Modeling Impact of Weather Conditions on 5G Communication and Mitigation Measures on Control of Automated Intersections

Final Report

by

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DISCLAIMER

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16. Abstract

Recent research activities are focused on improving Vehicle-to-Vehicle Communication (V2V) based on the 5G Technology. V2V applications are important because they are expected to reduce the risk of accidents up to 80%, enhance traffic management, mitigate congestion, and optimize fuel consumption. Typical autonomous vehicle applications require a high bandwidth transmission channel, so the 5G communication channel might be a reliable solution to support this technology. The dedicated short-range communications (DSRC), characterized by a frequency bandwidth of 5.9 GHz, were used as vehicular connectivity with bandwidth up to 200 mb/s and limited capacity, and it is here utilized for comparison to 5G. The 5G band can support connected autonomous vehicles with higher data rates and larger bandwidth. The 5G communication channel is suitable for vehicular connectivity since it has a very high bandwidth in the millimeter waves spectrum range. The quality of 5G wireless communication channels between connected vehicles is affected by weather conditions such as rain, snow, fog, dust, and sand. In this report, the effect of dust and sand on the propagation of millimeter waves is presented. The effect of dust and sand on the communication path loss of DSRC and 5G frequency band is investigated in the case of Urban areas and Highway conditions. Results show that the attenuation caused by dust and sand depends on the particle size of sand, frequency of propagating wave, and concentration of dust. Finally, a new model of link margin is presented to estimate the effect of dust and sand on DSRC (5.9 GHz) and 5G (28 GHz-73.5 GHz) communication path loss.

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EXECUTIVE SUMMARY[1]

In this project, we propose to model the impact of weather on dust and sand weather conditions under 5G V2V network and develop a robust intersection control. Studies showed that 5G will be capable of meeting latency standards for connected vehicles (CVs) Currently, CVs intersection control deals with perfect communications and focuses on control algorithms. We aim to address the communication layer with the impact of weather. Based on the degradation/statistical models, optimum control parameters will be revised. Existing intersection control uses scheduling, polling, and reservation-type control.

We extend ns3-Millicar model by adding weather impacts to path loss functions. The code and results of our simulation and implementation details are published on GitHub (https://github.com/ericliujian/ns3-mmwave-weather). Our simulation results show that the attenuation of the 5G propagating signal increases when the operating frequency, the concentration of the dust, and the particle size of the sand are increased.

Our findings show that dust and sand affect the 5G communication channel more than the DSRC channel. This effect is logical because the wavelength λ of the propagating 5G mmwave is short compared to the particle size of dust and sand. Our simulation results also suggest a range of harsh weather of particle size, visibility and humidity that can affect 5G mmWave.

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CHAPTER 1

Introduction and Background

Intelligent transportation systems (ITS) contain the most upcoming technologies that span different traffic applications involving vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) communications. They help to increase the efficiency of traffic, reduce crashes, ease traffic congestion, and improve fuel efficiency [2], [3]. However, many ITS applications require reliable communication to support integral functions such as intersection control, queue warning, gap assistance, curve speed warning, and alike. Disruption of communication would result in catastrophic results such as collisions and costly congestion [4]. Since 5G can support connected autonomous vehicles with a high data rate, 5G wireless communication is considered one of the connected vehicles solutions. De facto, 5G wireless communication is becoming the optimum communication channel used to support new features. The quality of wireless communication channels between vehicles at high frequencies can be potentially affected by weather conditions such as rain, snow, fog, dust, and sand. Due to the absorption of the energy of the transmitted signal and the scattering at high frequencies, the dust and sand cause significant attenuation at these high-frequency bands, especially at the E-band. The effect of the dust and sand on the propagating signal can show up for four different reasons: (i) the backscattered signal, (ii) the interference according to the time delay of the received signal, (iii) the change the polarization of the transmitted signal, and (iv) absorption of the energy of the transmitted signal. Climate circumstances influence wireless communication channels. Usually, in the northern and southeastern U.S. regions, these communication channels are affected by climatic factors like rain, snow, and humidity. In contrast, these channels are affected more by dust and sandstorms in the dry southwest regions. Such climate factors absorb and scatter part of the information of the transmitting signals. The performance of service of many wireless applications, such as 5G networks, cellular telephones, public service radio, pagers, broadcast television, radio stations, and differential GPS transmitters, Code Division Multiple Access (CDMA) and Worldwide Interoperability for Microwave Access (WiMax) networks, Wifi and Bluetooth networks that require radio frequency (RF) or microwave propagation from point to point very near the Earth's surface, depends on many factors such as area of coverage and climate conditions. When the propagating electromagnetic waves pass through a medium containing precipitations like sand and dust particles, the signals are attenuated through absorption and scattering of the energy by particles of the sand and dust [5]. It is seen that Vehicle-to-Vehicle (V2V) communications have received increasing attention, but it is required to conduct a deep analysis of certain important quantities such as path loss.

