

Expediting Lunar Exploration: A study of 5G mmWave Communications for Upcoming Human Missions on the Moon – Relationship between Transmit Power, Antenna Height, and Pathloss Exponent

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Abstract— This study introduces the use of a Lunar Digital Elevation Model (LDEM) map of the connecting ridge of the south pole for the characterization of radio signals in the 5G mmWave frequency communication systems over the lunar surface. Wireless Insite (WI) was used as the simulation software for this investigation. Simulation results indicate that while antenna height significantly influences path loss exponent (PLE), with higher elevations leading to greater signal attenuation, transmit power (20dBm, 30dBm, 40dBm) shows a non-linear relationship with PLE. The results spanning multiple transmitters (Tx1 to Tx4), revealed another trend of analysis regarding the PLE values on the lunar surface compared to terrestrial PLE established parameters.

Keywords— Path Loss Exponent, 5G, mmWave Frequency Wireless Insite, Lunar Surface, Signal propagation, FSPL

I. INTRODUCTION

National Aeronautics and Space Administration (NASA) vision for advancing lunar exploration continues with the draft for Lunar Network (LunaNet) interoperability specifications that was released in July 2022. This initiative can be conceptualized as a collection of networks cooperating together to offer communications, navigation, and other services for individuals in and near the lunar environment [1]. The primary goal of LunaNet is to leverage a wireless network on the lunar surface to improve the framework for communications and navigation on the

The Artemis mission planned by NASA includes Wi-Fi communications for data and Ultrahigh Frequency (UHF) communications for voice services. However, the range of operation for this system cannot accommodate the Artemis released concept of operation for a Lunar Terrain Vehicle (LTV) to transverse up to 10 km and maintain a connectivity with the lander. Moreover, as the international community's presence increases, including private and public sectors on the Moon, the UHF bands do not scale well to support a large number of users. To overcome the challenges faced by the Wi-Fi system, the adoption of cellular technologies and standards such as Fifth Generation (5G) or higher, is proposed. This approach is more suited to effectively support the assets on the lunar surface [2].

The office of Space communications and Navigation and the Space Technology Mission Directorate at NASA are interested in the actualization of lunar communications and

networks with similar attributes to the 3rd Generation Partnership Project (3GPP) cellular communication networks that is prevalent on Earth [3]. One of the technical considerations discussed by NASA for lunar surface networking using 3GPP technology is the feasibility of designing adequate radio frequency coverage models for mission planning [4]. The Fifth Generation (5G) network is a wireless network capable of providing terrestrial services to billions of interconnected users with the ability to provide ultrahigh gigabit connection seamlessly. The adaptation of mmWave frequency in 5G contributed to the possibility of high data rate transmission [5]. The design of a coverage model for the lunar surface requires good observation of the characteristics of radio signals with the properties and environment of the Moon. The effective design and implementation of 5G technology on the lunar surface calls for proper planning and the estimation of the reduction in signal strength known as pathloss as it propagates through the channel [6].

The reduction of the signal strength is subjected to various conditions experienced by the signal, such as multipath, reflection, scattering from obstructions like mountains and hills, with no atmospheric condition as non-exist on the Moon. Features such as optimum transmit power, antenna characteristics, distance between the transmitter and the receiver, frequency, and the channel as the physical layer between the transmitter and the receiver and path loss exponent all play a crucial role in the quality of signals being received. Path loss exponent (PLE) is a vital metric in the engineering of wireless communication systems. It quantifies the channel's propagation characteristics and the signal attenuation rate along the transmission path [7] [8]. The need to accurately estimate the PLE for a specific location is crucial due to its role in delineating the radio propagation profile of the area. This information is instrumental for network planning engineers in making informed decisions regarding the design, deployment, and optimization of wireless networks, ensuring efficient and effective communication infrastructure.

