Ka-Band VSAT System Models under Measured DUSA Attenuation

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Abstract—**The satellite industry's need for Ka-band is increasing due to capacity abundance and cost efficiency. The commonly used C-band and Ku-band satellites have a limited number of geosynchronous orbital slots for given frequency bands. Thus, industries are turning to Ka-band satellites. Operating at high frequencies making them vulnerable to atmospheric conditions like rain, scintillation, dust, humidity, etc. Performance analysis of Ka-band Very Small Aperture Terminal (VSAT) system under Dust and Sand (DUSA) storms induced impairments in Dhahran city, Saudi Arabia, is presented in this paper. In this area, DUSA storms are usually observed due to desertification. Satellite communications and microwave networks are among the most commonly utilized means of communication, scattered all over the country. These networks observe radio wave degradations due to the frequently occurring DUSA storms. This study precisely quantifies attenuation due to DUSA based on real time measurements, being observed in the Eastern region of Saudi Arabia. Simulation results of real time measurements based on the level of visibility during DUSA storms are being proposed to counter the impairments in an optimized manner. These results are then analyzed in a digital video broadcasting - satellite - second generation (DVB-S2) VSAT system environment. The mentioned analysis of received signal strength during such anomalous weather conditions can aid in performance optimization by monitoring the received signal and maintaining it within acceptable level.**

***Keywords*–*Broadband services*; *Digital video broadcasting-satellite-second generation*; *Ka-band Very Small Aperture Terminal*; *Signal to Noise Ratio*.**

I. INTRODUCTION

Satellite service suppliers are targeting the consumer market for the provision of broadband access, knowledge of information and communication technologies and other multimedia applications [1]–[3]. The availability of alternative services, such as Digital Subscriber Line (DSL) or cable, is not common in rural and sub-urban areas. Thus, making the delivery of broadband services to customers via Ka-band satellites is more suitable [2]. Ka-band systems do not use the concept of single service area, rather they employ spot beams. Utilization of Ka-band satellites is an immediate consequence of the industry's need to give more satellite services, which would have resulted in higher cost if provided by legacy bands.

Previously, the Very Small Aperture Terminals (VSAT) market has depended upon C and Ku bands [4]–[7]. Therefore, there is a tight number of geosynchronous orbital slots that could be utilized for a given frequency band, and nearly all orbital openings are represented with current and arranged C-band and Ku-band. So, the Ka-band seems to be a definitive answer for any new satellite correspondence framework. Nevertheless, Ka-band has an immense disadvantage in comparison with C-band and Ku-band due to higher frequency range allotment [8]–[14]. Working at high frequencies makes it more prone to indicator quality issue due to climatic conditions incorporating rain blur, Dust and Sand (DUSA) storms, etc. Dissection of such climate induced weakening impairments in the Eastern district of Saudi Arabia is the essential contribution of this paper.

In this research, climatic information for DUSA storms has been gathered from Saudi Arabian sources and used in physical estimations to get precise gauges in the region of interest. In parallel to the focus of this analysis, many researchers have shown great interest in estimating the high frequency wave attenuation due to DUSA particles [2][3][15]–[18]. Very few studies are conducted at the Ka-band. The impacts are analyzed in a digital video broadcasting - satellite - second generation (DVB-S2) VSAT broadband framework, as depicted in Figure 1, with an adaptive scheme to gauge atmospheric attenuation, due to change in DUSA density at any given area with certain propagation angle and operational frequency. In the wake of quantifying such impairments at diverse and remote locations, improved back propagation-learning calculation – by iteratively computing operational frequencies, elevation angles, modulation and coding – is done to improve the Signal to Noise Ratio (SNR).

This paper is described in five sections. Section II describes the DVB-S2 for supporting forward and receive channels in a flexible way. Section III presents the methodology and simulation of DUSA storm. It also describes different research methods for dust storm. Section IV presents analysis and modeling for DUSA attenuation variations with other propagation factors. Consequently, SNR under DUSA storm conditions were calculated. Finally, we conclude this study in Section V.

