# Modeling and analysis of millimeter-wave propagation in dusty environments

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**ABSTRACT**

In the fifth generation of wireless communication systems (5G), the millimeter wave (mmWave) signal can be affected by many challenges in irregular environments such as dust and sand storms. In this paper, we investigate the attenuation that faces a mmWave link signal in a dusty environment for different sizes of dust particles. Further, we derive a model to calculate the total attenuation in mobile communication systems and/or internet of things (IoT) in different base stations highnesses. The obtained results show that in a dusty environment it is better to have high base station transmitters as the signal may escape the dense dust area. The paper also studies the case of the city of Mosul to find that not only the dry weather is increasing the attenuation, but wet weather also may impact more on the attenuation in the mmWave systems.



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## 1. INTRODUCTION

Wireless communication systems, which include microwave links, mobile communication systems, and the internet of things (IoT), are growing daily and reaching new areas on the surface of Earth. However, many propagation challenges can scatter wireless signals while traveling between base stations and mobile stations. One propagation challenge is the dust and sand storms that usually occur in/or close to dryland areas [1]–[10].

The country of Iraq is considered to be among other Middle Eastern countries that are most affected by sand storms. These dust storms impact humans' health, economic systems, as well as mobile wireless communication systems. As sand and dust storms occur more frequently in the last couple of years in Iraq, as seen in Figure 1 [11], [12] we need to study and model the wireless communications signals in these irregular environments.

Dust storms lead to having sand particles in the Ghobrial and Sharief [1]. Further, as millimeter-wave (mmWave) is planned to be used in the fifth generation of wireless communications (5G), the wavelength of the signal will be close to the dust particle dimensions. The 5G is promised to have higher data communication rates. High-frequency bands, such as a super-high carrier frequency band (S-band), 3 GHz to 30 GHz, and an extremely high carrier frequency band (E-band), 30 GHz to 300 GHz, are going to be used to be able to fulfill the high data rates demand in the network. Rising frequencies may cause issues to the wireless signals, such as scattering, depolarization, and phase noise [2]–[5].

In IoT systems, where sensors are used to monitor different environmental parameters and report the obtained data to the central access point (CAP), the wireless link faces attenuation in the dust climate. The same description can be applied to wireless sensor networks as explained [13]. Therefore, to capture the impact of dust storms on the signal propagation attenuation, many articles discussed this attenuation in microwave communication networks [9]–[16]. However, most of these papers discuss microwave to microwave antenna links on the same height base stations. The altitude is very important as the dust particles become heavier and bigger closer to the ground [17]–[26].

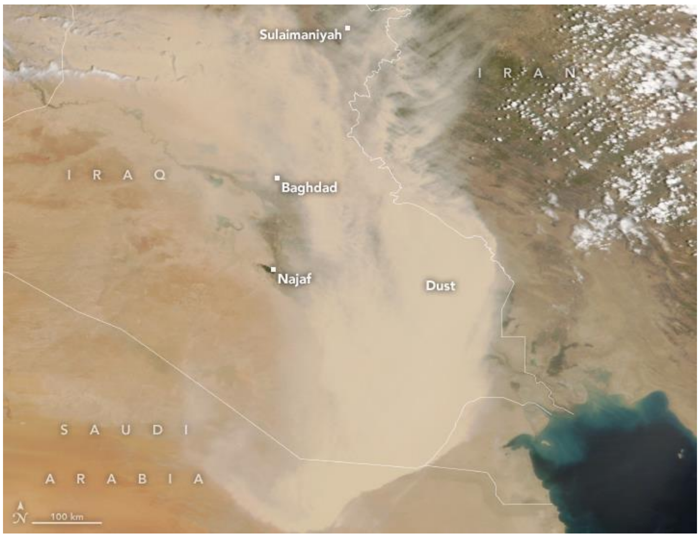


Figure 1. The dust storm in Iraq [11]

The radio channel model can be classified into analytical models and physical models [10]. The analytical models are usually founded on the mathematical analysis of the propagation channel. The physical channel models are based on the double-directional radio channel between the transmitter and the receiver of the electromagnetic wave propagation. Saleh *et al.* [9] provide a ray-tracing model about the impact of dust on wireless communications. However, the model is so complicated and they neglect the impact of different sizes of dust for different altitudes. The impact of attenuation of dust on the signal has also been discussed thoroughly in satellite communication systems in [10]–[12]. However, typically, the base stations are above the ground about 5−10 meters, will be slightly away from the heavy and big dust particles. The problem of mobile is more complicated as the phone is very close to the ground and in different places in the area.