A few researchers have tried to characterize the behavior of radio signals on the lunar surface, [9] modified the Longley-Rice model for path loss prediction utilizing digital elevation data representative of an analog lunar site by performing

Environments	Path Loss Exponent
In building line of site	1.6 – 1.8
Free Space	2
Obstructed in factories	2 – 3
Urban area	2.7 – 3.7
Sub-urban area	3 – 5
Obstructed indoor	4 – 6

analysis at 30MHz, 401 MHz, and 2.4GHz. In [10], signal propagation analysis was performed on NASA wireless communication and sensor systems utilizing 401MHz and S-band at 2.1GHz. The authors indicated that the signal strength experienced more degradation than in free space such that the antenna height, frequency, and the surface material impacted the outcome. A theoretical approach to understand transmission loss over the lunar surface with obstacles was predicted by [11], where the analysis considers diffraction loss, antenna gain, the ground proximity loss, and space transmission loss which revealed a close outcome with the measured data. However, in this previous work, none of the studies have considered the investigation into the 3GPP cellular communication technology. Additionally, no single article reported the characterization of signal propagation through path loss exponent in the mmWave frequency band on lunar surface, which is a crucial factor in developing an adequate radio frequency coverage model for mission planning. Hence, the aim of this project is to study the characterization of signal propagation in the 5G mmWave frequency on lunar surface.

The objectives of this study are:

- (i) Investigate the optimum power transmission for mmWave frequency on the lunar surface.
- (ii) Determine the impact of the receiver's antenna height for mmWave frequency on the lunar surface.
- (iii) Characterize the rate at which a signal deteriorates through lunar surface channel in the 28GHz mmWave frequency band to inform better approach to develop the radio frequency coverage model for successful planning of lunar surface operations and exploration.

II. BACKGROUND

Terrestrial signal propagation in the 5G mmWave frequency is prone to high path losses and absorption losses. This phenomenon can be attributed to shorter wavelengths, which are more susceptible to attenuation as they travel through the air. Nonetheless, in scenarios involving line of sight (LoS) and non-line of sight (NLoS), reflection and scattering form wireless connections between the transmitter and receiver. The Earth atmospheric conditions also contribute to the absorption losses as the mmWave frequency transverse through the medium over distance. The absorption losses were characterized in [12] as path loss resulting from oxygen absorption and various environmental influences.

The idea of path loss (PL) technically describes the attenuation of electromagnetic power density as it propagates through space. This metric is pivotal in the formulation of predictive models for radio wave propagation in wireless systems [13]. PLE as a variable in these models delineates the propagation environment profile needs to be accurately

determined to model accuracy and stability on the lunar surface. Terrestrial PLE values obtained for signal propagation that exhibit different environment are shown in Table 1 [14]. In our investigations, the estimation of PLE for the lunar surface has no comprehensive report of these values.

For simplicity, the first approach employed for the path loss prediction in this work uses the Alpha-Beta Gamma (ABG), Close-In (CI), and Floating Intercept (FI) models [5]. The Floating Intercept model estimates reduction of signal strength in an environment where signal propagation does not align well with models that assume reference distance. The model relies on parameters FI (α) and the slope (β), below is the mathematical expression as shown in Equation (1):

$$PL^{FI}(d)[dB] = \alpha + 10\beta \log_{10}(d) + X_{\sigma}^{FI} \quad (1)$$

where PL^{FI} is the PL model in dB, (α) as average floating FI in dB and the β is the slope and correspond to the path loss exponent (n).

The ABG model exhibits a more comprehensive approach to understanding how signal strength diminishes over distance and across different frequencies which is represented in the mathematical formula in equation (2):

$$PL(d)[dB] = \alpha + 10\beta \log_{10}(d) + 10\gamma \log_{10}(f) \quad (2)$$

Where: PL is the loss at distance d , α is PL at reference distance, β as the pathloss exponent and γ a dependency of pathloss on frequency.