In the literature, empirical path loss models were developed using measurement data for different environmental areas [6]– [8]. These studies considered the effect of distances between vehicles, small and large-vehicle obstruction, climate factors such as rain and fog, and the height and characteristics of the antenna on the path loss. Also, the effect of sand and dust storms on wireless communication, such as microwave links and Global System for Mobiles (GSM) signal coverage, was addressed and was found that the effect of sand and dust attenuates the propagating signal [5]. This report addresses path loss analysis and modeling for Vehicle-to-Vehicle communications with sand and dust storms by determining the attenuation factors. The attenuation and phase shift constants for a medium with dust or/and sand particles depend on the frequency, visibility, greatest particle size, shape of the scattering particles, concentration, and orientation relative to
the wave polarization.

This report discusses the weather effect on 5G communications, particularly the impact of dust and sands on the propagating mm-wave [1]. The difference between the dust and sand particles is the diameter, where the sand diameter is larger than the dust particles' diameter. The dust particle size varies in the range of 10 µm to 80 µm, and sand particle size varies in the range of 0.15 mm to 0.3 mm. The attenuation caused by the dust and sand is one of the major problems in the use of terrestrial and space wireless communication (microwave and mm-wave signals). One misconnection can cause significant damage to circuit traffic, and this study aims to help provide a better reliable connection between vehicles in this weather condition. There are limited studies in the literature on the impact of weather on 5G (mm-wave) communications [9]. Only a handful of them discusses the effect on vehicular communications. Previous research studied attenuation and backscattering effects incorporated via formulations and quantified the impacts of weather particle sizes [2] using Monte Carlo simulations. In general, studies focused on the impact on the communication range. The effect of dust and sand on the communication range depends on different factors such as the operating frequency, particle size, humidity and concentration of the dust. According to these studies, a range of 1.8 km would drop to 300 m with heavy rain and fog, while snow would induce noise in communications during the attenuation of the received signal. Hence, applications such as intersection control with such reductions would have increased risks. For instance, in an isolated intersection, we would expect to track up to at least 200 m (e.g., 150 m was given in [10]).

The empirical path loss models were developed using measurement data for different environmental areas [2], [6], [9]. These results considered the effect of distance between vehicles, small and large-vehicle obstructions, climate factors such as rain and fog, and the height and characteristic of the antenna on the path loss. In addition to this, the effect of sand and dust storms on wireless communication, such as microwave links and GSM signal coverage, was addressed and it was found that the propagating signal is attenuated by the effect of sand and dust [5], [11]. In this report, 5G mm-wave is proposed as a solution to the connectivity of the vehicle since the 5G can support multiple connected autonomous vehicles with a high data rate and massive transmitting bandwidth. For these main reasons, the 5G wireless communication channel is considered the preferred vehicular connectivity option. This report considers most of the wireless interactions between the self-driving vehicles on a low-height level, approximately a range between 1 m to 4 m.

Currently, there are alternative 5G mm-wave simulators available. Some of these simulators were investigated for this study. The first simulator considered was NYUSIM [12]. NYUSIM is an open-source mm-wave channel simulator and is written in MATLAB. It has an interface to change channel parameters, antenna properties, and so on. The simulator's functions are all predefined. The second simulator was the 5G Toolbox [13] in MATLAB. This toolbox supports link-level simulation and test waveform generation. It has a waveform generator and transmitter. Simu5G [14] is another open-source simulator based on OMNeT++ framework, it allows one to simulate network scenarios where 4G and 5G coexist in both Standalone (SA) and E-UTRA/NR Dual Connectivity (ENDC) deployments. Millicar [15], a mmWave-based V2X network simulator based on NS-3, has the functionality of simulating vehicular networks with a 3GPP channel model. Among these simulators, due to the functionality of direct modification of the path loss function and smoother interaction with vehicle mobility, we utilized the NS-3-based Millicar simulator to study the weather impact on the 5G communication channel for connected vehicles.