II. DVB-S2 VSAT SYSTEM

DVB-S2 VSAT system is used to control record readings for weather attenuation. The remote terminal presented in Figure 1 sends data packets to a satellite and receives back an acknowledgement through Indoor Unit (IDU).

In the initial phase, several modern techniques to estimate the effects of DUSA storms on satellite communications were simulated in MATLAB environment for Ka-band frequencies. Later the parameters of DUSA storms relevant to Saudi Arabia were extracted and incorporated in the simulations to estimate their effects on Ka-band VSAT systems.

Furthermore, the estimates of DUSA density existing in air are gathered from various nearby weather stations and incorporated into simulations to quantify their effects in retarding

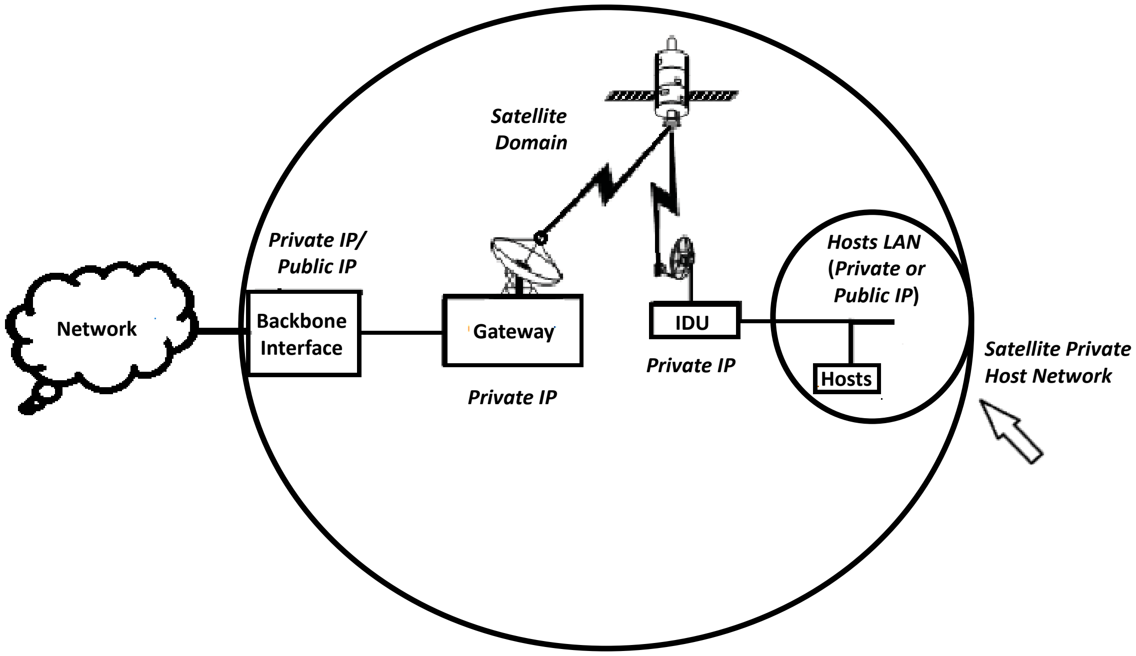

Figure 1. Example of DVB-S2 VSAT Complete Network.

the SNR, as well as Quality of Service (QoS) and therefore effective throughput of VSAT system.

DVB-S2 VSAT system has been modeled in MATLAB to analyze DUSA storms effects related to the concerned region. This system has been simulated in a flexible way such that the primary parameters of VSAT system can be adjusted by changing modulation, coding, transmit power, operating frequency, elevation angle, etc., based on the estimates of DUSA storms, to provide uninterrupted service while optimally managing the radio resources.

