Performance of HAPs Communication Systems in DUSA Storm: Analysis and Modeling

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***Abstract* – High Altitude Platform Station (HAPS) systems are currently under improvement and development. Technology is advancing towards the reliability and creative performance under reasonable fee for service providers and customers. HAPS technology represents one of the most revolutionary way of communication that appears to be convincing and effective under different weather conditions for any location in the world. For desert areas, such as Saudi Arabia, the main impact factor of HAPS is Dust and Sand (DUSA) storms. This attenuation varies with the operational satellite parameters such as frequency, location and other factors. This paper proposes some modifications to an existing DUSA storms model presented by a 3-D mesh model having different visibilities. This model for visibility depends on horizontal and vertical layers with reference to variations in altitude and space along with probabilistic dust particle size distributions in each layer. Such strategies help in conducting reasonable impairment estimates and in providing an optimal design for the HAPS system. As a result, an appropriate enhanced attenuation mitigation model is suggested.**

***Keywords*–*High Altitude Platform Stations*; *Permittivity indices*; *Quality of Service*; *Dust and Sand*; *Signal to Noise Ratio*.**

I. Introduction

Satellite communications are going toward High Altitude Platform (HAP) technology to cover specific locations such as crowded areas. This system uses an emerging wireless access technology represented by balloons or aircrafts for altitudes ranging between 15 and 25 Km above sea level. This system provides wireless communication networks for different users with the help of aircraft controlled or uncontrolled systems [1][2].

Some advantages of HAPS systems are represented by replacement of terrestrial mobile networks that is quite expensive, has potential health hazards and associated environmental impacts. On the other hand, besides the advantages of satellite systems, unequivocal disadvantages include building and launching them being reasonably expensive, the time interval efficiency associated with geostationary (GEO) satellites and movement requirements for other satellite systems [3]–[8].

Terrestrial systems, on the contrary, have also some difficulties, such as tower implementation for wireless networks, which is quite expensive, and safety problems. Therefore, implementing HAPS technology has became superior.

HAPS is the technology for providing wireless narrow band, broadband telecommunication and broadcasting services, particularly in remote rural areas where the deployment

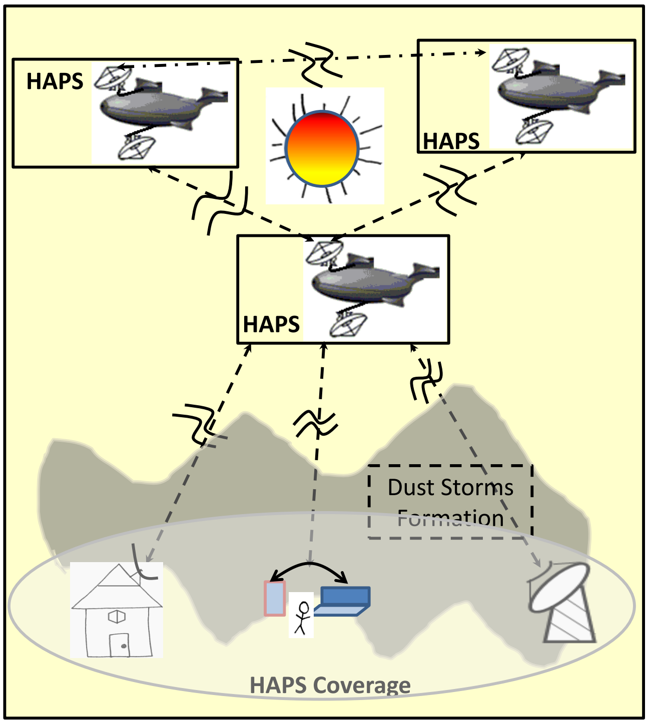

Figure 1. Effects of DUSA storms on HAPs communications.

of terrestrial network infrastructure is not only difficult, but costly as well. The HAPS technology attempts to present a new concepts and has several advantages in comparison to the implemented systems such as satellite and terrestrial. The maintenance of HAPS is also easy and can be relocated as needed. Besides that, HAPS maintenance is easy, not expensive, and can be reallocated as needed. Note that, a round-trip delay is less than 0.5 ms and satisfies human safety [1][2][9]–[12]. Moreover, HAPS can be easily integrated with the existing satellite and terrestrial systems, as depicted in Figure 1.