In 5G the mmWave signals have mostly a direct path via a narrow beam. This beam is very power-focused but much influenced by the environment such as the dust. Further, as mmWave has a high frequency, the wavelength is very close to the dust particles' diameters. In Yahya and Seker [14] the model of mmWave has been derived, but the article focuses on the signal delay more than the power attenuation loss.

In this paper, we derive a dust attenuation mathematical model to study the impact of dust on the mobile communications of mmWave signal for different base station heights and at different distances between the mobile and the associate base station. The provided model discusses the link from the antenna of the base station to a mobile handset at different mmWave frequencies taking into consideration the fact that the dust particle size varies with the height of the base station. We, mainly, used the parameters that are suitable for Iraq. However, the proposed model can also be applied in different areas by applying a small modification.

The paper is organized as follows: section 2 will be the model development process, where the parameters will be set and the proposed models will be developed. In section 3, the total attenuation cellular link will be discussed. In section 4, the results will be presented and discussed. In section 5, a summarized conclusion will be listed.

## 2. DEVELOPING THE MODEL

In this section, we will discuss two terms: the relationship between the transmitter height and the size of the dust particles. This is a significant step for our model to determine the real attenuation in mmWave signal. The second term will be to determine the amount of attenuation based on the particle's characteristics of the dust and the impact of that on the signal propagation. The symbols are defined in Table 1.

Table 1. The symbol definitions of the model

| Symbol | The definition or the considered values |
|---|---|
| $M$ | The dust mass concentration in kg/m$^3$ |
| $\rho$ | The density $\rho$ = 2.57 gm/m$^3$ |
| $H$ | The altitude |
| $h_{BS}$ | 25 m |
| $h_{MS}$ | 1.5 m |
| $C$ | 2.31×10$^{-5}$ |
| $V$ | The amount of visibility in the unit of kilometers |
| $V_0$ | The amount of visibility at a reference height $h_0$, which in our case $h_0$ = $h_{MS}$ = 1.5 m and $V_0$ = 5 m |
| $\nu$ | The relative volume occupied by particles: particle/m$^3$ |
| $\lambda$ | $\lambda$ is the wavelength (in meter) of the transmitted signal |
| $sin\theta$ | $\theta$ is the elevation angle |
| $L$ | The direct communication link distance between the base station and the mobile station |
| $Dh$ | The differentiation altitude |
| $\gamma$ | 1.07 |
| $H$ | The amount of humidity |

### 2.1. Relationship between height and dust particle size

In meteorology, visibility can be used as a scale for the strength of a dust storm, needless to say, visibility declines in a storm with rising intensity. The visibility was found to be connected to the amount of dust mass over cubic-meter-air [1].

$$M = \frac{C}{V^{\gamma}} \tag{1}$$

Where $V$ represents the amount of visibility distance in the unit of kilometers, $M$ represents the amount of dust mass concentration in the unit of kilograms in each cube of a meter. Lastly, $C$ and $\gamma$ represent constants that depend on the surrounding environments such as the type of soil and the link distance in the dust storm.

For the case of Iraq, the following values can be applicable: $C$ = 2.31×10$^{-5}$ and $\gamma$ = 1.07. On the other hand, the density $\rho$, in gram per m$^3$, can be stated, based on empirical data as (2), [7].

$$\rho = \frac{C}{\nu \times V^{\gamma}} \tag{2}$$

Where the constant $\nu$ represents the relative volume of dust deployed in a volume of space. For instance, we can write the relative volume in terms of m$^3$ of dust particles in m$^3$ of air. Furthermore, the amount of dust can be noticed to decrease as you increase the altitude above the ground. This can be modeled in an empirical model among the dust mass $M$ in kg/m$^3$ and the altitude $h$ in $M$ as (3).

$$M = \frac{a}{h^{t}} \tag{3}$$

Where $a$ and $t$ are constants that depend on the sand storm's properties such as speed, intensity, and atmospheric range [2]–[7]. By substituting $M$ from (1) in (3) we can write the visibility as (4).

$$V^{\gamma} = \frac{C \times h^{t}}{\mathrm{a}} \tag{4}$$

Consider the visibility $V_o$ to be the visibility at a reference altitude $h_{MS}$; therefore, the from (2) to (4) becomes as (5).

$$V^{\gamma} = V_o \left(\frac{h}{h_{MS}}\right)^{t} \tag{5}$$

### 2.2. Determining the attenuation

In this paper, using an interpretation based on Garnett's work [3] the influence of altitude (tower height) on visibility and the attenuation factor in dB/km is expressed as (6) and (7).

$$\alpha = \frac{2.46 \times 10^{5} \times \nu}{\lambda} \times \frac{\epsilon''}{\epsilon''^{2} + (\epsilon' + 2)^{2}} \tag{6}$$

$$\nu = \frac{C}{\rho \times V_o^{\gamma} \times \left(\frac{h}{h_{MS}}\right)^{t}} \tag{7}$$

Where the value of $\lambda$ is the wavelength (in meter) of the transmitted signal, $\rho$ = 2.57 gm/m$^3$, $V_o$ is the visibility, which is considered to be a minimum of 5 m, at the mobile height of $h_{\mathrm{MS}}$ = 1.5 m. The dielectric constant of dust particles $\epsilon = \epsilon' - j\epsilon''$ is a complex number that contains the real value called the dielectric constant, and a real value called the dielectric loss [4].

