# Path Loss Analysis of Terahertz Communication in Mars' Atmospheric Conditions

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***Abstract*—There has been much focus on the potential for wireless links that use THz frequencies. Despite their theoretical advantages, the very high channel path loss here on Earth presents practical challenges. This paper compares the path loss performance of THz links in atmospheric gas compositions and environmental conditions on Mars and Earth. Simulations using data from the Mars Climate Database and HITRAN indicate that conditions on Mars ensure that path loss between surface-based transceivers is reduced compared to Earth. Greater effective transmission distances for THz can be achieved on Mars: at frequencies of 1.67 THz and 1.64 THz, the transmission distance is 60–70 times longer than Earth. However, severe dust storms that are common on Mars can increase path loss, so the maximum transmission distance reduces by 1–2 orders of magnitude during such storms. Some of this additional path loss can be reduced by raising antennas higher above the ground and by configuring antennas to suit different usage scenarios.**

***Index Terms*—Terahertz communication, Path Loss Analysis, Mars Wireless Communication.**

## I. Introduction

Explorations is a quest that has enabled humans to survive through generations and has led to the discovery and human habitation in diverse conditions across all continents. As part of this quest, space exploration is a new leap for humanity to understand our solar system and provides unique opportunities to obtain scarce resources on Earth and new sites for humans to inhabit. Recent decades have seen increased exploration of Mars to further our understanding of this rocky planet and its environmental conditions. NASA estimates that flights to Mars will take about 7 months to traverse the minimum 480 million kilometers between Earth and Mars. With round-trips taking over a year, it makes sense for humans to set up bases on Mars and develop the means to become self-sufficient. This will take many years to achieve and require the phased deployment of resources (over many trips from Earth, bootstrapping with resources collected from Mars itself). The goal is to build self-sustaining communities and infrastructures on Mars, with sufficient scale and scope to thrive with minimal input from Earth. In that regard, Mars might even act as a proving ground for future interplanetary or interstellar missions.

The early exploration missions to Mars have seen several countries sending robotic rovers to the planet. Three robotic rovers are currently active on the surface of Mars. This includes *Curiosity* and *Perseverance* (NASA), and *Zhurong* (National Space Agency, China). Both *Curiosity* and *Perseverance* communicate with Earth using UHF (400 MHz) and X-band (8-12 GHz) low and high-gain antennas. Communications have been to and from Earth-based stations, either directly or via satellite-based relays, and *Perseverance* also communicates with its helicopter in an ad hoc fashion.

Conditions on the surface of Mars are hostile to human life, where radiation levels are higher, and the atmospheric gas composition is quite different from that found on Earth (see Table I). Humans will likely spend most of their time in the safer, more Earth-like environments of Mars surface vehicles and the *habitats* that are proposed to be built. In such circumstances, reliable communication over high data rate, low latency wireless links within and between *habitats* as well as other infrastructures (e.g., UAVs, rovers) will be essential. As is the case on Earth, a combination of short-range and long-range communication links need to be considered.

To the best of our knowledge, very few research publications consider the provision of wireless communication on the surface of Mars. Sacchi *et al.* [1] describe bidirectional mobile communication using Long Term Evolution on Mars (LTE-M) on the Martian surface between landers and rovers for short distances (50m). Bonafini *et al.* [2] extends this work and compares the communication between two Martian landing sites with separation distances 100m and 1000m. Daga *et al.* [3] showed that utilizing antennas with few tens of milliwatts of radiated power and antenna heights within 1 to 2m, IEEE 802.11a can have excellent PHY performance in terms of bit error rate and packet error rate for distances up to a few hundred meters on Mars.

Terahertz (THz)-based communication links will play an essential role in a future Martian planetary network [4], even in use cases where THz communication links would not be considered viable on Earth. The THz spectrum is generally agreed to extend from about 300 GHz (0.3 THz) to 10 THz and had been relatively neglected until recently, probably owing to the lack of sufficient sources and detectors. THz communication has been investigated for wireless communication purposes because a) the spectrum is relatively unused, b) its higher frequencies offer increased bandwidth even compared to mmWave, and c) its shorter wavelengths mean that antennas and other devices for THz communication can be miniaturized. However, the adoption of THz communication is held back by many Physical Layer concerns, such as low energy conversion