The CI model estimates its signal reduction in relation to distance and frequency. It is used to clearly show how the nearby environment affects the channel [15]. The CI model is expressed in equation (3):

$$PL^{CI}(f, d)[dB] = FSPL(f, d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}^{CI} \quad (3)$$

where n denotes PLE, X_{σ}^{CI} refers to a Gaussian random variable characterized by σ^{CI} , this is the standard deviation (SD) in dB, and d_0 is the reference distance.

The FSPL at a reference point d_0 can be expressed as:

$$FSPL(f, d_0) = 20 \log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \quad (4)$$

where λ is the wavelength.

III. LUNAR SURFACE APPROACH

This research investigates how varying transmit power influences the path loss exponent with varying receiver antenna height for 5G mmWave band frequency on the lunar surface. The study employs the use of Wireless Insite software® [16] to simulate the Lunar Digital Elevation Model (LDEM) maps. The area of focus is the connecting ridge on the lunar surface environment (Site01), with simulations conducted in the 28GHz frequency band. The generated data was analyzed with the log-distance propagation model for the calculation of the PLE. The expression for the log-distance large scale PL model for any given transmitter spacing can be found in Equation (5).

$$\overline{PL}(d) = a * \log(d) + C \quad (5)$$

Where a represents the slope and C denotes the intercept

Equation (5) can be expressed in its generic form as

$$\overline{PL}(d) = PL(d_0) + 10 * n * \log\left(\frac{d}{d_0}\right) \quad (6)$$

where $\overline{PL}(d)$ means the PL (in dB) at point d , d_0 represents the reference distance, n is the PLE.

Shadowing is a concept in wireless communication where signal strength fluctuates which can be caused by reflection, scattering, and absorption due to objects like buildings and trees on Earth. The lunar surface also consists of materials that can reflect, scatter, and absorb radio signals as they propagate through space. Surface materials like regolith's, craters, mountains, and hills are found on the surface of the Moon [17]. Because of shadowing, the goal is to determine for model development, the total PL from equation (6) is represented as Equation (7):

$$\overline{PL}(d) = PL(d_0) + 10 * n * \log\left(\frac{d}{d_0}\right) + X \quad (7)$$

where X (dB) is the normal distributed random variable with SD in dB.

Path loss and the logarithmic distance correlation involves variability between transmitter and receiver which can be expressed by the application of regression analysis to equation (7) which can be represented as equation (8).

$$Y = c + bX \quad (8)$$

where c represents the PL which is the intercept at a reference distance, b is the slope which represent the path loss exponent.

IV. METHODOLOGY

This section outlines the details about the simulation software utilized, the chosen location, and the parameters implemented for this study.

A. Simulation and Data Gathering

This study utilized an LDEM map that we imported into the Wireless Insite (WI) software. The WI software has the capability of loading the LDEM map and supports a frequency range from 50 MHz to 100 GHz. It employs high frequency electromagnetic methods for accurate simulations [16]. The imported LDEM map is characterized by the attribute present on the lunar surface such as craters, regolith's mountain, hill, to mention a few. A customized terrain material was created from the dielectric half-space type of International Telecommunication Union (ITU) dry earth for 28GHz on the software by specifying the reported study values for permittivity and conductivity of the lunar surface. A sinusoidal waveform featuring a carrier frequency of 28GHz and effective bandwidth of 5000MHz was applied. Nine simulation procedures were carried out utilizing 40dBm, 30dBm and 20dBm four transmitting half-wave dipole antenna with 28GHz sinusoid waveform transmitter stations that were set-up at different location on the 2km grid map on the connecting ridge of the lunar surface environment (Site01) which is labelled as 1 in Fig. 1 [18].