The system model is based on DVB-S2 for the forward channel and digital video broadcasting - return channel via satellite (DVB-RCS) for the return channels. DVB-S2 is currently the latest satellite communications standard in production and is commonly used for video based applications. It has the feature of low encoding complexity and also has variable and adaptive coding and modulation modes, which can be used for fluctuating noise conditions. In the forward direction, the system uses DVB-S2 in accordance with the DVB-RCS specification EN 301 790. It offers both QPSK and 8PSK modulation schemes. Figure 2 depicts the E_s/N_0 versus spectral efficiency for the various modulation schemes. While these signal-to-noise ratios are readily achievable for trunking applications between large earth stations, they are not generally available for VSAT networks. On the other hand, DVB-RCS utilized in this study uses the most advanced modulation and coding on the return (remote to gateway) satellite links available in the DVB-RCS specification where Table I

TABLE I. SPECTRAL EFFICIENCY DVB-RCS RETURN LINK.

Channel Spacing Factor = 1.25.	
Turbo Coding (Rate)	Spectral Efficiency (Bits/sec/Hz)
1/3	0.53
2/5	0.64
1/2	0.80
2/3	1.07
3/4	1.20
4/5	1.28
6/7	1.37

the performance of the return link. In the return direction, the system uses QPSK modulation with Turbo coding as per EN 301 790 exclusively. The system offers a variety of Turbo coding rates depending on the nature of encapsulation chosen for the return traffic.

Data traffic in all cases terminates/originates to/from the backbone routers and telephone switches located at the gateway location. This system model supports data communication between a remote in one sub-network and the corporate network, between two remotes in one sub-network and between two remotes in a different sub-network (one remote in sub-network 1 and one remote in sub-network 2). The space segment of the VSAT network consists of two transponders

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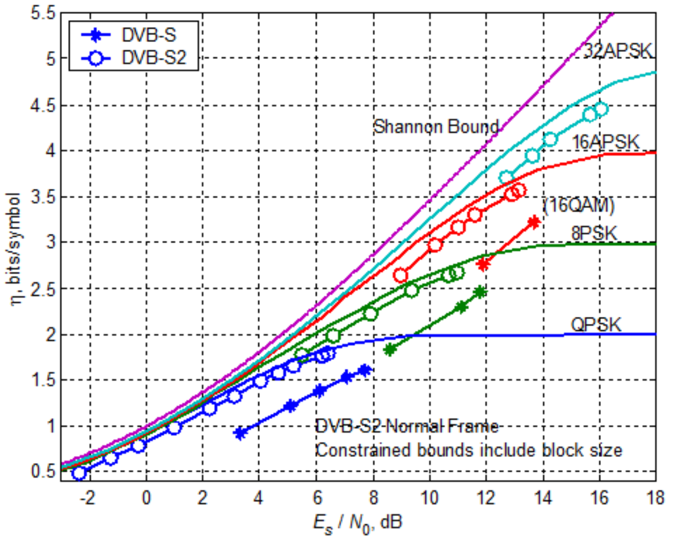

Figure 2. Spectral efficiency of DVB-S2 modulation schemes.

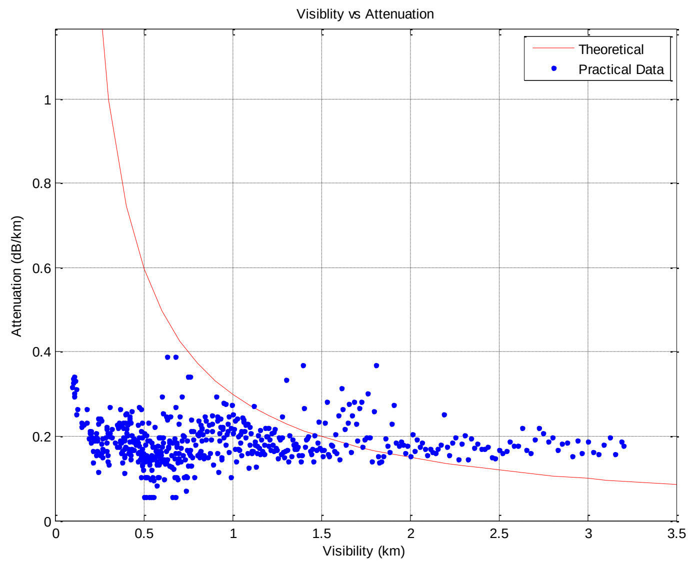

Figure 3. Comparison Uncompensated for Attenuation with Visibility.

on Intelsat 1002.