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| Gas | Composition on Earth | Composition on Mars |
|---|---|---|
| $N_2$ | 78.084% | 2.7% |
| $O_2$ | 20.946% | 0.13% |
| Ar | 0.93% | 1.6% |
| $H_2O$ | 1-3% | 100-400$ppm$ |
| $CO_2$ | 0.003% | 95.32% |
| $CH_4$ | 1.5$ppm$ | - |
| $SO_2$ | 1$ppm$ | - |
| $O_3$ | 0.05$ppm$ | 0.1$ppm$ |
| $N_2O$ | 0.02$ppm$ | - |
| CO | 0.01$ppm$ | 0.08% |
| $NH_3$ | 0.01$ppm$ | - |
| NO | - | 100$ppm$ |

TABLE I: Atmospheric gas composition comparison between Earth and Mars [6]; ppm is a concentration of parts per million.

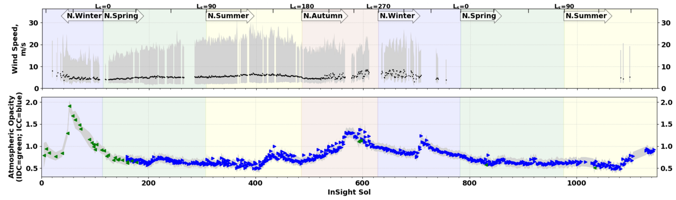


Fig. 1: The seasonal change of wind speed and atmospheric opacity at the InSight landing site. The black line shows the daily average wind speed in meters per second at the InSight site. The green triangles are measurements of opacity taken by the Instrument Deployment Camera (IDC) on the robotic arm. Blue triangles are measurements made with the Instrument Context Camera (ICC), mounted below InSight's top deck. *Image credit: NASA/JPL-Caltech/Cornell/CAB* [7].

efficiency at the THz transceivers and the fact that molecular absorption (e.g., water vapor and many common materials such as building structures) can block THz signals. At the Physical Layer, researchers have improved device efficiency [5]. They have also developed improved high-gain antennas with narrow beams to focus the energy to increase the received signal strength. The goal is that signal-to-noise ratio remains acceptable as channel distance increases. Moreover, THz-based communication experiments are difficult on Earth due to highly absorbing gases (especially water) in the atmosphere. However, researchers could readily perform such experiments on Mars due to its thin atmosphere. Therefore, integrating THz into wireless communications on Mars will significantly benefit people on Mars and science on Earth.

The contributions of this paper are

1) Path Loss simulations based on Mars climate conditions indicate effective THz transmission distances on Mars are typically 60–70 times those on Earth;
2) An extended Path Loss expression (11) for Mars that includes attenuation due to dust storms (which are frequent on Mars but rare on Earth);
3) Antenna configuration supporting both trunk and "edge" networking scenarios, motivated by raising antennas above the most dense dust distribution during storms.

This paper is arranged as follows. Section II describes the atmospheric composition on Mars and how the Martian surface has many dust and sand storms. Section III describes our propagation model for the THz band on Mars. The impacts of these conditions on THz communication links, both favorable and unfavorable, are discussed in Section IV compared to how THz communication links operate on Earth. Section V presents the maximum transmission distance measurements in different settings on Mars and Earth. Section VI concludes the paper.

## II. Mars Environmental Conditions

Our study investigates THz link attenuation caused by spreading and molecular absorption loss due to the atmospheric gas composition and the wide-area dust storms commonly found on Mars. Significant differences in the molecular absorption loss compared to conditions on Earth will significantly impact the THz signal path loss. For instance, the Martian atmosphere is considerably thinner than Earth, and its gas composition differs dramatically from Earth (see Table I). At the same time, the pressure and temperature are significantly lower compared with those on Earth. For example, Martian mean atmospheric pressure is 0.6% that of mean atmospheric pressure on Earth (101.325 kPa), and its mean temperature is $210K$ compared to $289K$ on Earth [6]. Lower temperatures (due to a lower noise floor) and pressures (due to lower absorption) increase performance, see Table II.

