

TUTORIAL

K_a-Band Link Budget Analysis for Deep Space Communications

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ABSTRACT The emerging demand for increased data rates between Earth, the lunar gateway, Mars, and various other deep space probes will stretch existing deep space network (DSN) antennas beyond capacity. The DSN antennas distributed across Canberra, Madrid, and Goldstone are capable of tracking the Mars Reconnaissance Orbiter (MRO) travelling tens of millions of kilometers from Earth, and life extension efforts continue to support such critical space infrastructure. However, these legacy systems still suffer failures and outages that have resulted in delays in data communication and this situation continues to be a significant challenge. This explains the current interest in this area. Thus it is timely that we present a fresh tutorial on a link budget to Mars, elucidating use of the latest ITU-R model recommendations for propagation through the Earth's atmosphere. To facilitate communication to Mars, we target a downlink frequency in the K_a band (31.8–32.3 GHz) as it allows for increased data transmission rate, increased effective isotropic radiated power (EIRP) and reduced antenna size. In this tutorial paper, we therefore focus on a link budget in the K_a band and take into account all major sources of attenuation including free space path loss (FSPL), rain, fog, and system noise temperature (T_{sys}), which are critical for ensuring a positive link margin. As a case study, the presented link budget uses parameters for actual MRO communications and the Canberra DSN antenna assuming communication from the Mars Reconnaissance Orbiter (MRO) to the Canberra DSN-DSS-35. For point of comparison, we compare this with the case of Lunar to Earth communications.

INDEX TERMS Deep space network, K_a band, link budget analysis, ITU-R models.

I. INTRODUCTION

Due to current plans for long duration Mars missions, the demand for advanced deep space communication systems has significantly increased. In particular, there is a current focus on unmanned missions to Mars to explore the planetary terrain. The ideal is to deliver a higher data

rate communication link with more advanced electronically steerable antennas, in contrast to the traditional parabolic dish antenna paradigm. Although traditional parabolic dish antennas have the advantage of high gain and directivity, increasing the link margin for a specific bit error rate (BER), such antennas require gimbal mounting, suffer from pointing accuracy, inefficient calibration, and reliability issues. The costs of such large antennas with precise gimbal mounting can be excessively high and a single point of

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mechanical failure can typically lead to a few months of service interruption [1]. Considering these issues we envision future research on alternate DSNs such as flat panel antennas that can achieve advanced functionality, employing, electronically steerable beams at comparatively lower cost. A link budget tutorial, such as this, assists in application of the latest ITU-R atmospheric models to arrive at the necessary power requirements for future flat panel array design.

The future aim is to increase the data transmission rate for MRO to Earth communication; therefore, our focus is on the K_a band instead of the traditional X and K bands. The K_a band is three times higher in frequency than the X-band and has the potential advantage of increased effective isotropic radiated power (EIRP) with a constant MRO transmitter power and effective antenna size. The other advantages of the K_a band include higher data throughput, increased bandwidth, high power transmission, and smaller physical antenna sizes.

In order to design a telecommunication system for a specific frequency band, the first task is to carry out a link budget analysis to give insight into an achievable data rate, estimate of the required EIRP of the MRO transmitter, and required antenna gain of the Earth station's deep space network etc. The link budget is a prediction of the end-to-end communication link performance. In a specific set of conditions, targeting a specific BER, the link budget accounts for all the gains and losses both in the spacecraft and the Earth station's DSN, and the results is a range of figure of merits, such as the signal to noise ratio (SNR) of the link, throughput etc. The gain includes the transmitter and receiver antenna gain while the major losses occur due to the travel of electromagnetic waves in free space. According to the Friis transmission equation, the loss increases with the increase of transmitter to receiver path distance. In addition to the physical losses of the antennas, other major losses include atmospheric attenuation due to rain, fog, gases in the air, clouds, and system noise temperature.

In this paper, we demonstrate the link design analysis for downlink transmission from a MRO to an Earth station DSN. The case study aim is to achieve 5 Mbps data rate with a BER of 10^{-6} using a BPSK modulation scheme with low-density parity-check (LDPC) error correction coding, as is typical of NASA missions. This link budget analysis will then inform future design of a phased array antenna having circular polarization capable of establishing a link with a MRO, replacing the existing 70-metre parabolic antenna. The mission description and link requirements are discussed in Section II where in Table 1 a summary of these parameters is given, in Section III all the possible atmospheric losses are discussed, Section IV describes the affect of environmental system temperature that plays a vital role with the satellite communication link budgeting, moreover the Mars the moon scenario is discussed in Section VI, the discussion of BPSK modulation and error correction coding is discussed in Section VII, the overall discussion and possible future directions are discussed in Section VIII.

TABLE 1. Link design parameters from MRO to DSS-35 [3], [5].

Parameter	Value	Units
Downlink Frequency (f)	31.8	GHz
DSN to Mars Distance (R)	4×10^{11}	km
Bit-Rate	5	Mbps
Bit-Error Rate	10^{-6}	–
Availability	95	%
Polarization Type	Circular	–
Modulation Type	BPSK	–

II. MISSION DESCRIPTION AND LINK REQUIREMENTS

The example mission considered in this tutorial is the MRO over the Martian pole. In the MRO, the antenna is pointed towards the Earth station while the solar panels are pointed towards the sun. A relatively powerful amplifier and larger antenna is used in the MRO as compared to any previous deep space missions [2]. Also, we assume the MRO has an established link with one of NASA's DSNs, more specifically we consider the Canberra DSN–DSS–35 [3]. To elaborate, NASA's Deep Space Network is the largest and most sensitive telecommunication network system in the world. The DSN comprises NASA's international array of giant radio frequency antennas, supporting interplanetary MRO missions. The DSN also provides radio astronomy and radar observations that elucidate solar systems in the universe.

Since the distance between the MRO to Earth can vary from 54.6 million to about 401 million km, we consider the worst case scenario, i.e. the maximum distance and associated major loss mechanism—free space path loss (FSPL) [4].

A. LINK OBJECTIVES

The important first step in any link budget is establishing the performance and availability objectives to be met, together with other objectives such as desired capacity or throughput. For this analysis we take the availability objective from the DSN link design handbook [3]. The requirement is 95% for nominal commanding, and 98% for mission critical events, which is achieved by the use of back-up stations. We conclude then that 95% availability from a single link is needed, requiring only modest availability from back-up stations during mission critical events. This 95% single link availability must include an allowance for equipment failure, so setting this at a generous 2%, we require a maximum of 3% unavailability, considering only propagation impairments to the signal, from any single link. For this analysis we assume 10^{-6} BER at the propagation availability objective of 97%.