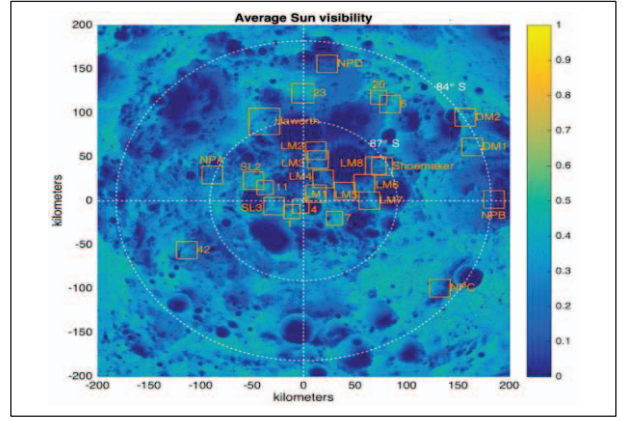


Fig. 1: Representation of LOLA Topography for Lunar South Poles Sites [18]

Receiver height varied at 1.5 meters, 1.8 meters and 2 meters which are positioned in an XY grid within the 2-kilometer coverage area with a grid spacing of 25 meters as shown in Fig. 2. The ray tracing X3D model was implemented in WI and used an APG acceleration method involving two diffractions and six reflections on an Intel-based windows 11 pro Core™ i7-10700 CPU at 2.90GHz, 8 cores 16 Logical processors and Graphic Processing Unit (GPU) Nvidia Quadro P2200. This specific simulation scenario utilizes half-wave dipoles, and it was configured to extract five scenarios of PL data: excess PL with antenna pattern, excess PL without antenna pattern, free space PL with antenna pattern, free space PL without antenna pattern and path loss. Other data such as received power, throughput, received signal strength indicator files were extracted. Each set-up consisted of four, 12-meter high, half-wave dipole transmitter antennas and 4320 receivers in the XY grid coverage of 2 kilometers with a half-wave dipole antenna. The extracted text files were later converted to a CSV format for analysis. Table II presented the simulation parameters before running the simulation to extract the five aforementioned path losses data. The methodology of the simulation is illustrated with Fig. 2.

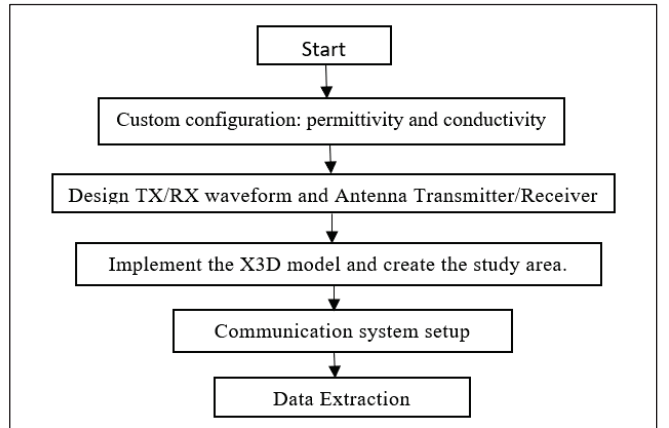


Fig. 2: Block Diagram for Simulation Procedure

Table II. MODELING VARIABLES

Variables	Values
Frequency (GHz)	28
Antenna Polarization	Vertical
Propagation model	X3D ray tracing model
Bandwidth (MHz)	50
Transmit Power (dBm)	20, 30 and 40
Transmitter Height (m)	12 (4Tx)
Receiver height (m)	1.5, 1.8. and 2
Permittivity	$\mu r = 3$
Conductivity	$\sigma = 1 \times 10^{-4} \text{ S/m}$
Antenna Gain (dBi)	20
Antenna type	Half-wave dipole
User spacing (m)	25

The simulation parameters are consistent throughout the nine (9) experiment for this study.

B. Study Location

The connecting ridge on the lunar south pole is the location of study. The lunar south pole is distinguished by its extreme environment, featuring craters with permanently shadowed areas due to mountains and hills, as shown in Fig. 3, and peaks of constant light due to the Moon's small axial tilt. These shadowed craters are potential repositories of water ice, making them scientifically significant and a potentially useful resource. The south pole's rugged terrain with features like thick regolith's creating a mix of sunlight and darkness, offers unique challenges and opportunities for future lunar missions.