Moreover, Mars' atmosphere is significantly drier due to the low water vapor concentration. Given the relatively high horizontal and vertical wind speeds [8] on Mars, the dry atmosphere and the dusty landscape, sand and dust storms are relatively common on Mars. Dust storms on Mars can be local, regional and global, are more frequent in summer, and last hours, days and months, respectively. In addition, atmospheric opacity indirectly measures the severity of dust storms as the ratio of how much sunlight is blocked by dust in the atmosphere before it reaches the ground. Fig.1 presents atmospheric opacity and wind speed measurements at the InSight landing site (near the equator of Mars) in each Martian sol throughout the InSight mission. Furthermore, the radius of dust particles in storms varies from 0.5 - 4 microns [9], and dust density has a massive impact on visibility on Mars. Moreover, the particle size density varies with height because particles with larger radius, hence larger mass, are more likely to fall to the ground if the wind speed is constant. The average wind speed on the Martian surface is low compared to Earth, but is enough to make wind turbulence, and Fig. 6 shows how increasing wind speed helps create a dusty atmosphere.

## III. THz Propagation on Mars

Similar to the conditions on Earth, THz band Electro-Magnetic (EM) waves propagation in the Martian atmosphere is affected by spreading and molecular absorption losses due to gases listed in Table I. Additionally, the THz link attenuation mechanism includes additional scattering and absorption due to dust storms on Mars. These additional losses in the Martian atmosphere are briefly discussed below.

*1) Spreading Loss:* The spreading loss measures the fraction of power that a receiver can not detect when transmitting a frequency $f$ by a transmitter in the distance $d$. Since spreading loss depends only on frequency and distance, spreading loss



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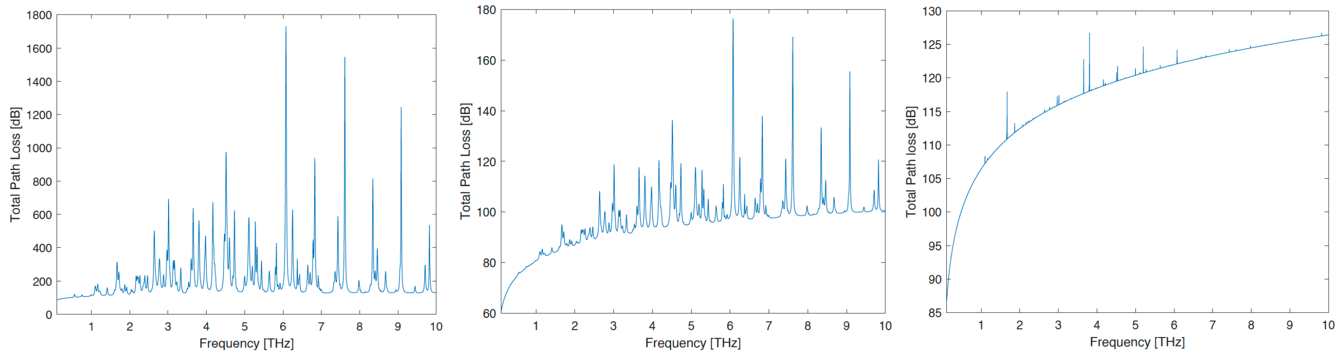


(a) On Earth at a 5m distance. (b) On Earth at a 25cm distance. (c) On Mars at a 5m distance.

Fig. 2: Comparison of Earth and Mars total path loss only considering spreading and molecular absorption losses in 0.1 to 10 THz frequency range. Figure a) and b) illustrates the total path loss on Earth when the distance between the transmitter and the receiver is 5m and 25cm. Figure c) demonstrates the total path loss on Mars when the distance between the transmitter and the receiver is 5m. Note that the total path loss scale is vastly different between Fig.2 (a) and Fig.2 (c).

[10] on Mars can be measured similarly to Earth and is represented as follows

$$PL_{spr} = \left(\frac{4\pi df}{c}\right)^2, \quad (1)$$

where $c$ is the speed of light in the medium.

*2) Molecular Absorption Loss*: The molecular absorption loss measures the fraction of power loss converted to kinetic energy due to molecular vibration when EM waves propagate through the atmospheric molecules. Thus, when transmitting frequency $f$ through a homogeneous medium between a transmitter and receiver at a distance $d$, the molecular absorption loss obtain with the help of Beer-Lambert law is represented in [10] as,

$$PL_{abs} = e^{k(f)d}, \quad (2)$$

where $k(f) = \sum_{i,g} k_g^i(f)$ and $k_g^i(f)$ is the monochromatic absorption coefficient of the $i^{th}$ isotopologue of $g^{th}$ gas at frequency $f$. The monochromatic absorption coefficient for each isotopologue of a particular gas in the Martian atmosphere at frequency $f$ is given by [11],