The test setup mainly consists of a VSAT remote terminal and a visibility sensor both located in Dhahran. The SNR of the transmitted data is physically measured to quantify the effects of such factors on the composite attenuation. Also, the visibility was observed at the same time.

III. METHODOLOGY

This section covers a brief review of different mathematical expressions used in the estimation of DUSA impairments. General formulas for electromagnetic (EM) wave passing through DUSA particles have been implemented in [3] using Rayleigh approximation attenuation and phase shift factors for a VSAT environment where DUSA particles are estimated considering two major components namely visibility and frequency.

A. Rayleigh Approximation

In [3], generic models for DUSA storms affected wave propagation constant based on Rayleigh approximation were developed. The satellite medium parameters experiencing DUSA storms impairment were derived considering location, visibility, frequency, and other factors. These formulas are correlated with the principles by Goldhirshs estimation [19]. By following the analysis for different particles model, the propagation will be:

$$K_{V,\,H}(\varphi) = k_0 + \frac{2\pi}{k_0}\int_0^{\infty} f_{V,\,H}(\varphi,\ r)\ N(r)dr \qquad (1)$$

where:
k_0: the free-space propagation constant,
φ: the incident radiation propagation angle,
$N(r) = N_0\ P(r)$: DUSA distribution per (cm^3) having radius in the region of $r \rightarrow r + dr$.
$f_{V,H}(\varphi, r)$: the forward scattering amplitude for vertical (V) and horizontal (H) polarizations.

B. Goldhirsh's Formula

Contingent on the Rayleigh approximation, the attenuation model for satellite signal propagation in DUSA storms derived by Goldhirsh is [19]:

$$\alpha = \frac{2.317 \times 10^{-3} \times \varepsilon''}{[(\varepsilon' + 2) + \varepsilon''^2] \times \lambda} \cdot \left(\frac{1}{V_b^{\gamma}}\right) \quad [dB/Km] \qquad (2)$$

λ: the wavelength in m,
ε' and ε'': the dielectric constant of the DUSA particles,
$\gamma = 1.07$, and V_b visibility in Km is a key component for evaluating of dust induced impairments. Equation (3) presented in [20] shows dependence of visibility and height (h).

$$V = V_0 \left[\frac{h}{h_0}\right]^{0.26}, \qquad (3)$$

where V_0 and h_0 are the reference visibility and height, respectively.

C. Ahmed Derivation

Ahmed et al. derived a DUSA storms attenuation model for millimeter-wave based on measured probability density function and Mie theory. The model is expressed by [21]:

$$\alpha = 5.670 \times 10^4 \cdot \left(\frac{1}{V_b}\right) \cdot \left(\frac{r_e}{\lambda}\right) \cdot \frac{\varepsilon''}{[(\varepsilon' + 2) + \varepsilon''^2]} \qquad (4)$$

Here, r_e is the effective particle radius in μm.
Similarly, a generic model suitable for different particle sizes

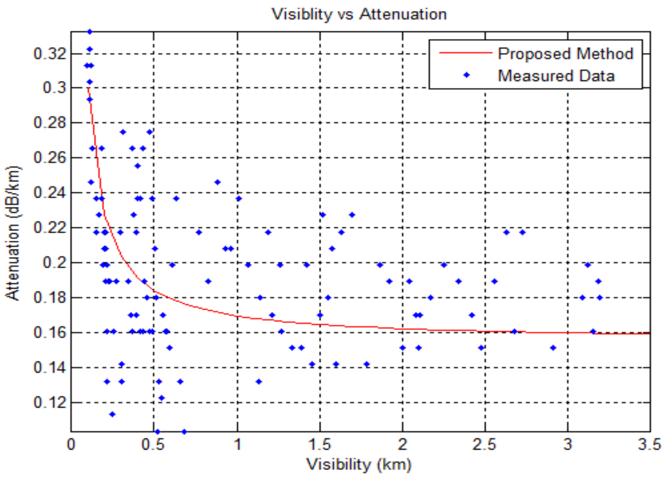

Figure 4. Comparison Compensated for Attenuation with Visibility.

distributions developed in [21] for microwave propagation in DUSA storms is shown as:

$$\alpha = 0.629 \times 10^3 \cdot \left(\frac{F \cdot r_e}{V_b}\right) \cdot \left(\frac{\varepsilon''}{[(\varepsilon' + 2) + \varepsilon''^2]}\right) \quad (5)$$

F: the frequency in GHz.