B. TRANSMITTER: MRO DETAILS

The mission MRO in our case study has an antenna gain of 56 dBi, and two flat solar panels directed towards the Sun.

TABLE 2. MRO details [3], [5].

Parameter	Value	Units
Transmitter Power (P_T)	100–1000	W
Transmitter Gain (G_T)	56	dBi
Feedline Loss	0.42	dB
Half Power Beam Width (HPBW)	0.017	deg
Pointing Accuracy ($P_{t_{acc}}$)	0.004	deg

The MRO details are listed in Table 2 that are taken from the NASA DSN handbook [3], [5].

Using the associated HPBW and the pointing accuracy, $P_{t_{acc}}$, the pointing loss, $L_{txpoint}$ can be estimated, within the main lobe, using the following equation [2], [6]

$$L_{txpoint} = 12 \left(\frac{P_{t_{acc}}}{HPBW} \right)^2. \quad (1)$$

C. RECEIVER: EARTH STATION DSN DETAILS

Out of the three NASA DSNs located at Madrid, Canberra, and Goldstone we consider the Canberra DSN, DSS-35 as a case study. The strategic placement of these three DSNs provide constant communication with the MRO. With the rotation of our planet, before a distant MRO sinks below the horizon of one DSN, another DSN can pick up the signal and carry on the communication. We consider the rain height, cloud height, and rain rate for Canberra DSN [11].

The DSN consists of three sites, approximately equally distanced in longitude as shown in Fig. 1, with multiple radio antennas at each site. Table 3 lists the GPS coordinates of each site [7].

III. ATMOSPHERIC LOSSES

As electromagnetic waves propagate through the atmosphere, different molecules that compose the air absorb energy at different rates depending on the frequency. While the data transmission rate for the K_a band is higher than the X-band, the propagation loss is significant. The propagation loss includes the FSPL, and various forms of atmospheric attenuation. Therefore, the total path loss of the link, L_{path} , becomes

$$L_{path} = FSPL + A_{atm}. \quad (2)$$

Our atmospheric modelling includes the rain attenuation, cloud attenuation, gas attenuation, and attenuation due to the antenna's physical environment-such as feedline loss and pointing loss.

A. FREE SPACE PATH LOSS (FSPL)

Free space path loss (FSPL) is the loss in signal strength as a wave travels through free space. For our scenario, the FSPL is dependent on the frequency and distance between the Earth and the MRO. The distance of MRO from Earth can vary considerably depending on their orbits around the sun. They can get closest when the MRO reaches closest to sun (perihelion) and farthest to Earth (aphelion). The closest

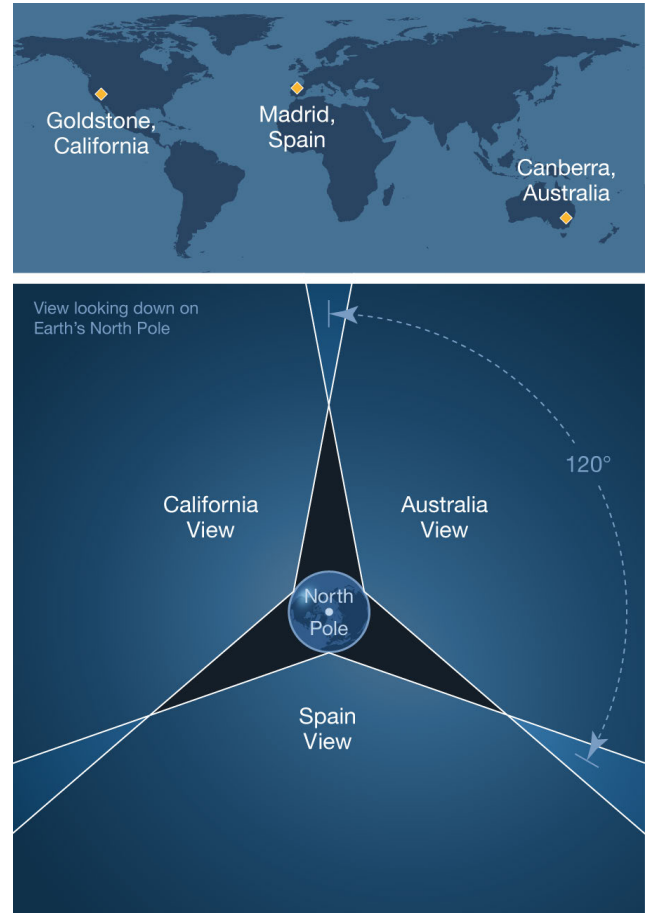


FIGURE 1. NASA DSN locations worldwide that are at 120° angles with one another [6], [8]. The DSNs are equidistant to one another, ensuring constant communication between Earth and any space assets.

distance between the two planets can be 54.6×10^6 km, but that has not yet happened in NASA history [12]. The closest recorded distance between the two planets was found to be 56×10^6 km apart in August 2003 [13]. The maximum distance is about 400 million km, with an average distance of 225 million km. In our link budget analysis, the maximum distance between them, 400 million km, is considered for all presented calculations.

The effects that are considered in the calculation of FSPL are the loss of power density of electromagnetic waves as they spread through space equally in all directions (isotropically). The power density can be found from inverse square law,

$$S = P_t / 4\pi R^2; \quad (3)$$

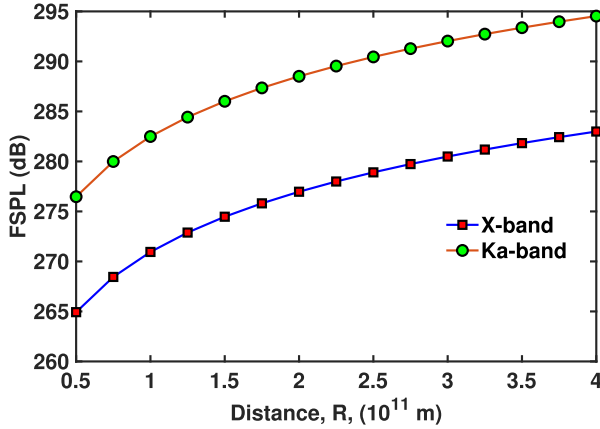
where S is the power density in W/m² at a distance R , P_t is the transmitted effective isotropic radiated power (EIRP).