$$k_g^i(f) = S_g^i(T)F^i(f), \quad (3)$$

where $S_g^i(T)$ is the line intensity at Martian temperature $T$ (210K) reference to the temperature 296K of the $i^{th}$ isotopologue of $g^{th}$ gas, which can be easily calculated using the high-resolution transmission (HITRAN) molecular spectroscopic data and $F^i$ is the spectral line shape function at frequency $f$. Since Doppler-broadening dominates the line shape in low-pressure environments such as Martian environment, a Gaussian profile can be assumed as the line shape function and it is given by [11],

$$F_G^i(f) = \sqrt{\frac{\ln 2}{\pi {\alpha_D^i}^2}} \exp\left(-\frac{(f - f_g^i)^2 \ln 2}{{\alpha_D^i}^2}\right), \quad (4)$$

where $f_g^i$ is the resonant frequency for the isotopologue $i$ of gas $g$ and $\alpha_D^i$ is the Doppler broadening half-width,

$$\alpha_D^i = \frac{f_g^i}{c}\sqrt{\frac{2N_A k_B T \ln 2}{M^i}}, \quad (5)$$

where $M^i$ is the molar mass of isotopologues which can be obtained from the HITRAN database [11], and $N_A$ and $k_B$ are the Avogadro and Boltzmann constants.

*3) Attenuation due to Dust Storms:* Here we assume degradation of THz link budget upon propagation through the dust particles, causing additional absorption and scattering losses. Therefore, the extinction or total cross-section efficiency of the dust particles given by,

$$\sigma_{ext}(\epsilon, r, f) = \sigma_{abs}(\epsilon, r, f) + \sigma_{sca}(\epsilon, r, f), \quad (6)$$

where $\sigma_{abs}(\epsilon, r, f)$ and $\sigma_{sca}(\epsilon, r, f)$ are the absorption and scattering cross-sections, and $\sigma_{ext}(\epsilon, r, f)$ is expressed by *Mie* solution for a spherical particles with dielectric constant $\epsilon$ [12]. We can take the complex refractive index of dust particles on Mars as $1.52 + 0.01i$ [6]. Therefore, the attenuation of THz waves in a dust environment on Mars due to particle with radius $r$ can be expressed as [13],

$$PL_{ds} = 4.343d \times 10^{-6} \int_0^{2r_{max}} N\sigma_{ext}(r, f)P(r)dr, \quad (7)$$

where $d$ is the distance between the transmitter and receiver, $N$ is the number of dust particles in a unit volume, $r_{max}$ is the maximum radius of the dust particles, $P(r)$ is the dust particle size distribution. Dust density in the Martian atmosphere can be defined through the particle size distribution and it takes the form of a log normal distribution as [14], [15]:

$$P(r) = \frac{1}{2r\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln(2r) - \mu)^2}{2\sigma^2}\right], \quad (8)$$

where $\mu$ and $\sigma$ is the mean and standard deviation of $\ln(2r)$. The density of dust particles in the Martian atmosphere is expressed as:

$$N = \frac{15}{3.4744V_b \times 10^{-2} \int_0^{2r_{max}} \pi r^2 P(r)dr}, \quad (9)$$

where $V_b$ is the visibility parameter that models the density of the dust particles in the channel, where low visibility is associated with high dust particle density, hence more


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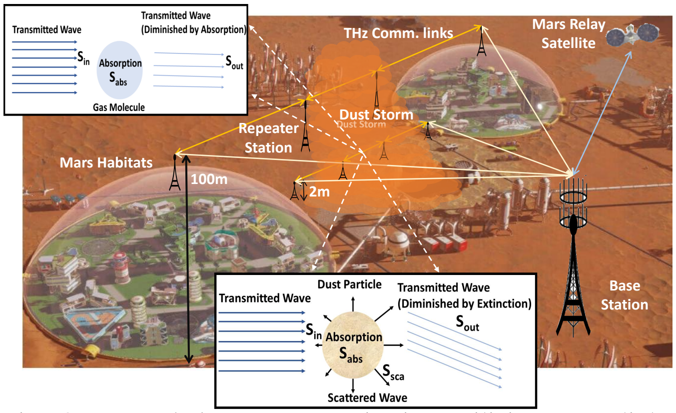



Fig. 3: Mars *habitats* communicating utilizing THz links through dust storms using antennas with 2m and 100m heights.

attenuation of EM waves [16], [17]. Moreover, [18] explains the relationship between dust particle concentration and wind speed. Therefore the relationship between the wind speed ($u$) and visibility is given by,

$$V_{b<3500m}[m] = \frac{323127.4}{\exp\left(0.7u\right)^{(25/21)}}. \tag{10}$$

The Mars Climate Database (MCD) v5.3 [19] can be utilized to generate wind speeds for a specific day on Mars with dust storms under average solar radiation for a given altitude.