For arid and semi-arid areas such as Saudi Arabia and its surrounding countries, which are affected with extreme DUSA storms for almost six months per year, the microwave signals are impaired by different weather parameters including dust particle size distributions, visibility and humidity level within DUSA storms [13]. Since DUSA particles from different regions have different characteristics, such as relative permittivity and average sizes, it has hitherto remained a challenge in creating a generic storm model. This paper proposes visibility variations inside DUSA storm represented by four layers or

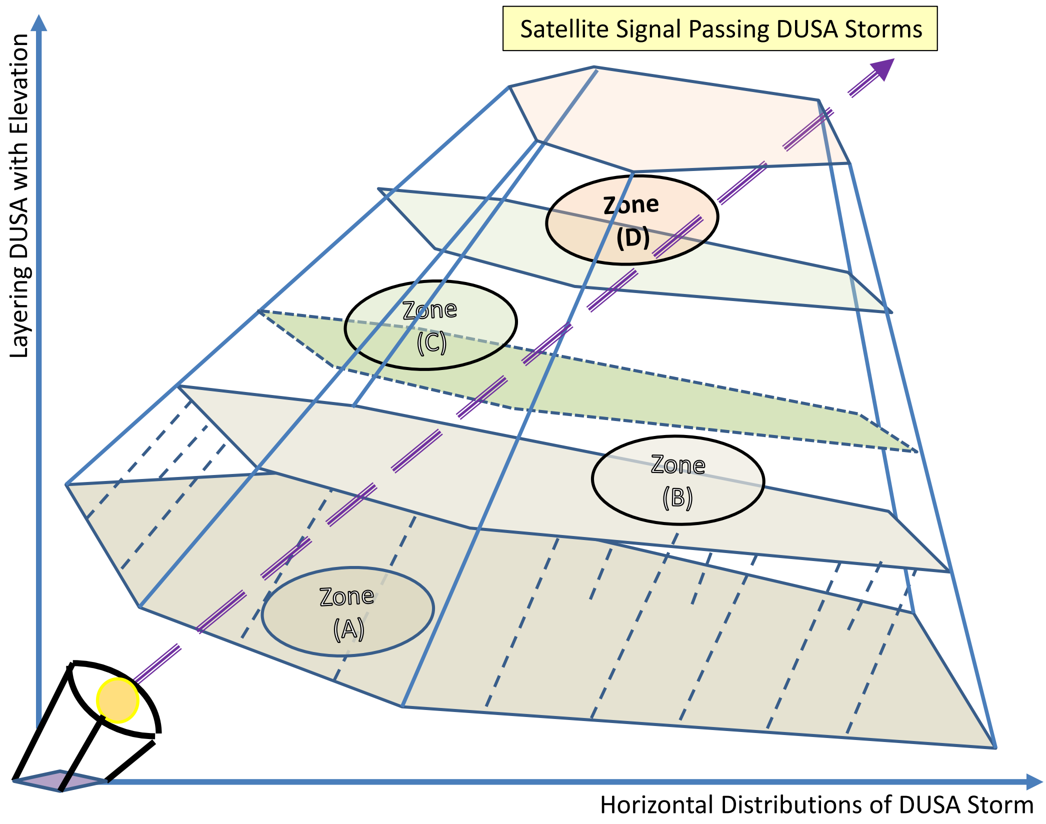

Figure 2. Visibility distribution model within DUSA storm according to different heights.

zones A, B, C, and D, as shown in Figure 2. Also, it presents wireless signal penetrations through multiple layers along the storm that contained different visibilities and particle sizes, etc. According to DUSA storm behavior such as location, intensity, and height, designers have the ability to select the number starting at two up to ten layers. Note that, increasing the number of layers in some cases might not be necessary, especially at high visibility form, as it may not lead to a better system performance and improvement.

This paper is presented in six sections. Section II describes the modeling of DUSA storm in the presence of layering. Section III presents the methodology of DUSA storm variation with visibility level. Section IV discusses different research methods for HAPS systems. Also, it presents analysis and modeling for DUSA storm, propagation effects and link budget calculation. Section V presents SNR results and discussion for HAPS behavior under heavy storm conditions. Finally, we conclude this study in Section VI.