The efficiency of an antenna in receiving power from an incoming electromagnetic signal is another effect that is considered in calculation of FSPL. The power collected by an isotropic receiver antenna as a function of wavelength is given by,

$$P_r = S \lambda^2 / 4\pi \quad (4)$$

TABLE 3. The location of deep space network complexes.

Name	Longitude	Latitude	Antennas
Canberra	148°58'56"E	35°24'06"S	DSS-43 (70 m), DSS-34, DSS-35, DSS-36 (34 m)
Goldstone	116°46'44"W	35°16'53"N	DSS-14 (70 m), DSS-24, DSS-25, DSS-26 (34 m)
Madrid	4°14'59"W	40°25'45"N	DSS-63 (70 m), DSS-54, DSS-55 (34 m)

**FIGURE 2.** FSPL versus MRO to Earth distance for the K_a band. The X-band is included for comparison. In the K_a band the highest loss is 295 dB for a maximum possible MRO to Earth distance.

where P_r is the received power in W/m², and λ is the operating wavelength in meters. Combining Eqn. 3 and Eqn. 4, the FSPL expression becomes,

$$\text{FSPL} = P_t/P_r = 10 \log_{10}(4\pi R/\lambda)^2. \quad (5)$$

The characteristics of the FSPL for electromagnetic wave propagation from the Earth station to the MRO for the X and K_a bands is shown in Fig. 2. Equation 5 indicates that the FSPL is inversely related to the operating wavelength, therefore for a lower wavelength such as for the K_a band, the FSPL is higher. For the same distance from Earth to MRO, Fig. 2 shows that for X-band the loss is comparatively lower than the K_a band due to its longer wavelength. For the longest distance of 400×10^6 km considered, we see the FSPL in the K_a band is 295 dB.

B. RAIN ATTENUATION

Rain is a major contributor to signal degradation at higher microwave frequencies, especially in the K_a band. This attenuation is mostly dependent on the rain rate and also depends on the operating frequency, DSN location, and rain height. Rainfall causes both the absorption and scattering of radio waves that results in the reduction of the received signal level [15]. It is the most critical form of atmospheric attenuation in the K_a band. Therefore for the MRO link budget we must take rain attenuation into consideration.

The first step is to determine the rain height, h_R , and this can be obtained from Rec. ITU-R P.839 [18]. Next we calculate the slant-path length, L_s , that is dependent on the elevation angle (θ). For different θ according to Rec. ITU-R P.618-13 [16] the L_s is given by,

$$L_s = \frac{h_R - h_s}{\sin \theta}, \text{ km; when } \theta \geq 5^\circ \quad (6)$$

$$L_s = \frac{2(h_R - h_s)}{\left(\sin^2 \theta + \frac{2(h_R - h_s)}{R_e}\right)^{\frac{1}{2}} + \sin \theta}, \text{ km; when } \theta < 5^\circ \quad (7)$$

where, h_s is the height of the Earth station from mean sea level, and R_e is the effective radius of the Earth, 8,500 km.

The horizontal projection, L_G from the slant-path length L_s can be calculated by

$$L_G = L_s \cos \theta, \text{ km.} \quad (8)$$

After obtaining the rain height, slant path length, and the horizontal projection the rainfall rate, $R_{0.01}$, for any location in the world can be obtained from Rec. ITU-R P.837-7 [19]. The $R_{0.01}$ for the Canberra DSN is 33.94 mm/hr.

Following Rec. ITU-R P. 838-3 [17], the specific attenuation can be obtained from a power law relationship

$$\gamma_R = k(R_{0.01})^\alpha, \text{ dB/km} \quad (9)$$

where, R specifies the rain attenuation at the particular location, which is the location of the DSS-35 in our case. The latitude and longitude for DSS-35 are -35.401389 and 148.981667 respectively.

From scattering calculations, the following equations give the value of constants k and α for a frequency in the 1 to 1000 GHz range [17],

$$\log_{10} k = \sum_{j=1}^4 \left(a_j \exp \left[- \left(\frac{\log_{10} f - b_j}{C_j} \right)^2 \right] \right) + m_k \log_{10} f + c_k \quad (10)$$

$$\alpha = \sum_{j=1}^5 \left(a_j \exp \left[- \left(\frac{\log_{10} f - b_j}{C_j} \right)^2 \right] \right) + m_\alpha \log_{10} f + c_\alpha \quad (11)$$

where f (in GHz) is the operating frequency. The values of k and α are frequency dependent coefficients for horizontal and vertical polarizations.

The values of k and α can be calculated for the general case by using the following equations [17],

$$k = [k_H + k_V + (k_H - k_V) \cos^2(\theta) \cos(2\tau)]/2; \quad (12)$$

$$\alpha = [k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2(\theta) \cos(2\tau)]/(2k); \quad (13)$$

where θ and τ are the path elevation angle and polarization tilt angle relative to horizontal respectively. Note that the

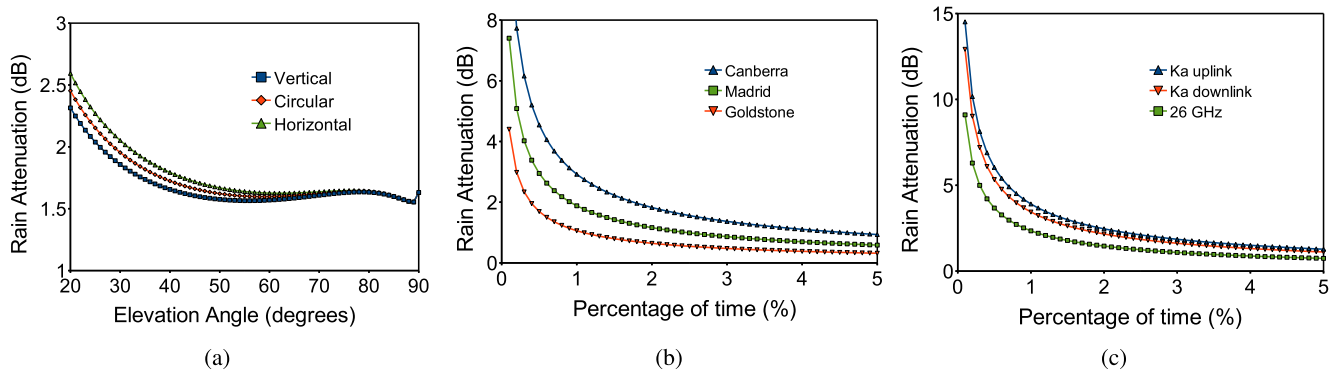


FIGURE 3. Rain attenuation with respect to (a) elevation angle, 31.8 GHz for 3% of the time, (b) percentage of time for all three DSNs, 31.8 GHz circular polarization, and (c) percentage of time at different frequencies (circular): K_a band uplink (34.2 GHz), K_a band downlink (31.8 GHz), and K band (26 GHz). Here, the percentage of time specifies the total time a specific rain attenuation will be exceeded over a sufficiently long observation period [10]. Fig. 3a and Fig. 3c are for the Canberra DSN.

coefficients k and α are frequency dependent and can be obtained from ITU-R P.837 [19]. Note, for circular polarization the tilt angle τ is 45° .