V. RESULTS AND DISCUSSION

The rate of signal deterioration for the mmWave at 28GHz is depicted as a function of the distance between the transmitter and receiver, based on the value of the path loss exponent. The terrestrial acceptable path loss exponent was given in Table 1. Additionally, for LoS the value should be between 1.8 and 2.2 while for NLoS conditions it changes to 4 and 5 or when in LoS if transmitter and receiver experience a misalignment [12]. The five path losses data; *excess path loss with and without antenna pattern free space path loss (FSPL) with and without antenna pattern, and path loss* were analyzed, and the results are presented.

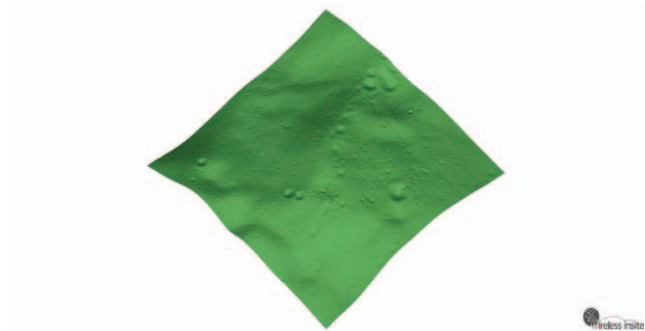


Fig. 3: Connecting Ridge LDEM Map on the Lunar South Pole

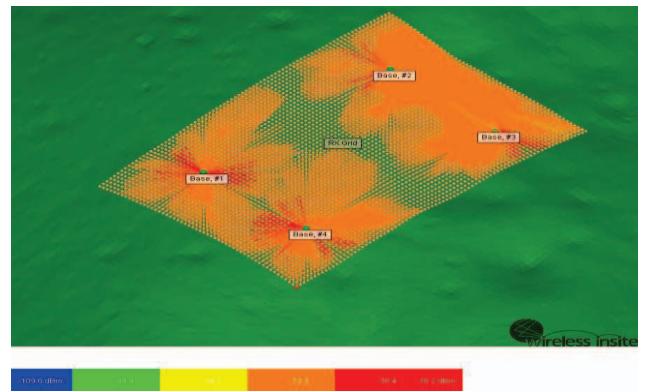


Fig. 4: Study Scenario Design

The excess path loss with antenna pattern quantifies the loss exceeding the free space path loss in scenarios where the antenna pattern is accounted for. While the excess path loss without pattern quantifies the loss exceeding the free space path loss in scenarios lacking an antenna pattern. The free space path loss with antenna pattern quantifies the loss when antenna pattern is included in the communication system design and the free space path loss without antenna patterns is calculated when the antenna pattern is omitted, and an isotropic pattern equivalent to 0dBi is assumed. The path loss is the reduction in power loss between the transmitter and the receiver. Each transmitter produces five (5) separate results from the analysis. Fig. 5 to Fig. 8 summarize the simulation results.

Fig. 5 shows the empirical results derived from Transmitter 1 (Tx1) across varying power levels and receiver antenna heights. The figure illustrates a composite of path loss data compared with their corresponding path loss exponent (PLE) values, offering a comprehensive perspective on signal propagation characteristics. Trends observed in the dataset reveal a distinct correlation between the receiver antenna height and PLE values. For instance, the 'Excess Path Loss with Antenna Pattern' indicates a peak PLE at 23.89 for a 2m antenna height across all transmit powers, while the lowest is observed at 1.5m, displaying a PLE of 23. This suggests that antenna height plays a pivotal role in signal attenuation, with higher elevations encountering more significant path loss on the lunar surface. Moreover, the transmit power levels 20dBm, 30dBm, and 40dBm exhibit a relatively consistent influence on PLE for Tx1, yet the data does not suggest a simple linear relationship. For 'Path Loss', the average PLE at 30dBm and 2m antenna height is 13.69, slightly higher than at 20dBm and 40dBm, which report a PLE of 13.64. This could imply that there are other factors at play, such as the ground wave reflection, multipath.