II. DUSA Storm Modeling

The visibility, in desert areas, is usually regarded as a measure for the severity of DUSA storms, and is considered to be severe storm if visibility is below 500 m [14]. A low value of visibility implies that the wireless signal has to pass through a heavy concentration of DUSA particles, which have a particular size distribution depending upon the region of study. DUSA mechanics terms the particles below $60\ \mu$m as dust particles otherwise it is sand [15]. Accurate quantification of DUSA attenuation highly depends upon particle sizes, permittivity indices and maximum attenuation that occurs when the particles are of the order of the wavelength of transmitted signal. Most of the DUSA storm prediction models assumed uniform distribution and then neglected the different particle size distributions within DUSA storm [16], which is a most likely reason for slight inaccuracy between real and expected impairments.

In most cases, DUSA storms extend up to 5 Km above the satellite ground station [9], making it almost impossible to recover or immunize the satellite signals against its impairments. Reasonable information of expected impairments due to several factors leads to better satellite link utilization and effective radio resource management. The overall systems' Signal to Noise Ratio (SNR), which is also referred to in terms of Quality of Service (QoS) can be increased by weather adaptive variations in modulation, power, antenna beam shape, site diversity, etc. [7][17]–[21]. From engineering's perspective, the goal is to optimally utilize all radio resources including channel bandwidth, computational complexity, etc. Furthermore, parameters of such communications must also abide by the imposed limitations concerning to human health.

Chu's model for DUSA prediction was implemented based on Rayleigh approximation in [22]. This model presents an enhanced method for the measurement of dust attenuation, by introducing vertical path adjustment factor (r_v). This factor is dependent upon earth station's reference height (h_0), overall DUSA storm elevation (h_l), propagation angle (θ), and the

 ISBN: 978-1-61208-397-1

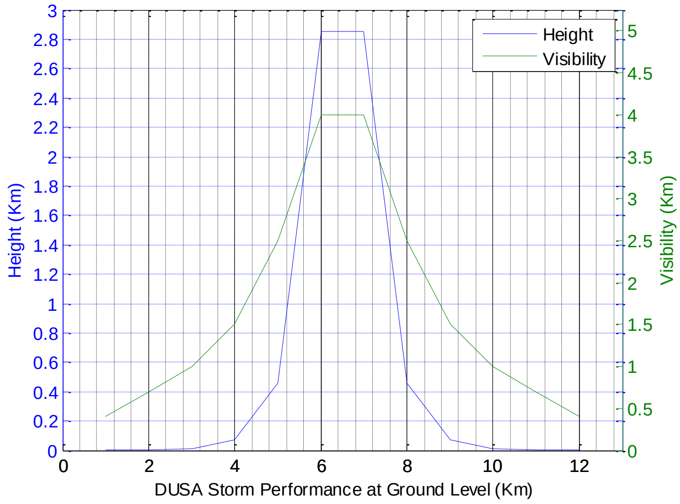

Figure 3. DUSA storm mirrored model for HAPS with visibility and height variations.

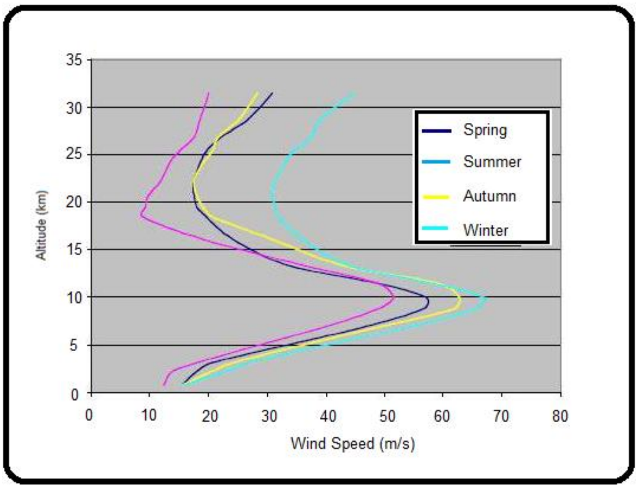

Figure 4. Variation of wind speed with altitude at Spokane, Washington [2].

slant path (L) where the radio wave traverses in dust filled regions.