The next task concerning rain attenuation calculation is to calculate the horizontal reduction factor, $r_{0.01}$, and the vertical adjustment factor, $v_{0.01}$ for 0.01% of the time. These are empirical models [16], derived from observations of satellite systems. The horizontal reduction factor can be calculated by

$$r_{0.01} = \frac{1}{1 + 0.78 \sqrt{\frac{L_G \gamma_R}{f}} - 0.38(1 - e^{-2L_G})}. \quad (14)$$

The $v_{0.01}$ can be found under the following conditions

$$\zeta = \tan^{-1} \left(\frac{h_R - h_s}{L_G r_{0.01}} \right), \text{ degrees} \quad (15)$$

for $\zeta > \theta$,

$$L_R = \frac{L_G r_{0.01}}{\cos \theta}, \text{ km} \quad (16)$$

else,

$$L_R = \frac{h_R - h_s}{\sin \theta}, \text{ km} \quad (17)$$

if $|\phi| < 36^\circ$,

$$\chi = 36 - |\phi|, \text{ degrees} \quad (18)$$

else, $\chi = 0^\circ$, giving a vertical reduction factor of,

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin \theta} \left(31 \left(1 - e^{-\frac{\theta}{1+\chi}} \right) \frac{\sqrt{L_R \gamma_R}}{f^2} - 0.45 \right)}. \quad (19)$$

In relation to the vertical adjustment factor, the effective path length is as follows

$$L_E = L_R v_{0.01}, \text{ km}. \quad (20)$$

Thus the predicted attenuation exceeded for 0.01% of an average year ($A_{0.01}$) can be obtained by

$$A_{0.01} = \gamma_R L_E, \text{ dB}. \quad (21)$$

Note that $A_{0.01}$ is a useful convention for empirical modeling of rain attenuation. It simply is a conventional starting point for the empirical model and other percentages of an average year, in the range 0.001% to 5%, are determined

from the attenuation to be exceeded for 0.01% for an average year. This can be found by using the following equation,

$$A_p = A_{0.01} \left(\frac{p}{0.01} \right)^{-\gamma}, \text{ dB} \quad (22)$$

where γ is defined as

$$\gamma = 0.655 + 0.033 \ln(p) - 0.045 \ln(A_{0.01}) - \beta(1 - p) \sin \theta. \quad (23)$$

The values of $A_{0.01}$, p , and β can be found from the ITU-R recommendations, [17], [18], [19].

Here, if $p \geq 1\%$ or $|\phi| \geq 36^\circ$, $\beta = 0$, if $p < 1\%$ and $|\phi| < 36^\circ$ and $\theta \geq 25^\circ$, $\beta = -0.005(|\phi| - 36)$, otherwise, $\beta = -0.005(|\phi| - 36) + 1.8 - 4.25 \sin \theta$.

Following the equations for calculating the rain attenuation and following the data from the ITU recommendations, the slant path rain attenuation A_p (in dB) is calculated for different frequencies, polarization, elevation angles, and percentage of time the indicated attenuation is exceeded, as shown in Fig. 3. The rain attenuation over different elevation angles for different polarizations is shown in Fig. 3a. It shows for the K_a band that the slant path rain attenuation generally decreases with increasing elevation angle—since the slant path length decreases [22]. However, this variation is not entirely monotonic near the zenith. The reasons for this are under study by Radio Study Group 3 of the International Telecommunication Union (ITU-R). There could be a physical explanation for this during convective rain events, or it may be an artifact of the empirical models in the Recommendation [16]. According to the NASA DSN handbook, each DSN shows best performance for an elevation angle about 40–50 degrees. Therefore, in all our calculations we consider an elevation angle of 50 degrees.

The rain attenuation is also dependent on location and frequency, which is shown in Fig. 3b and 3c. From Fig. 3b it can be seen that the rain attenuation for Canberra is higher than either Goldstone or Madrid. This can occur because of the rain rate and rain height variation at the different locations. Moreover, rain attenuation is higher at high frequencies because of higher values of K and α as

can be seen from Eqn. 10–13. For the K_a band, the rain attenuation is significant for small percentages of time. Therefore the MRO may need to store captured data during adverse weather conditions and transmit during dry weather.

For example in Canberra, with our atmospheric fading objective of $p = 3\%$ of the time, we estimate rain fading loss $A_R(p)$ at 31.8 GHz to be 1.37 dB.

C. ATTENUATION DUE TO CLOUD AND FOG

Cloud and fog consists of small droplets, generally less than 0.01 cm in diameter, according to ITU-R P.840–9 [9]. The specific attenuation within a cloud or fog can be written as

$$\gamma_c = K_l(f, T)\rho_l, \text{ dB/km} \quad (24)$$

where, γ_c is the specific attenuation within the cloud, K_l is the liquid water specific attenuation coefficient in (dB/km)/(g/m³), ρ_l is the liquid water density in the cloud or fog (g/m³), which is 0.05 g/m³ for medium fog and 0.5 g/m³ for thick fog, and T is the cloud liquid water temperature [9].