D. Al-Haider derivation

Considering 10 years visibility data and the Rayleigh approximation, Al-Haider developed another attenuation model for microwave propagation in DUSA storms [5] as:

$$\alpha = \frac{0.189}{V_b} \cdot \left(\frac{r}{\lambda}\right) \cdot \left(\frac{3\,\varepsilon''}{[(\varepsilon' + 2) + \varepsilon''^2]}\right) \quad (6)$$

r: the particle radius in m.

The above model is applied to our region of interest in Saudi Arabia. The data pertaining to visibility has been extracted from literature [4]–[12] and is physically measured to quantify the effects of such factors on composite attenuation.

IV. ANALYSIS

The measured data presented in Figure 3 and Figure 4 are used for analyzing DUSA attenuation variations with different values of collected visibility. The uncompensated data for theoretical and practical scenarios presented in Figure 3 show that the theoretical line marginally models the practical data with a higher degree of variations up to approximately 1.25 Km of visibility. This discrepancy at low visibility is due to the lack of appropriate model that match real measurements. It presents a big challenge for researchers and providers as signal could be totally blocked by DUSA storm.

The theoretical line follows a decaying exponential trend, but the recorded data (blue dots) resembles a linear relationship due to outcome discrepancy. It shows that the theoretical line (red) closely models the practical data only around 1.75 Km of visibility and missed it for the rest of data.

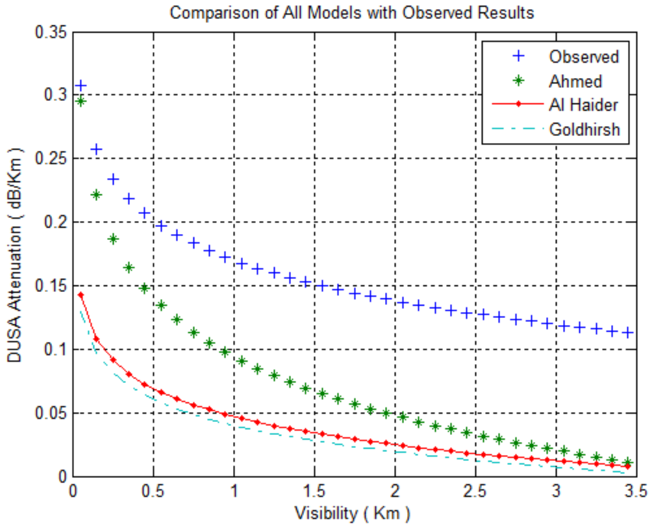

Figure 5. Comparison between different Models.

The proposed analysis for the compensated data was implemented to get better matching results especially at low visibility by tuning variables presented in (7). This improvement result for attenuation with different visibility is clearly shown in Figure 4. This outcome will lead to an appropriate value for SNR, as well as the overall system's throughput. The practical data (blue dots) follow the trend of recorded data though it is scrambled. However, we see roughly that at a visibility higher than 1.3 Km, the attenuation becomes constant.

DUSA attenuation model for real time measured data compared to other developed models is presented in Figure 4. Note that, the DUSA storms level above the ground, according to Saudi Arabia region, ranges between 4 Km to 6 Km for maximum.