Fig. 6 presents the results obtained from Transmitter 2 (Tx2) depicting all path loss exponent values revealing the behavior of radio signal propagation on lunar south pole surface. It was also observed that the highest receiver antenna height experienced the highest PLE value of 29.74 for the excess pathloss with antenna pattern and 28 as the lowest at 1.5m Rx for 40dBm power and 28.8 for 30dBm and 20dBm. The transmit powers for excess path loss without antenna pattern all recorded 28.77 at 1.5m Rx height and 29.71 at 2m Rx height. The FSPL with and without antenna pattern follows

suit in the same direction revealing lowest PLE values of 10.31 and 10.36 at 1.5m Rx height respectively and highest of 10.84 and 10.86 at 2m Rx height respectively. The path loss value is also 16.44 at 1.5m for 40 dBm and 20dBm but 16.8 at 30 dBm power level while at 2m Rx height the value reported 16.95 for all power levels.

Fig. 7 illustrates the results from Transmitter 3 (Tx3) graphing the PLE values as obtained from the data analysis. It was observed that at 1.5m Rx height, the excess path loss with antenna pattern and without antenna pattern lowest value are 31.7 and 31.79 respectively and highest value of 32.52 and 32.49 at 2m Rx height respectively while the FSPL with antenna pattern and without antenna pattern shows the PLE lowest value at 1.5m Rx height of 13.89 and 13.9 respectively whereas the highest value revealed 14.43 and 14.44 respectively.

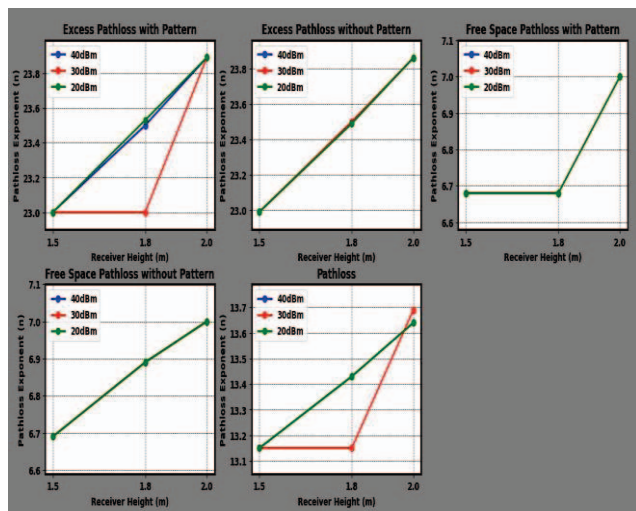


Fig. 5: PLE Value for all Power and Receiver Heights at Tx 1

Also, the result for Transmitter (Tx4) is presented in Fig. 8, showing that excess path loss with and without antenna pattern, free space path loss (FSPL) with and without antenna pattern, and path loss revealed varying PLE values at 1.5m Rx height with 25.9 as the lowest value for 40dBm power and 25.93 for 20dBm and 30dBm power while all three power levels show 26.88 as the highest PLE value for. The trend continues as the previous graph had depicted for FSPL with antenna pattern and without antenna pattern. The path loss value revealed 14.77 at 1.5m Rx height and 15.29 at 2m Rx height.