The K_l in Eqn. 24 depends on many factors such as the cloud liquid water temperature, T , the operating frequency, f , and the complex dielectric permittivity of water. A mathematical model based on Rayleigh scattering that uses a double-Debye model for the water dielectric permittivity $\epsilon(f)$, can be used to calculate K_l upto 200 GHz [9]. Following the procedure of ITU-R P.840–9 [9], the model is as follows,

$$K_l(f, T) = \frac{0.819f}{\epsilon''(1 + \eta^2)} \quad (25)$$

where the frequency is in GHz and η can be defined as follows

$$\eta = \frac{2 + \epsilon'}{\epsilon''}. \quad (26)$$

The complex dielectric permittivity of water can be given by

$$\epsilon''(f) = \frac{f(\epsilon_0 - \epsilon_1)}{f_p[1 + (\frac{f}{f_p})^2]} + \frac{f(\epsilon_1 - \epsilon_2)}{f_s[1 + (\frac{f}{f_s})^2]} \quad (27)$$

$$\epsilon'(f) = \frac{(\epsilon_0 - \epsilon_1)}{[1 + (\frac{f}{f_p})^2]} + \frac{(\epsilon_1 - \epsilon_2)}{[1 + (\frac{f}{f_s})^2]} + \epsilon_2 \quad (28)$$

$$\epsilon_0 = 77.66 + 103.3(\frac{300}{T} - 1) \quad (29)$$

$$\epsilon_1 = 0.0671\epsilon_0 \quad (30)$$

$$\epsilon_2 = 3.52. \quad (31)$$

The principal and secondary relaxation frequencies f_p and f_s , in Eqn. 28 can be determined by

$$f_p = 20.20 - 146(\frac{300}{T} - 1) + 316(\frac{300}{T} - 1)^2, \text{ GHz} \quad (32)$$

and

$$f_s = 39.8f_p, \text{ GHz} \quad (33)$$

where T is the liquid water temperature (K).

However, practical methods for estimating attenuation due to cloud and fog depend on the available data, as outlined in Section III of the Recommendation [9].

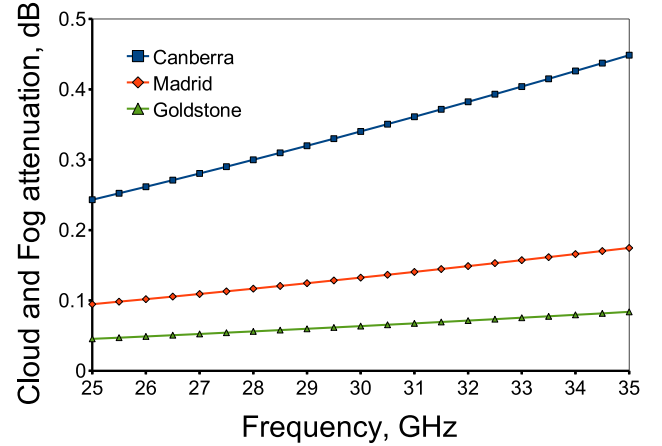


FIGURE 4. Losses due to cloud and fog attenuation vs Frequency at 50 degrees elevation, for 3% of the time at DSN locations.

If local data of total columnar content of liquid water is available from sources such as radiometric measurements, Earth observation products, or meteorological numerical products, they should be used, but otherwise methods of attenuation prediction based on global maps are provided by ITU-R, and we follow that procedure in this paper. The procedure of section III-B of [9] uses an estimate of the integrated cloud liquid water content $L(p)$ (kg/m²), for the required probability $p\%$, from the digital maps provided with Recommendation ITU-R P.840–9 [9], using bilinear interpolation for the required location.

The values of $L(p)$ obtained by this method vary considerably for the three DSN locations. For our $p = 3\%$ objective we have $L(p) = 0.068$ for Goldstone, $L(p) = 0.141$ for Madrid, and $L(p) = 0.362$ for Canberra, so the cloud attenuation differs markedly between the stations. The attenuation is estimated by

$$A_c(p) = \frac{K_L(f)L(p)}{\sin \phi}, \text{ dB} \quad (34)$$

and

$$K_L(f) = K_l(f, T) \left(A_1 e^{\frac{(f-f_1)^2}{\sigma_1^2}} + A_2 e^{\frac{(f-f_2)^2}{\sigma_2^2}} + A_3 \right) \quad (35)$$

for $T = 273.75$ K, with

$$A_1 = 0.1522, A_2 = 11.51, A_3 = -10.4912,$$

$$f_1 = -23.9589, f_2 = 219.2096,$$

$$\sigma_1 = 3.2991 \times 10^3 \text{ and } \sigma_2 = 2.7595 \times 10^6,$$

where ϕ is the elevation angle, between 5 and 90 degrees.

At $f = 31.8$ GHz and $p = 3\%$, for 50 degrees elevation angle we have $A_c(p) = 0.38$ dB for Canberra, $A_c(p) = 0.15$ dB for Madrid, and $A_c(p) = 0.07$ dB for Goldstone. Cloud attenuation as a function of frequency for these three locations is shown in Fig. 4.

D. ATMOSPHERIC SCINTILLATION ATTENUATION

Tropospheric scintillation is caused by refractive index variations along the radio path, which is found to be

well correlated to the median value with time, of the wet term of radio refractivity N_{wet} [20]. This may be estimated for a particular location, using bilinear interpolation, from a world-wide digital map at 0.75 degree resolution in latitude and longitude, provided by Recommendation ITU-R P.453-14 [20]. The median value of N_{wet} for Canberra obtained by this method, is 47.7 N-units (ppm in excess of unity).

The scintillation loss increases with frequency but reduces with increased antenna gain, due to aperture averaging [16]. Using the estimation method in Section 2.4.1 of [16], for elevation angles greater than or equal to 5 degrees, with 50 degrees elevation angle, we find that the calculated scintillation loss at 31.8 GHz vanishes for antenna gains in excess of 74 dBi, so may be assumed to be zero for very high gain antennas at the DSN Earth stations, 79 dBi for DSS-35, for example. However, scintillation loss may need to be included in calculations for lower gain antennas, especially at small percentages of time and at low elevation angles.

This model is valid at frequencies from 4 to 55 GHz, and for $0.01\% < p \leq 50\%$. If frequency was increased to 55 GHz, p reduced to 0.1%, antenna gain reduced to 56 dBi, and elevation angle reduced to 10 degrees, in our example, $A_S(p)$ would no longer be negligible, at 3.24 dB.

At elevation angles below 5 degrees, scintillation can become severe, and multipath propagation may also contribute to signal variation. Methods to estimate these effects are provided in sections 2.4.2 and 2.4.3 of Recommendation ITU-R P.618-14 [16].

E. ATTENUATION FROM ATMOSPHERIC GASES

Attenuation due to atmospheric gases, A_O from oxygen and A_W from water vapour, may be calculated from the models in Recommendation ITU-R P.676-12 [21], which may be applied to detailed models of the atmosphere. However, gas attenuation in the K_a band is a relatively minor contributor to overall attenuation in the atmosphere, so for simplicity, we use an estimate of zenith attenuation from sea level, for pressure = 1,013.25 hPa, temperature = 15 degrees C, and water vapour density = 7.5 g/m³, from Figure 11 of [21]. For 31.8 GHz we have $A_O + A_W = 0.23$ dB. The attenuation at elevation angle $\phi = 50$ degrees is then given by

$$A_G = \frac{A_O + A_W}{\sin \phi} = 0.3 \text{ dB.} \quad (36)$$

We assume that attenuation A_W for typical conditions of 7.5 g/m³ water vapour density applies for 5% of the time. This may be an under-estimate but the other assumption we make above is the use of zenith attenuation from sea level instead of zenith attenuation from station altitude, which would be an over-estimate.