Weather predictions can be used to dynamically reconfigure the radio resources for better link performance as well to keep the required level of QoS for the most important network components. A generalization of this concept is to utilize minimal resources during clear weather conditions whereas optimally manage resources based on weather predictions. Weather attenuation estimates have been presented by accounting for the variations in the probability distribution of DUSA particles.

III. METHODOLOGY

Visibility level keeps on increasing in a monotonic fashion while moving in a vertical direction as shown in Figure 2. This model is developed in an attempt to improve the existing one considering uniform duststorm distribution. Also, the simulation outcomes of this model is presented in Figure 3. The horizontal axis of this figure showed the DUSA performance at ground level with both vertical axes presented by height in blue color from the left side and visibility in red color on the right side. The results depict almost $100\ \mathrm{m}$ visibility at the ground station, i.e., the base layer which keeps on increasing to reach $5\ \mathrm{Km}$ elevation, at which transmitted signal gets out of the dust influenced region. Based on this fact, this paper presents a strategy to divide the whole DUSA storm into several layers according to visibility level.

$$h_i = h_{i-1}\left[\frac{V_i}{V_{i-1}}\right]^{3.85} \tag{1}$$

Equation (1) is being recursively used to obtain DUSA storm height layering or partition in accordance to visibility variations at several altitudes.

IV. RESEARCH METHODS

A. HAPS System Geometry

HAP is intended to provide different wireless communications of services such as mobile, TV, and internet, which are located in a fixed point according to earth station and belong to the stratosphere ranges of around $15 - 25\ \mathrm{Km}$ of altitude [1][12]. The footprint, and hence the coverage area of the HAPS communication system is uniquely defined by the accepted minimum elevation angle and its height.

In this paper, the height of the platforms were defined to be $22\ \mathrm{Km}$ taking into account the ITU-R recommendations and the wind behavior. From the mathematical calculation of the coverage areas either urban, suburban, or rural areas were determined by the subscriber, the corresponding slant path is $64.324\ \mathrm{Km}$ and the coverage radius is $60.445\ \mathrm{Km}$ [12].

B. HAP Location and Wind Behavior

The wireless channel between satellite hub and transponder consists of several layers starting with the troposphere above $10\ \mathrm{Km}$ in altitude. Within this layer, air temperature and pressure decrease with elevation. Going forward, the stratosphere is the next layer, up to $50\ \mathrm{Km}$ in altitude. Much research has been done to conclude that this layer is stable, i.e. slightly windy, and temperature increase with elevation. Also, there is no effect for clouds that help using the solar energy in an efficient manner [1][2]. Therefore, Figure 4 presents useful data for designers to select the ultimate location for HAPS transponder in the space at different areas with relatively low wind, minimum demanding power, high stability which located between 15 and 25 Km. Note that, wind speed variations with height at different location is presented by different researchers [23][24].

C. Propagation Effects

The propagation losses along the fuzzy path connected between ground station and HAPS can be attributed to rain,

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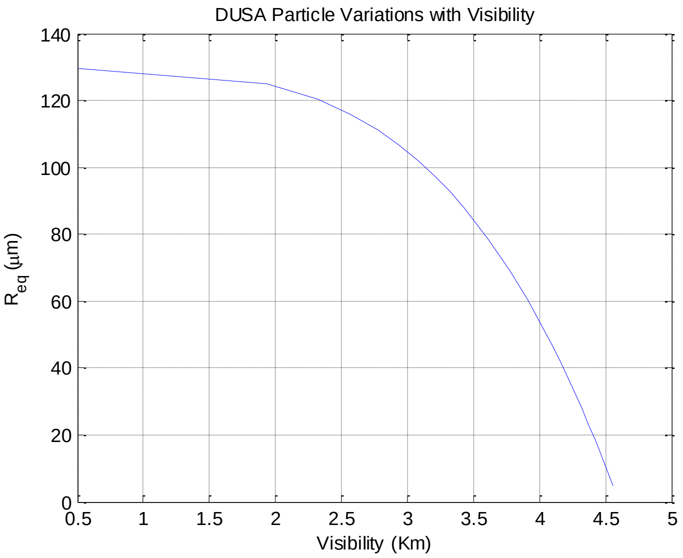

Figure 5. Visibility and DUSA size variations.