According to numerical methods used for estimations presented in Figure 4, we present a model for DUSA point attenuation (A_p) as follows:

$$A_p = 2.2909 \times 10^{-16} + \left\{\frac{567}{V\,r_e^2\lambda} \times \cdots \right. \\ \left. \cdots \times \frac{\varepsilon''}{\left(\varepsilon' + 9.9595 \times 10^8\right)^2 + \varepsilon''^2} \times \sum_i^n p_i r_i^3 \right\} \; dB/Km \quad (7)$$

where $\sum_i p_i\, r_i^3$ represents the summation of different probabilities of particle sizes multiplied by the dust particle size. V is the visibility. Whereas, the parameters λ, r_e, ε' and ε'' are constant values at various frequencies as defined in Table II. The outcome of (7) represents the compensated expression of DUSA model. The constant value is extracted by inspection using MATLAB tests. This value can be integrated back into the original expression with changing of $(\epsilon' + 2)^2$ to $(\epsilon' + 9.9595 \times 10^8)^2$.

TABLE II. LISTING OF DIELECTRIC CONSTANTS AT VARIOUS FREQUENCIES MEASURED BY [5][6][19].

Dielectric Constants Values			
Frequency GHz	Soil Type	ε'	ε''
1 - 3	loam	3.5	0.14
3 - 10.5	clay, silt	5.73	0.474
10.5 - 14	sand	3.9	0.62
14 - 24	sad	3.8	0.65
24 - 37	loam	2.88	0.3529

A comparison between the observed attenuation model and others presented in this paper which resulted in deviation between the empirical values and the theoretical models is shown in Figure 5. There are many possible reasons for the deviation. One of the main reasons is that attenuations were simulated at different regions with different DUSA properties.

Thus, the proposed point attenuation along the radio wave path resulted in Figure 6 as a function of frequency and propagation angle with different particular sizes.

A. SNR Calculation

The improvement in SNR, as well as system's throughput based on estimation specific to the region is analyzed in [22][23]. The ratio between signal and noise are presented as:

$$SNR = P_t + G_t - A_t + G_r - T - K - R_s \quad dB, \quad (8)$$

A_t (total attenuation) = $A_{DS} + A_0$,
where the free space loss $A_0 = (4.\pi.d/\lambda)^2$,
d the distance in Km between the transmitter (ground station) and the receiver (satellite),
A_{DS} represents DUSA attenuation.
P_t and P_r represent the transmitter and receiver powers respectively.
G_t and G_r are antenna gains at the transmitter and receiver respectively. R_s is the transmission rate, K represents the Boltzman constant, and T represents the effective noise temperature.

A receive bandwidth (B_r) is considered. Thus, the noise power (N) will be:

$$N = N_0 \cdot B_r = K \cdot T \cdot B_r \quad (9)$$

System preformance of a digital system can be determined using the SNR or vice versa. Thermal noise power spectral density is given by $N_0 = K . T$, where, $K = 1.38 \times 10^{-23}\ Ws/K = -228.6\ dB\ Ws/K$, $T = T_a + T_r$, with T_a represents the noise temperature of the antenna, and the noise temperature of the receiver is:

$$T_r = \left(10^{\left(N_r/10\right)} - 1\right) \cdot 290 \quad (10)$$

$N_r \approx 0.7 \rightarrow 2$ dB: represents noise figure of low-noise amplifier, and R_s: represents the symbol rate.

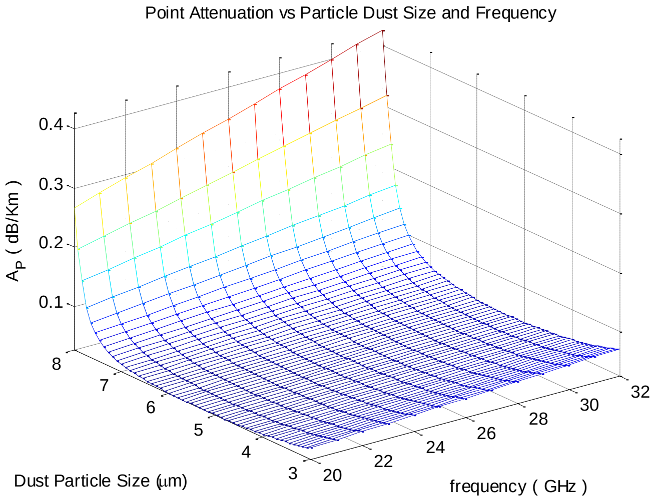

Figure 6. Point Attenuation with Visibility and Frequency under Dusty Weather in Dhahran, Saudi.