More detailed methods for estimating slant path attenuation are available in the Recommendation [21]. These methods may be employed, depending on available data, in cases where gas attenuation is a more significant contributor, such as in higher frequency bands.

F. COMBINING ATMOSPHERIC ATTENUATION MECHANISMS

A general method for estimating total atmospheric attenuation $A_T(p)$ for percentage of time p , between 0.001% and 5%, is provided in ITU-R P.618-14 [16] as follows:

$$A_T(p) = A_G(p) + \sqrt{(A_R(p) + A_C(p))^2 + A_S(p)^2} \quad (37)$$

where attenuations in dB for probability p are

$A_R(p)$: attenuation due to rain

$A_C(p)$: attenuation due to clouds

$A_G(p)$: gaseous attenuation (water vapour and oxygen)

$A_S(p)$: attenuation due to tropospheric scintillation.

For Canberra at 31.8 GHz, for $p = 3\%$, we have $A_R(p) = 1.37$, $A_C(p) = 0.38$, $A_G(p) = 0.3$, $A_S(p) = 0$ dB. We then have total atmospheric attenuation $A_T(p) = 2.05$ dB. Adding the antenna feedline loss (Table 2) and pointing loss (Eq. 1) the total attenuation A_{atm} becomes 3.13 dB.

IV. RECEIVER GAIN VS SYSTEM TEMPERATURE

The receiver gain G_R and the environmental system temperature T_{sys} both play a vital role in satellite communication link budgeting. With the increase of the system temperature the G/T_{sys} decreases and this affects the overall link performance. The G/T_{sys} can be calculated as,

$$G/T_{\text{sys}} = G_R - 10 \log_{10}(T_{\text{sys}}) \quad (38)$$

where, G_R indicates the DSN gain at the Earth station which is 79 dB for DSS-35, the system temperature can be calculated from the following equation [3]

$$T_{\text{sys}}(\theta) = T_{\text{AMW}} + T_{\text{sky}} \quad (39)$$

where, $T_{\text{AMW}} = [T_1 + T_2 \exp(-a\theta)]$ is the antenna and microwave hardware noise contribution, and $T_{\text{sky}} = [T_{\text{atm}}(\theta) + T'_{\text{cmb}}(\theta)]$ is the sky noise temperature, where T_{atm} indicates the atmosphere noise temperature, and T'_{cmb} is the attenuated cosmic noise. The atmospheric noise contribution,

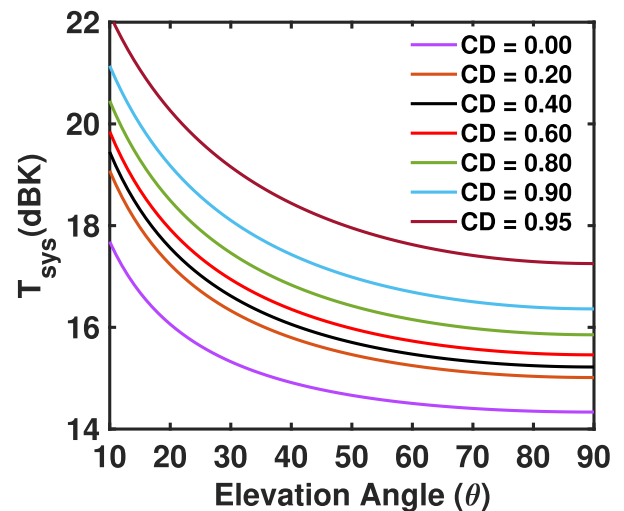


FIGURE 5. System temperature in terms of elevation angle and cumulative distribution (CD).

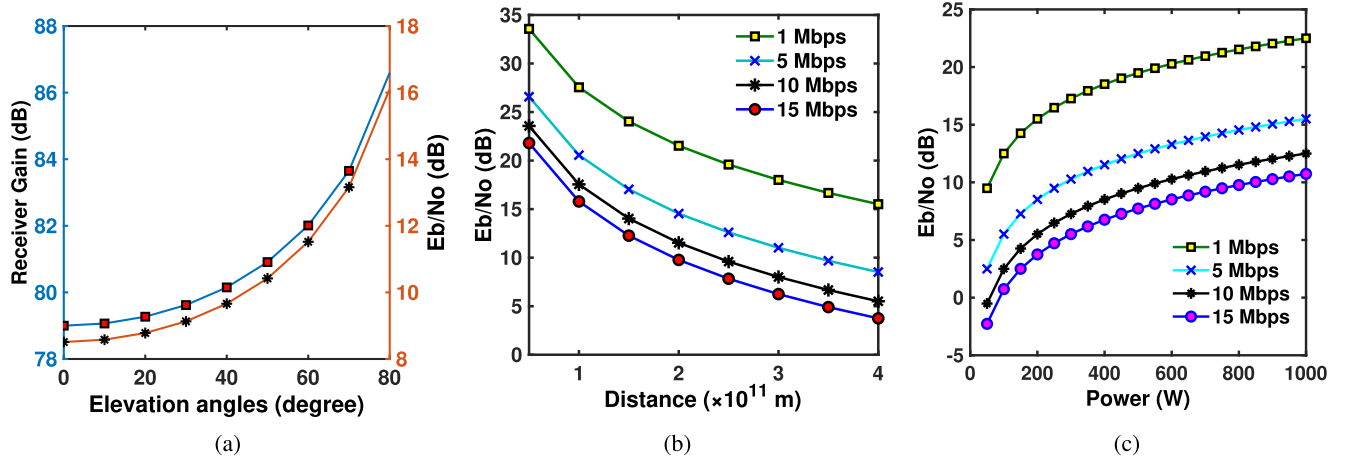


FIGURE 6. The available signal to noise ratio E_b/N_0 for different MRO scenarios such as changing the MRO position, distance, and power for different data rates are shown. (a) Change of DSNs gain and available E_b/N_0 for different variation of MRO angles, (b) the available data rates at various distance of the MRO, and (c) the available data rates at various power of the MRO.

