASA Science. (n.d.). https://science.nasa.gov/mission/mars-2020-perseverance/rover-components

[27] Puumala, M. M., Sivula, O., & Lehto, K. (2023). Moving to Mars: The feasibility and desirability of Mars settlements. *Space Policy*, *66*, 101590. https://doi.org/10.1016/j.spacepol.2023.101590

[28] Schauer, K. (2023, July 26). Data rate increase on the International Space Station supports future exploration - NASA. NASA. https://www.nasa.gov/missions/station/data-rate-increase-on-the-international-space-station-supports-future-exploration/

[29] Single Event effects. (n.d.). https://radhome.gsfc.nasa.gov/radhome/see.htm

[30] Taylor, J., Lee, K., & Shambayati, S. (2006). Article 12 Mars Reconnaissance Orbiter Telecommunications. In jpl.nasa.gov (No. 12). National Aeronautics and Space Administration. https://descanso.jpl.nasa.gov/DPSummary/MRO_092106.pdf

[31] The European Space Agency. (2019, May 31). The radiation showstopper for Mars exploration. Esa. https://esa.int/Science_Exploration/Human_and_Robotic_Exploration/The_radiation_showstopper_for_Mars_exploration

[32] United States Frequency Allocation Chart | National Telecommunications and Information Administration. (n.d.). https://www.ntia.gov/page/united-states-frequency-allocation-chart

[33] https://parts.jpl.nasa.gov. (n.d.). Component Engineering & Assurance. Component Engineering & Assurance. https://parts.jpl.nasa.gov/

[34]Wang, H., Myint, S., Verma, V., Winetraub, Y., Yang, J., & Cidon, A. (2023). Mars Attacks! *ACM*, *12413*, 245–253. https://doi.org/10.1145/3626111.3628199