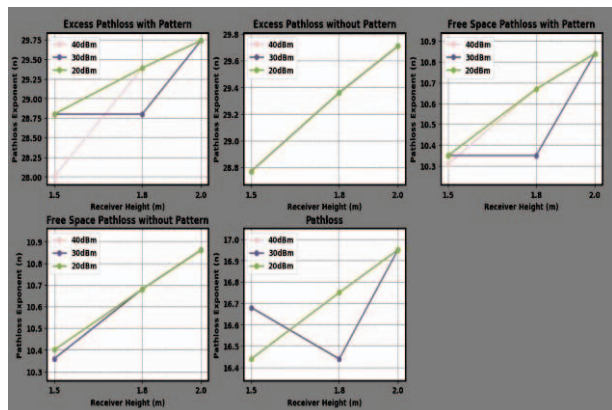


Fig. 6: PLE Value for all Power and Receiver Heights at Tx 2

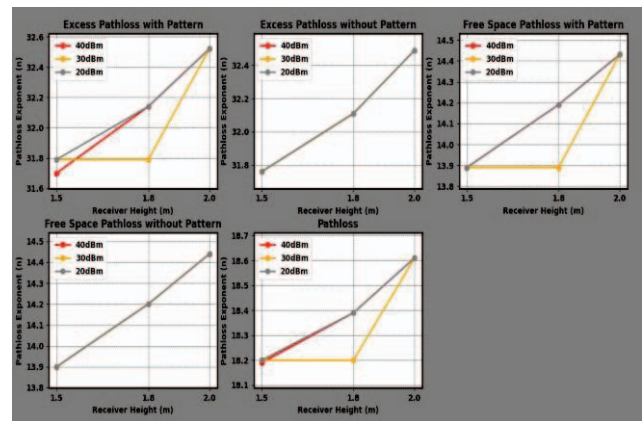


Fig. 7: PLE Value for all Power and Receiver Heights at Tx 3

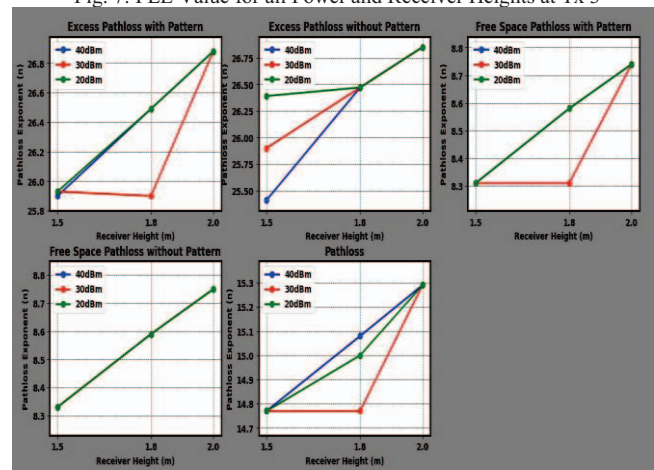


Fig. 8: PLE Value for all Power and Receiver Heights at Tx 4

VI. CONCLUSION

This research employed the Wireless Insite software to present pioneering research in the characterization of signal propagation, varying power levels and receivers antenna height at 5G mmWave frequency at the lunar south pole, utilizing the Lunar Digital Elevation Model (LDEM) for detailed terrain mapping. The first transmitter figure provides foundational understanding by revealing that increases in receiver antenna height led to increases in PLE - indicating that height is a significant factor in signal attenuation. At peak PLE at 2m shows 23.89 while at lowest PLE at 1.5m suggesting that propagation is adversely affected by elevation. These observations are consistent in all power levels from each path loss scenario, also suggesting that antenna height is a dominant factor over transmit power in this context. Transmitter 2 reinforces the same trend with even higher PLE values with a peak at 29.74 at a 2m antenna height. Intriguingly, the relationship between transmit power and PLE remains non-linear, as observed with transmitter 1. This non-linear relationship could be because of the complex surface interactions, such as ground wave reflections and multipath effects from the regolith and shadowed craters. Transmitter 3 and transmitter 4 continue a similar trend, however, the PLE values for transmitter 4 are somewhat lower than those of transmitter 2 and 3 which may be due to transmitter-specific location on the lunar surface. Moreover, the consistent pattern across multiple transmitters suggests that understanding signal propagation on the lunar surface

must account for elevation as a primary factor of influence. This research has provided a novel understanding of the behavior of 5G mmWave frequency radio signal attenuation on the lunar surface, suggesting that an increase in transmit power does not linearly affect signal deterioration, but an increase receiver antenna height does. Future work should investigate a lower frequency band and its bandwidth on the PLE for 4G and 5G cellular networks for more understanding of the lunar terrain.

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