in units of K, can be represented as follows

$$T_{\text{atm}}(\theta) = T_M[1 - 1/L(\theta)]. \quad (40)$$

The atmospheric mean effective radiating temperature T_M in K can be expressed as

$$T_M = 255 + 25 \times \text{CD}, \quad (41)$$

where CD indicates the cumulative distribution. The cosmic background noise, in units of K, is given as

$$T'_{\text{cmb}}(\theta) = T_{\text{cmb}}/L(\theta). \quad (42)$$

According to the DSN handbook, the $T_{\text{cmb}} = 2.725$ K. The dimensionless atmospheric loss factor $L(\theta)$ in Eqn. 42 can be defined as

$$L(\theta) = 10^{A(\theta)/10} > 1.0. \quad (43)$$

The atmospheric attenuation $A(\theta)$ is as follows

$$A(\theta) = \frac{A_{\text{zen}}}{\sin(\theta)}, \text{ dB}. \quad (44)$$

The values of the required coefficients T_1 , T_2 , and a are coefficients from Table A-3, and A_{zen} is from Table A-2 of the DSN Telecommunication Link Design Handbook [3].

The system temperature in terms of elevation angle and cumulative distributions (CD) are plotted and shown in Fig. 5. The T_{sys} vs θ for various CD shows that, as θ increases the T_{sys} decreases—as the slant-path length between the Earth station and satellite decreases. The CD is a measure of sky weather condition. Lower CD implies the sky is clearer and drier, whereas higher CD indicates a wet sky condition. It can be seen that the lowest T_{sys} is at CD = 0.00, whereas the highest is at CD = 0.95. The system temperature rises in adverse weather conditions and that significantly affects the overall link performance.

V. RECEIVED SIGNAL TO NOISE RATIO

Here, the task is to calculate the signal to noise ratio E_b/N_0 that gives rise to a positive link margin for our case of BPSK

coding. The E_b/N_0 can be calculated using the following equation

$$E_b/N_0 = \text{EIRP} + G/T_{\text{sys}} - \text{FSPL} - A_{\text{atm}} + k_B - D_{\text{rate}},$$

where, EIRP is equal to $10 \log(P_T) + G_T$, and k_B denotes Boltzmann's constant, and D_{rate} is the data rate. Here, both k_B and D_{rate} are in dB.

By varying the MRO angle, distance of the MRO from the Earth, and the MRO power, the achievable E_b/N_0 is plotted for different data rates that is shown in Fig. 6.

A. AVAILABLE SNR FOR VARIOUS MRO SCENARIOS

The value of E_b/N_0 depends on many factors that include the MRO position from the Earth station, the propagation path length, the available MRO transmit power, and the

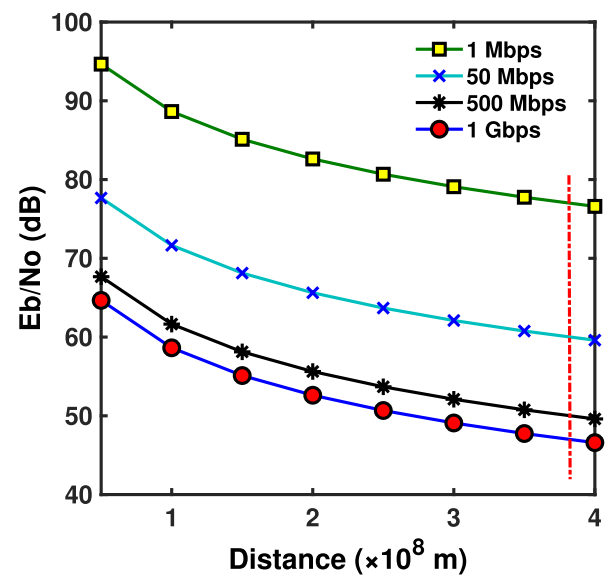


FIGURE 7. Moon scenario. The available E_b/N_0 in consideration of communications from the Moon at 26 GHz for a variation of D_{rate} . The red dotted line indicates the available data rate at the Moon's distance from the Earth station.

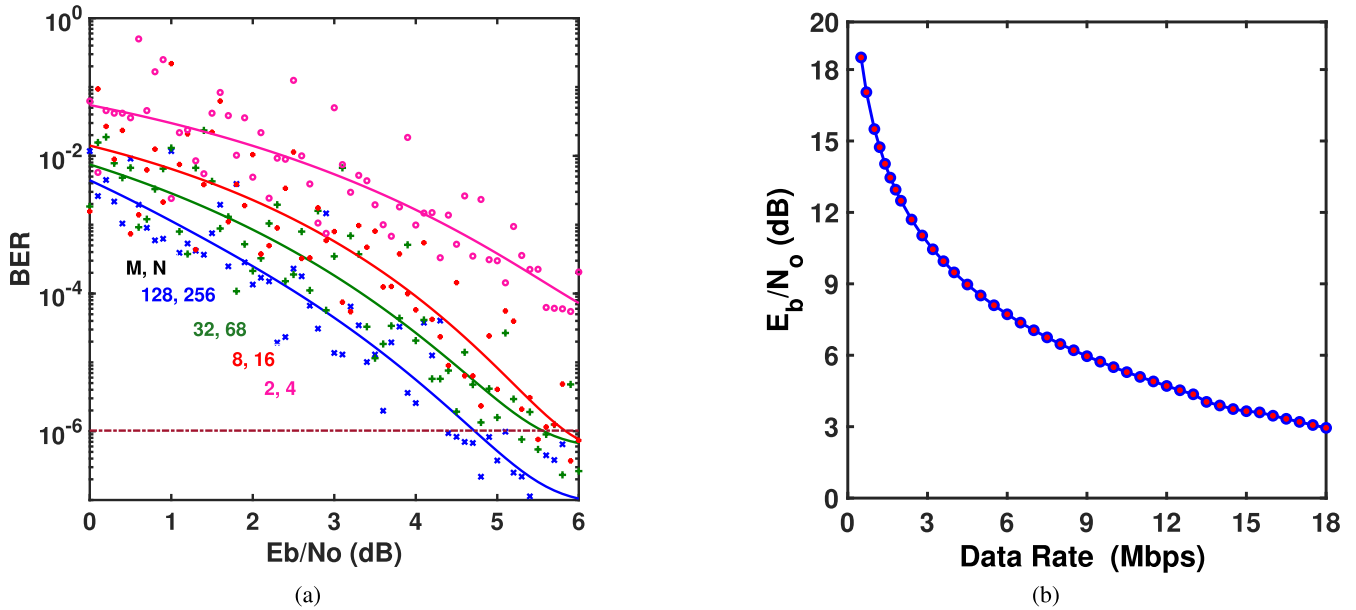


FIGURE 8. (a) The bit error rate (BER) over the signal to noise ratio, E_b/N_0 , for different matrix sizes of the low-density parity-check (LDPC) with binary phase-shift keying (BPSK) modulation. Here, $M \times N$ indicates the size of the parity check matrix. The points in the figure denote the simulated BER while the polynomial fit of them is shown by the solid lines. (b) The available E_b/N_0 for a data rate, D_{rate} .