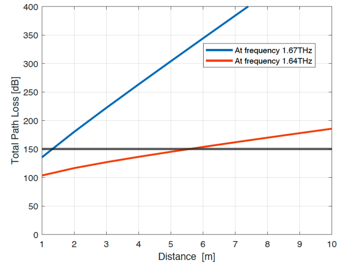
Therefore, the Total Path Loss ($PL_T$) of a THz wave in the Martian atmosphere can be determined by summing the spreading loss, molecular absorption loss, as well as attenuation due to dust storms, which is represented as

$$PL_T[dB] = 10\log(PL_{spr}) + 10\log\left(PL_{abs}\right) + 10\log\left(PL_{ds}\right). \tag{11}$$

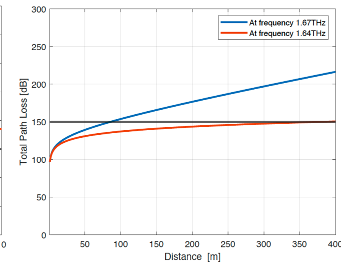
## IV. Comparison of Total Path Loss on Earth and Mars

Total THz link budget degradation due to losses on Earth and Mars is dramatically different. The spreading loss term depends only on the transmitting frequency and the distance between the transmitter and the receiver and so is unaffected by environmental conditions. Water vapor greatly increases molecular absorption loss on Earth. We consider water vapor and nine other gases for Earth and six gases for Mars, see Table I (except for Argon), considering the vastly different gas concentrations between the two planets. Also, THz wave attenuation caused by dust or sand in the channel needs to be regarded as a vital factor when trying to establish a point-to-point communication between the *habitats* on Mars because such storms are relatively frequent and long-lasting. By contrast, dust storms are relatively rare on Earth and rarely feature in the THz path loss models.

Therefore, in one scenario, we compare the total path loss between Earth and Mars on a day without dust storms, across the frequency range of 0.1 THz to 10 THz. According to Fig. 2, the total path loss on Earth at 5m distance varies approximately 100 dB to 1750 dB, and at 25cm distance, it varies between 60 dB to 180 dB. However, the total path loss varies between around 85 dB to 130 dB on Mars at a 5m distance. Moreover, the total path loss on Earth is significantly higher than on Mars at a 5m distance because of high molecular absorption of atmospheric gases, especially water vapor, on Earth. Notably, the total path loss on Earth at a 25cm distance is estimated as approximately equal to the total path loss on Mars at a distance of 5m. Therefore, we expect longer communication distances on Mars than Earth, as we discuss next.




(a) On Earth.




(b) On Mars.

Fig. 4: Distance comparison of total path loss variation in 1.67 THz and 1.64 THz frequencies a) on Earth and b) on Mars.

## V. Maximum Transmission Distance Analysis

To compare transmission distance on Mars with that on Earth, we selected two frequencies, 1.67 THz and 1.64 THz, associated with very high and very low molecular absorption, respectively, for typical conditions on *both Mars and Earth*. Molecular absorption loss measurements at these frequencies on Earth are significantly higher than on Mars. The maximum effective transmission distance depends on the maximum path loss (MPL) permitted for the communication link. Therefore, we defined a threshold value for the MPL using the following relationship,

$$\text{MPL} = \text{MCL} + \text{Tx Gain} + \text{Rx Gain}, \tag{12}$$

where Maximum Coupling Loss (MCL) measures the coverage a system or design can support. In the absence of a widely accepted MCL for THz comms, we use the equivalent MCL for 5G comms, which is 130 dB [20]. We assume that MCL for THz communication links is 120 dB and, in the near future, antenna gains of 15 dB at each end will become available for transmission on Earth and Mars. Thus, according to equation 12, MPL will be 150 dB. The horizontal lines in Fig.4, Fig.5 and Fig.7 represent the MPL threshold.