DUSA, gases, free space and other attenuations. The existing free space loss is calculated in (2). Our main concern in this paper; related to desert area, is DUSA attenuation as calculated in (4).

1) Free-Space Loss: The free space path loss (L_f) is:

$$L_f = 10 \cdot log(4\pi d/\lambda)^2, \tag{2}$$

where $\lambda(wavelength) = c/f$,
d is the distance between the satellite ground station and the HAP transponder with propagation angle (θ) is:

$$d = h/sin\theta, \tag{3}$$

where h represents the HAPS height above sea level.

2) DUSA Attenuation: DUSA storms can potentially result in serious impairments by increasing losses and destroying transmit signal especially at higher frequency of operation. Mostly, DUSA storms are considerable meteorological phenomenon characterized by strong winds and dust-filled air and water vapor over a wide area such as Saudi Arabia, Nevada, USA, etc. [9][16][25].

There is a number of different models that have been proposed for dust attenuation estimation, taking into account the variation of visibility, particle size, and concentration of the dust particles. An attractive model for the attenuation was proposed by [9][11][16] and is updated in this paper as:

$$A_{Pl} = \left[\frac{5.67 \cdot 10^2}{V_l \cdot r_{el} \cdot \lambda}\right] \left[\frac{\varepsilon''}{(\varepsilon' + 2)^2 + \varepsilon''^2}\right] \sum_i^N p_{il} \cdot r_{il}^3 \; dB/Km, \tag{4}$$

where point attenuation for each layer A_{pl}, ε' and ε'' are real and imaginary dielectric constant, r_{el} is the equivalent particle size corresponding to each layer, and V_l is the visibility of different layers along the signal path is given by:

$$V_l = V_{0l} \left[\frac{h_l}{h_0}\right]^{0.26}, \tag{5}$$

where V_{0l} is the visibility at the reference height h_0 that is dependent on the selected point within the storm. h_l is the height of one layer where each layer has different values. Usually, this height should be small while facing low visibility at low level and increase exponentially with elevation. Therefore, the variations of the visibility (V_l) inside DUSA storm according to travel distance (h) and radius particle size (R_{eq}) are illustrated in Figure 5. This figure shows the variation of visibility with dust particle radius, i.e., particle size decreases, visibility increases.

TABLE I. LINK SPECIFICATIONS AND INPUT PARAMETERS FOR HAPS.

Downlink Operating Frequency [GHz]	32
Transmitted Power [W]	0.5
Transmitting Antenna Gain [dBi]	5 (Minimum available)
Diameter of the Parabolic Antenna (Ground station)	1.3m
Aperture efficiency of Parabolic Reflector	0.55 (Minimum available)
Distance between Satellite and Ground Station (Km)	22
Ground Station Receiver Noise [K]	$\sim$ 119
Ground Station Antenna Noise [K]	$\sim$ 35
Ground Station Amplifier Noise [K]	$\sim$ 60
Bit Rate of the data (Mbps)	1
Bit Error Rate (BER)	10^{-6}
Modulation	QPSK

Therefore, the updated total attenuation based on DUSA layering, A_{DUSA}, can be obtained from the following expression:

$$A_{DUSA} = r_v \times d \times A_{pl}, \tag{6}$$

where r_v is the vertical path adjustment factor and all other symbols carry their usual meanings. The vertical path adjustment is estimated using the following relation [16] as:

$$r_v = \frac{h_0^{0.26} \times h_l^{0.74}}{0.74 \times \; d \; \times \; (\sin\,\theta)^{1.74}} \tag{7}$$

It is clear from the expression that, r_v is a function of the inclination angle (θ), height of the storm (h_l), reference height (h_0) and the slant path (d). Then, the values for DUSA attenuation were obtained, using the proposed model, by going through (2) to (7) for existing model, and for varying dust particle sizes with different heights (h_l), is presented in Figure 6.