targeted data rate. The noise power is proportional to channel bandwidth, so for a given noise temperature, E_b/N_0 depends on data rate. The MRO transmitter power has also a significant impact on the link design as well. Transmit power is limited on the MRO as it has only two flat solar panels directed towards the sun to produce the energy. Thus in our analysis we consider a feasible transmit power of 200 W.

The available signal to noise ratio versus MRO elevation angle, distance between the MRO and the Earth station, and the MRO power is plotted and shown in Fig. 6. The elevation angle of the MRO is varied and the available receiver gain and E_b/N_0 from the link budget is analyzed and shown in Fig. 6a. The realized receiver gain for different elevation angles is calculated from the following formula

$$\text{Gain (Realized)} = G_R - 10 \log \cos(\theta). \quad (45)$$

Figure 6a indicates that as the elevation angle increases the receiver gain also increases and therefore the E_b/N_0 increases. This happens due to the reduction of distance between the MRO and DSN with an increased elevation angle of the satellite. For different D_{rate} the available E_b/N_0 is calculated over a range of distances as shown in Fig. 6b. It is realized that for a certain data rate, as the distance between the Earth station and MRO increases the available E_b/N_0 decreases—as the FSPL and other forms of atmospheric attenuation decrease.

The available E_b/N_0 over a range of MRO transmit powers is shown in Fig. 6c. As the power increases, the EIRP of the transmitter also increases that increases the E_b/N_0 , therefore for a higher transmitter power, it is possible to achieve higher data rate. Up to now, we have mostly discussed the losses in case of the MRO finding the available E_b/N_0 , whereas in the next section we contrast this with lunar communications.

VI. MOON SCENARIO

The average distance of Moon from the Earth is around 384,400 km [23], therefore the FSPL is significantly lower for the Moon as compared to Mars. For a downlink frequency of 26 GHz the FSPL in case of the Moon is 232 dB, which is considerably lower than the Mars scenario at 295 dB. The available E_b/N_0 for a variation of D_{rate} is plotted and shown in Fig. 7. As expected, for the identical parameters the achievable downlink data rate from the Moon is considerably higher than from Mars.

VII. BER AND SNR ANALYSIS FOR DIFFERENT MRO SCENARIOS

In this section we will determine the BER using BPSK modulation and applying low-density parity-check (LDPC) error detection. Then the required link margin can be compared with the available E_b/N_0 for different MRO scenarios, as described in Fig. 6. The estimation of achievable data rates can be obtained from the comparison.

Following BPSK modulation, low-density parity-check (LDPC) error detection and correction is applied to improve the BER for a range of E_b/N_0 , Fig. 8. The BER is plotted for different dimensions of the parity check matrix, denoted by M and N in the plot. To obtain accurate results that are consistent with the simulation, 30 iterations are carried out for each $M \times N$ case for both coding and decoding. During simulation we found that a little over 10 decoding iterations closely follows the analytical results. However, a lower number of iterations, such as unity, results in degraded BER—a BER experiment over different iteration numbers is reported in [24], where they also found a similar impact of iteration number on BER. Note that, in considering the matrix dimension we always choose M and N , such as N is

always double M , this is to make the code rate consistent at $1/2$. The mission link design parameters are given in Table 1, the MRO uses a BPSK modulation scheme with a targeted BER of 10^{-6} . Thus according to Fig. 8, to obtain the targeted BER, the communication link, between the MRO and the Earth station, must have a minimum positive link margin of 4.7 dB. In the link design algorithm, by changing the targeted D_{rate} we analyze the available E_b/N_0 as shown in Fig. 8b. The figure indicates that for lower data rate link requirements we can achieve a larger available E_b/N_0 —this implies we can achieve an excellent BER performance when it is traded off with data rate.

VIII. CONCLUSION

From the discussion in sections V, VI and VII the achievable data rate of the communication link between Mars, Moon and the Canberra DSN can be achieved by design.

From the BER analysis using BPSK modulation with LDPC error correction, as shown in Fig. 8a, we can see that the message dimension increases the required E_b/N_0 , decreases to achieve 10^{-6} BER—therefore for a larger message dimension the E_b/N_0 will reduce. The analysis is consistent with a previous reports, [24], [25] where increase of message length reduces the required E_b/N_0 for a targeted BER. Fig. 8b indicates that the communication link requires a 4.7 dB positive link margin to achieve a targeted BER of 10^{-6} .

For the case of Mars, Fig. 6b indicates that for a maximum MRO distance (4×10^{11} m) with a D_{rate} of 15 Mbps, the available E_b/N_0 in our link budget analysis is around 4.2 dB—therefore we can obtain a D_{rate} around 16–17 Mps as shown in Fig. 8b.

For the Moon scenario the availability of E_b/N_0 is significantly higher compared to Mars. Therefore a significant increase of D_{rate} or significantly lower BER can be achieved for the Earth to Moon communication at 26 GHz.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

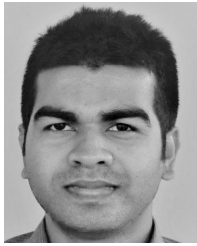
The authors declare that no generative AI was used in the writing of this manuscript. However, Perplexity AI was used as a productivity tool for assisting the debugging of the manuscript's L^AT_EX code.

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for 5G. His latest significant contribution has been developing the new multipath fading model for *Recommendation ITU-R P.530*, which was approved and published in September 2021. He is the Chairman of the Australian Radio Study Group 3 (radiowave propagation). In international meetings, he chairs ITU-R SWG 3J-4 (vegetation attenuation and obstacle diffraction) and ITU-R SWG 3M-1 (terrestrial paths).



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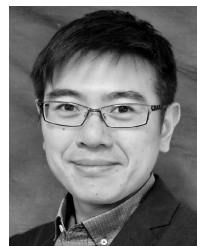


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