### A. Comparison of Maximum Transmission Distance on Earth and Mars

We first compare the maximum transmission distances on Earth and Mars without considering the impacts of dust storms on Mars. This analysis allows a quantitative comparison of THz communication based on the differences in spreading loss and molecular absorption loss on each planet. Accordingly, we analyze the maximum transmission distance subject to the defined threshold using Lagrange interpolation. The impacts of dust storms are then analyzed in Section V-B.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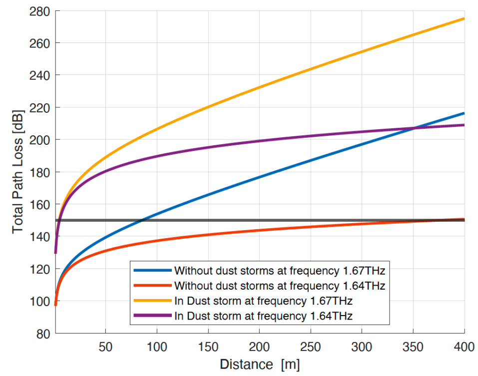


Fig. 5: Total path loss variation in 1.67 THz and 1.64 THz frequencies with respect to changes in the distance on Mars.

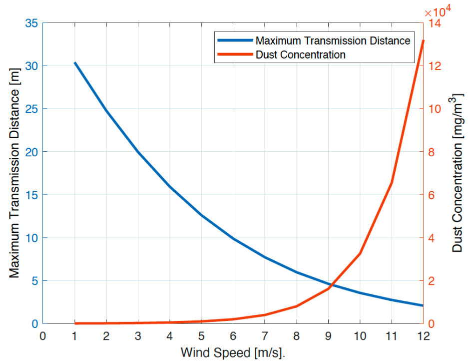


Fig. 6: Maximum transmission distance and dust particle concentration variation against wind speed at 1.67 THz frequency and antenna height 2m.

Fig. 4 demonstrates the total path loss variation with distance on Mars and Earth in the selected frequencies. The transmission distance on Earth using THz signals is possible only over short distances, as shown in Fig.4(a). However, Fig.4(b) shows a promising horizontal transmission distance on Mars. To investigate the maximum transmission distance numerically subject to the threshold of 150 dB value, we summarise the measurements obtained by Lagrange interpolation in Table II.

In the selected high molecular absorption frequency (1.67 THz), the equivalent transmission distance on Mars (85.64m) is roughly 64 times that on Earth (1.33m), and similarly, at 1.64 THz frequency, the transmission distance on Mars (377.95m) is approximately 67 times that on Earth (5.56m). Therefore, establishing longer-range communication using THz signals is easier on Mars, at least when no dust storms are present between transmitter and receiver.

### B. Maximum Transmission Distance Analysis on Mars

Now, we investigate the maximum transmission distance on Mars, considering factors such as dust storms and antenna height.

Fig. 5 illustrates the total path loss with respect to distance for the selected frequencies under diverse environmental conditions. These measurements are obtained assuming a THz link where both the transmitter and the receiver are at the height of 2m. Moreover, the dust particle sizes were randomly generated for the calculations in the range of 0.5 to 4 microns.

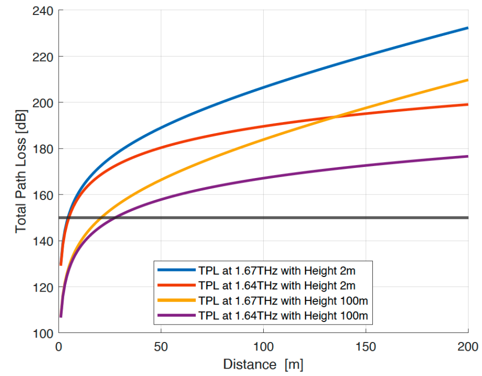


Fig. 7: Comparison of total path loss variation in 1.67 THz and 1.64 THz frequencies with changes in distances and antenna heights on Mars.

In addition, we chose wind speeds from the Mars Climate Database to configure the dust particle density, to simulate absorption and scattering by dust storms. Fig. 6 illustrates how wind speed increases the dust particle concentration and, hence, reduces the transmission distance. The *InSight* landing site on Mars date 2018/11/26 (My 34 MM10 SN 555) 295.5 degrees Solar Longitude was chosen, with the altitude above the surface being 2m.