Therefore, satellite system performance is improved by providing enhanced estimates for attenuation due to DUSA storms leading to adjustment of SNR output in lieu of a wide range of frequencies, transmitted power, for any specific propagation angle, transmission rate, gain, and location as shown in Figure 7.

After having quantified the effects of DUSA storms in a generic satellite system, the main wave propagation parameters can be mitigated according to these impairments to eventually enhance the SNR and data-rates. Based on achieved analogy for different signal attenuation and SNR, designers are able to build a clear estimation for signal propagation in dusty and sandy weather conditions. Different results for geometries and locations of this technique are investigated. Resulting prototype products can be hardware controllers, which take the values of DUSA storm estimated as explained above, and would give optimal values of output transmit power, modulation, coding, operating frequency, and elevation angle.

Uplink Power Control (UPC) is a technique of adjusting the output power of the uplink with the aim to maintain a constant SNR ratio at a remote terminal, which can be used in our system's model. Adaptive Coding and Modulation (ACM) is used to keep the received signal quality above designers' threshold level in varying SNR levels. The modulation scheme is altered between a high capacity modulation at high SNR to a low capacity robust modulation at low SNR levels. After measuring DUSA storm attenuation, UPC and ACM can be used in the case of rain fade in satellite links.

V. CONCLUSION

Analysis of DUSA storm effects on a generic satellite link was the starting point of the proposed work. A relationship that estimates the DUSA storm effects has been derived for real time data. In this paper, different means for enhancing the throughput of a Ka-band broadband VSAT system were studied. Such systems are much susceptible to weather

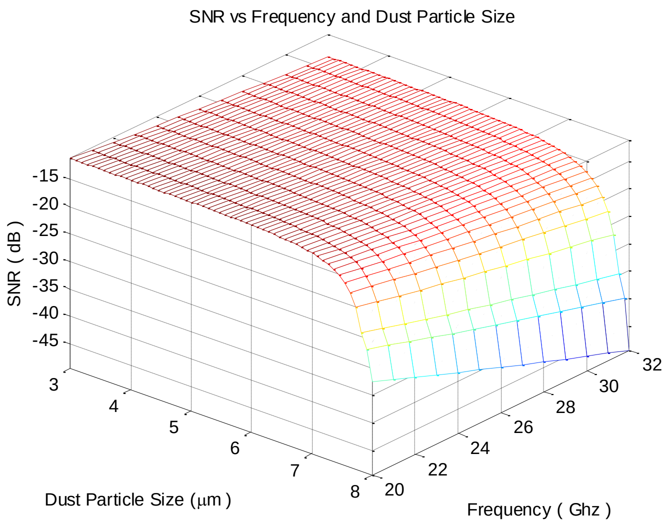

Figure 7. SNR Values vs Frequency and Dust Particle size in Dhahran, Saudi.

effects, in which DUSA storms impact transmitted signal and corresponding data rates are below the desired threshold levels. Hence, the performance of high throughput applications – like transmission of multimedia, interactive voice, etc. – is affected. The quantification of DUSA effects at different geographical locations, with the view to eventually upgrading the system parameters by virtue of an intelligent controller at the hub station. This system can ensure high throughput and reliable data transmission at all times. Estimating the attenuation due to DUSA storm is based on the latest techniques available in literature through incorporated weather data mainly about DUSA storms concentrations. In addition, the data is measured from different VSAT remote sites to achieve more specific physical results. Up to date techniques mitigate these effects and improve data-rates and QoS. The effects are analyzed in a DVB-S2 VSAT broadband system in which an adaptive scheme was used to estimate atmospheric attenuation due to DUSA density changes at any given location, with certain propagation angle and operational frequency.

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