The permittivity constant of dust particles depends on the amount of humidity $H$ that it has. The relationship between $H$ and $\varepsilon$ is stated in Sharief [4] as (8) and (9).

$$\epsilon' = 6.348 + 0.04 \times H \tag{8}$$

$$\epsilon'' = 0.092 + 0.02 \times H \tag{9}$$

And as $H$ usually is very low in the area west of Iraq, where the dust storm occurs most of the time, we can consider $\epsilon'$ = 6.348 and $\epsilon''$ = 0.092.

## 3. THE TOTAL CELLULAR LINK ATTENUATION

The total attenuation $A_m$ can be calculated via taking the integral over the distance between the mobile station and the base station $L$.

$$A_m = \int_0^L \alpha \, dL \tag{10}$$

As $\alpha$ is the attenuation that varies with dust intensity, hence, with the altitude, therefore, we consider the formula to be a function of $h$.

In Figure 2, we can see the communication link between a mobile station and a base station or can be between the monitor in IoT and the CAP. The Figure shows different layers of dust, which layers have different sizes of dust particles. The higher altitude above the ground the smaller the dust particles become.

As the communication link will cross these different layers, we can take integration of the attenuation factor for each small layer. And as we have the attenuation factor in (6) as a function of height, we can express the total attenuation based on the deferential height. The total attenuation in (dB) for a base station with height $h_{BS}$ above the ground to a mobile station with height $h_{MS}$ is:

$$\mathrm{A_m} = \int_{h_{\mathrm{MS}}}^{h_{\mathrm{BS}}} \alpha(h) \frac{1}{\sin\theta} dh \tag{11}$$

Where $\theta$ is the elevation angle between the mobile station altitude $h_{\mathrm{MS}}$ and $L$, the direct communication link between the basestation and the mobile station, as shown in Figure 2. As the dust mass varies with each value of $h$, we consider the total attenuation as an integral of attenuation factor overall values of $dh$ as (12).

$$\sin\theta = \frac{dh}{L} \tag{12}$$

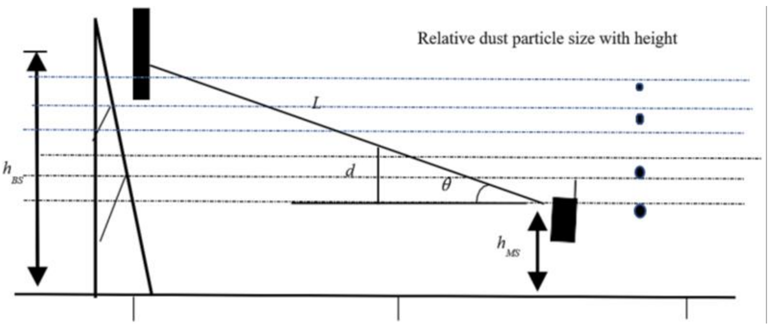


Figure 2. The communication layout in the dust storm

## 4. MODEL ANALYSIS

### 4.1. The analysis of attenuation

Figure 3 shows the attenuation in dB versus the distance between the base station and the mobile station for different mmWave frequencies at $h_{BS}$ = 25 m. The tested frequencies are the ones that are commonly used in mmWave and communications: 2.4 GHz, 5.2 GHz, 28 GHz, 38 GHz, and 60 GHz. We notice the amount of attenuation increases with the distance and increases with the frequency as well.

That is because the more distance the signal crosses the more dust it faces. Furthermore, we notice that the attenuation increases with increasing the frequency, which matches with (6).

Figure 4, illustrates the attenuation to be as a function of the base station height for different frequency bands in mmWave. It is clear that the higher the base station tower is the less attenuation of dust the signal will cross. That is because, at a higher altitude, a dust particle size is smaller due to it weighing less.