D. Algorithmic for SNR Calculation

In satellite communications related to desert area, the most prominent contributors to noise, beside rain, is the DUSA storm. Start SNR calculation by the thermal noise power spectral density as: $N_0 = K \cdot T$, where Boltzmann constant $K = 1.38 \cdot 10^{-23}\; Ws/K = -228.6$ dBWs/K and effective noise temperature $T = T_a + T_r$, T_a is noise temperature of the antenna, and T_r is noise temperature for the receiver represented as $\mathrm{T_r} = (10^{N_r/10} - 1) \cdot 290$, with noise figure of low-noise amplifier, $N_r \approx 0.7 \sim 2$ dB. Thus, the ratio between signal and noise power spectral density is:

$$\frac{C}{N_0} = \frac{C}{K \cdot T} = \frac{P_r}{K \cdot T} = \frac{P_t \cdot G_t}{A_T} \cdot \frac{G_r}{K \cdot T}, \tag{8}$$

where total attenuation A_T is:

$$A_T = A_{DUSA} + L_f \tag{9}$$

TABLE II. ASSUME MAXIMUM VALUES FOR HAPS LOSSES.

Atmospheric Loss (dB)	1
Rain Attenuation (dB)	1.3
Fog Attenuation (dB)	0.03
Atmospheric Reflection (dB)	0.2
Ionospheric Loss (dB)	0.6
Polarization Loss (dB)	0.3
Miscellaneous Attenuation (dB)	0.27
DUSA Attenuation (dB)	**0.92**
Total Atmospheric Losses (dB)	**5.12**

Therefore, SNR is presented as:

$$SNR(A_T, f) = P_t + G_t - A_T + G_r - R_s - T - K \quad dB, \tag{10}$$

where P_t and P_r are transmitter and receiver power, and G_t and G_r are antenna gain at transmitter and receiver sides respectively. It should be noted that the SNR estimation of (9) will be optimized by the virtue of having better estimation of A_T through (10), SNR result is presented in Figure 7.

E. Fading Mitigation Techniques

Some researchers including [9][11] proposed the use of intelligent mitigation schemes for SNR improvement. The mitigation techniques that were applied to compensate the attenuation impairment during heavy attenuation period, including Skillful Atmospheric Aware Model (SAAM) for satellite systems, and space diversity such that whenever a heavy DUSA storm condition is experienced, the traffic can be rerouted via the second back haul link. The latter is ineffective as far as mobile HAPS communication system is concerned [11]. SAAM algorithm does not only serve as mitigation technique during a heavy storm, but it provides cost effectiveness as well. The system will be transmitting power according to the demand. By knowing the required performance such as weather prediction, the system will maintain appropriate SNR level by changing the transmitted power according to the demand. The automatic power control mechanism is used whereby the transmit power changes as the dust attenuation changes and it transmits the minimum power during the clear air conditions. However, once weather attenuation increases and power factor reaches its limits, other parameters should be updated to maintain SNR values above minimum signal level that is needed for costumer's satisfaction and acceptable communication performance.

F. An Effective Downlink Budget

This section will introduce a unique calculation for the HAPS downlink operated at 32 GHz. Other parameters are defined from Table I and are used as input parameters to the simulation. Several other losses have been considered with their maximum values at HAPS to ensure an efficacious link margin. In this paper, we introduce DUSA attenuation in the downlink budget specifications. The value was extracted from the simulations in the previous section. A maximum estimated value of 0.92 dB is shown in Table II along with all other losses.

Finally, the link budget is re-estimated with DUSA attenuation considered. The output parameters are shown in Table III. The link margin is an important parameter in satellite links and represents the difference between the available and the required values of the energy-to-noise ratio. It can be viewed as the amount by which the received power exceeds the receiver sensitivity. According to the ITU-R recommendations, practical satellite-earth links must maintain a healthy link margin above 2 dB in order to have effective communication links with acceptable QoS. As can be inferred from the output parameters, the presented satellite link margin is found to be 2.07 dB, which is sufficient for a reliable satellite communication link.