As before, the maximum transmission distances for this scenario were estimated using the same method with the same threshold, and our predictions can be found in Table II. According to the simulations, dust storms leads to 2 and 1 orders of magnitude decrease in transmission distances compared to the absence of dust storm at 1.64 THz and 1.67 THz, respectively. Therefore, we can conclude that with a 150 dB threshold value for the dust storm scenario, the distance between the transmitter and receiver would need to be approximately 4m for acceptable transmission. If we need to communicate between two *habitats* with a separation distance of 300m, many more repeater nodes will be needed to ensure adequate connectivity, which would be highly expensive. Therefore, we conclude that dust storms would effectively cause a THz communications blackout for antennas placed near the ground.

As an extension of this analysis, we propose a solution that attempts to increase effective transmission distances even when the visibility is low. Since Mars has a relatively quiet seismic environment and Mars gravity is just 38% that of Earth, it is relatively easy to erect tall structures. Although wind speeds can be high, the aerodynamic forces are lower because Mars has lower atmospheric pressure. Therefore, we would be able to place antennas on top of Martian *habitats* up to tens of meters above the ground (see Fig. 3). We investigate the communication performance in dust storm conditions with antenna heights of 100m. As before, we utilize wind speeds at an altitude of 100m from the Mars Climate Database on the same Mars date mentioned above. We also assume that the upper limit of the dust particle radius reduces from 4 microns (at 2m) to 1.5 microns (at 100m) because larger particles will be situated close to the ground. Therefore, dust particle density



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| Frequency | On Earth | On Mars without dust storms at 2m height | On Mars with dust storms at 2m height | On Mars with dust storms at 100m height |
|---|---|---|---|---|
| 1.64 THz | 5.56m | 377.95m | 4.95m | 27.61m |
| 1.67 THz | 1.33m | 85.64m | 4.55m | 20.78m |

TABLE II: Maximum Transmission Distance on Earth and Mars.

declines with altitude resulting in improved visibility [21].

Fig. 7 presents the total path loss with respect to variations in the antenna heights. Similarly, maximum transmission distances were estimated using Lagrange interpolation and numerical root-finding procedures, and the results are presented in Table II. Comparing the transmission distance using 2m and 100m height antennas during dust storms, we see that placing antennas at 100m height results in an increase of 5.5 times transmission distance compared with 2m height at 1.64 THz frequency. Similarly, the transmission distance utilizing antennas with 100m height has increased about 4.5 times compared to a height of 2m for 1.67 THz frequency. We conclude that THz communication links can be used to communicate on Mars, except in dust storms lasting days or months, by increasing the antenna heights. Moreover, the signal path length is $\sqrt{d^2 + (\delta h)^2}$ where $d$ and $\delta h$ are the horizontal and vertical separations between Tx and Rx. To maximize effective $d$, we propose to stratify by altitude. For habitat$\leftrightarrow$habitat communication, we propose steerable antennas at 100m altitude, and for habitat$\leftrightarrow$vehicle/human communication, we propose multiple antennas per habitat, angularly distributed at 2m altitude, all connected by wires inside each habitat.

## VI. Conclusions

High speed and reliable communication between Mars *habitats* will expand the capabilities and lay the foundations to support human settlements on Mars. In this paper, we found that THz communication in Mars atmospheric and environmental conditions has better path loss performance than Earth. We compared the total path loss due to spreading and molecular absorption on Mars and Earth and measured the effective maximum transmission distance for a defined maximum path loss threshold. Using the Mars Climate Database and HITRAN data, our simulations indicate that Mars-based THz communication signals can reach a receiver more than sixty times more distant than a similar transceiver pair on Earth. Furthermore, increasing the altitude where antennas are placed can extend the transmission distance during dust storms, although without fully recovering the performance that is achieved in high visibility/clear sky conditions.

Nevertheless, it is clear that, even on Mars, longer distances will need additional infrastructure to relay signals. Therefore, we expect that the location and topology of such supporting infrastructure will benefit from the experience of achieving reliable link performance and adequate network coverage in cellular networks on Earth. Furthermore, we expect that THz links on Mars have the capacity to provide the dominant radio access technology but need to be supplemented with other (lower) frequencies that are less affected by dust storm particles and impaired visibility.

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