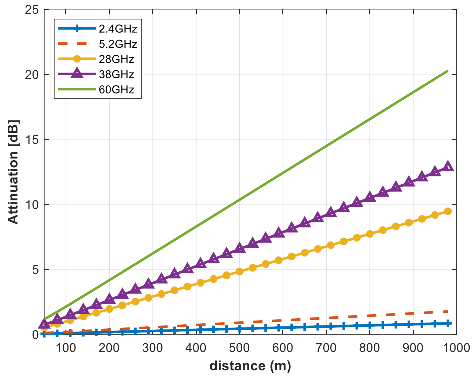


Figure 3. The attenuation for different distances from the base station

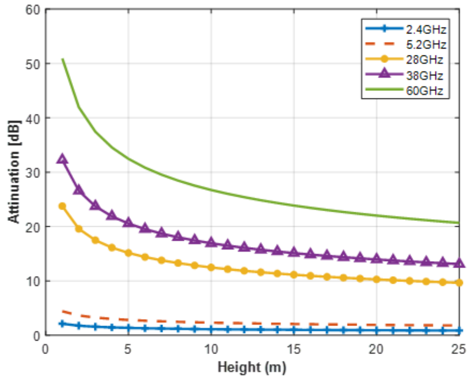


Figure 4. Illustration of the attenuation $\alpha$ per km as a function of height and frequency

### 4.2. Time series analysis

Based on the data of the meteorologist center in Iraq visibility in km is seen in Figure 5 for one year. The visibility is bouncing around 5 kms but varies from the summer to the winter. This is very important to be able to find the attention of the upcoming attenuation in mmWave mobile communication systems in Figure 6 or for the IoT. We use the time series prediction Box-Jenkins model [18]. This model utilizes the autoregressive and moving average (ARIMA) to predict the attenuation. To predict attenuation for the city of Mosul based on the available data, the ARIMA $(p, d, q)$ model is simple as ARIMA (1, 1, 1), with is the of:

$$(1 - \phi B)(1 - B)\, yt = (1 + \theta)\varepsilon t \tag{13}$$

Where $y_t$ is the output value, ε is the error in the prediction, $B$ is the shift back-ward operator.

$$Byt = y\,(t - 1) \tag{14}$$

And $\phi$ is the AR order, $\theta$ is the $MA$ order. Here both values equal 1.

From Figure 7, which shows the attenuation for different days/seasons, starting with January 1st to the end of the year, we notice that the attenuation in the wet seasons from January to March and October to December has more attenuation than the dry seasons. This can be due to the low visibility in these months. However, even these months has lower dry dust, the weather has high water drop that is also intervein the way of mmWave signal or makes the dust particle wet so it increases the attenuation.

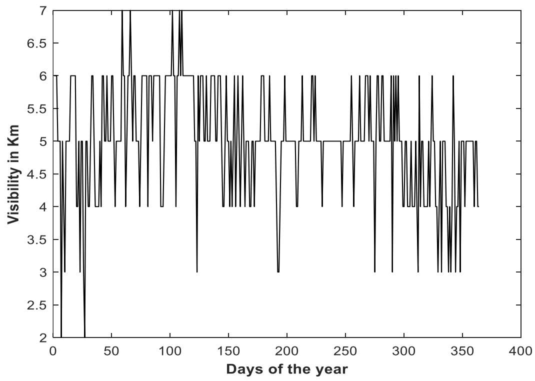


Figure 5. The visibility record in the city of Mosul for one year

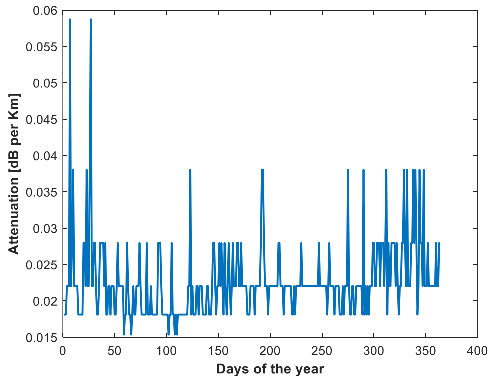


Figure 6. The attenuation as a function of the time for mmWave mobile communication systems


Figure 7. The prediction of attenuation in the city of Mosul

## 5. CONCLUSION

In this paper, we discuss the impact of dust particles on the wireless propagation factors of the mmWave signal between a base station and a mobile station. The link will penetrate a variable intensity of dust based on the height. We derive the attenuation power loss model in the dust environment using a mathematical model, then we obtain the results. The results reinforce the idea of crossing longer distances yields a higher attenuation loss. Furthermore, the results also show that the higher the base station the less attenuation power loss the signal may face. In terms of mmWave, the results show that higher frequency faces higher attenuation. The model also utilizes the data of the visibility in the city of Mosul to predict the amount of attenuation for mmWave. The model found not only does dry weather impact the mmWave, but the wet weather also increases the attenuation due to the lack of visibility. This model can help to study further complicated cases, such as the impact of moving dust particles in a dust storm on mmWave signal, using the doppler scenario.


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