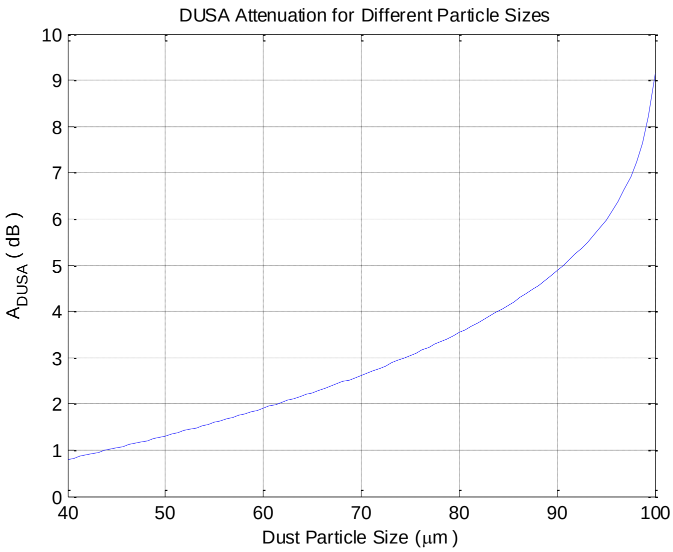

Figure 6. DUSA attenuation for variety of particle sizes at frequency = 30 Ghz and propagation angle = 45 degree.

TABLE III. SUMMARY OF DOWNLINK OUTPUT PARAMETERS FOR HAPS.

Effective Isotropic Radiated Power (dBW)	1.99
Free Space Path Loss (dB)	149.4
Atmospheric losses	5.12
Total Losses (dB)	151.39
Received Power (dB)	-132.23
Noise Density (dB)	-207.14
Received Power to Noise Ratio (dB)	57.01
Energy to Noise Ration (Available) (dB)	14.37
Energy to Noise Ration (Required) (dB)	10.29
Link Margin (dB)	**2.07**

V. RESULTS DISCUSSION

From the output result, the performance of the system was promising under dusty conditions. In case of clear weather, the only degrading component was the path loss. The available SNR ratios were ranging between (-14.0 and -4.0 dB). However, during the DUSA storm, the SNR were drastically reduced to be between (-12.0 and -23.0 dB), keeping other parameters constant, as shown in Figure 7. With the increasing of transmit power, during the heavy storm conditions, the system can provide the required services with relatively reasonable QoS. In this paper, the transmitted power was assumed to be 0 dBm and the results were satisfactory. Thus, a much better result is expected if the transmit power can be raised.

ISBN: 978-1-61208-397-1

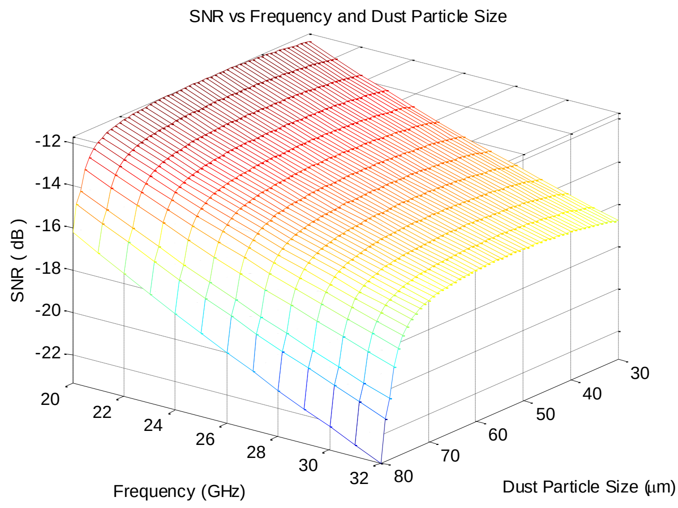

Figure 7. SNR for different DUSA particle size and frequency.

VI. Conclusion and Future work

This paper investigated the link reliability during the DUSA storm scenario. By implementing DUSA layering in order to estimate DUSA attenuation, it was found that the link margin dropped due to the fading effect of the DUSA storm that might destroy the signal at certain levels. Though, the system at this level can be considered operational, only an extra attenuation of around 2.1 dB is enough to make the system unreliable. Therefore, with the application of automatic power transmission and adaptive coding and modulation, the required QoS can be maintained.

Future work is in progress to consider real DUSA measurements at different locations, and to compare it with our simulation. Also, the study of hurricanes and other atmospheric phenomena, as well as proposing enhanced strategies to better present satellite systems.

Acknowledgment

The authors wish to thank King Fahd University of Petroleum & Minerals (KFUPM) and Hafr Al-Batin University, Electrical Engineering department. This work is supported by the Deanship of Scientific Research (DSR) at KFUPM through project No. FT121013.

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