In this report, the effect of dust and sand with standards of visibility, particle size, and different humidity levels (0%, 60%, and 100%) on the 5G vehicle channel is investigated in comparison with the dedicated short-range communication channel, DSRC, (5.9 GHz). Two possible scenarios are considered to estimate the path loss of the propagating signal. These scenarios are Urban and Highway conditions. These scenarios are according to the main driving categories, but they have different conditions. The path loss for each condition should be calculated differently to estimate the accurate value of the link margin. The specific formula that is used for each condition to estimate the path loss will be shown in Chapter III. Along with transmission parameters of used sensors such as transmitted power, antenna gain, and total free space loss; the attenuation of the transmitted signal is computed in terms of operating frequency, the concentration of dust, and particle size of sand. According to the received signal, it can determine whether the attenuation of the signal is high or low in comparison with the threshold of the received power. The worst weather condition is considered to calculate the attenuation factor in dB/km, when the visibility is low, and the particle size of dust and sand is large.

CHAPTER 2

Sand and Dust Attenuation

2.1 Definition of Dust and Sand

In general, attenuation is the loss of the transmitting signal strength in the transmission media. This transmission media could be a wireless channel, cables, or satellite link. In this study, the path loss of the wireless channel r is derived in terms of frequency, propagating path, visibility, and permittivity of transmission media. The deserts across the planet are a resource of the dust and sand particles that are distributed globally, and those deserts make up approximately 20% of the Earth's surface. For example, the desert of North Africa is the source of dust that affects Southern Europe [16]. Also, the desert of the southwest of the United States is the source of dust and sand in this country [16]. The proposed dust and sand attenuation model can be used to determine the effect of dust and sand storms on the propagating mmwave when the dust concentration and the particle size radius vary according to the change of the weather condition. This attenuation factor is dependent on different variables or parameters, such as operating frequency, humidity, height, particle size, and visibility. These factors contribute to a variation of the attenuation factor, so if these parameters change, the attenuation factor will vary as well. Frequency is the number of occurrences that a wave surpasses a point within a specific amount of time. Frequency is measured in the unit of Hertz (Hz). Humidity is the measure of how much water vapor is in the air. Height is a measure of distance above the ground where the attenuation factor is computed. Visibility is the measure of distance that a human being can see an object during dust and sand storms. All of these factors are considered when the attenuation factor is investigated. The visibility at reference height h_0 in m and reference visibility V_0 in km is defined in [17] and presented in Equation (1)

$$V^{\gamma} = V_0^{\gamma}\left[\frac{h}{h_0}\right]^{b} \quad (1)$$

where γ is a constant that depends on the distance from the point of origin of the storm type of soil and climatic conditions at the origin, b is a constant that depends on the climatic conditions, meteorological factors, and the particle size distribution of the dust and the sand, V_o is the visibility at the reference height (h_o), and h is the height m from the ground [18]. In this study, V_o and (h_o) are considered 4m and 2m, respectively [11].

The important direct measurement to investigate the effect of dust and sand storms is to predict the dielectric constant for dust and sand particles from their mineral and/or chemical composition values. The complex permittivity of the composite component ϵm is computed using the Looyenga Equation (2) as given by [19]

$$\epsilon_m^{1/3} = \sum_{i=1}^{n} v_i \epsilon_i^{1/3} \quad (2)$$

where ϵ_i is the complex dielectric constant of the i^{th} substance and v_i is the relative volume of the i^{th} sample from the volume of the total sample. The permittivity of transmission media is written as

$\varepsilon = \varepsilon' + j\varepsilon''$, where ε' is the dielectric constant and ε'' is the dielectric loss factor. The effect of humidity on permittivity can write as

$$\varepsilon_1 = \varepsilon' + 0.04\,H - 7.78 \times 10^{-4}\,H^2 + 5.56 \times 10^{-6}\,H^3 \quad (3)$$

$$\varepsilon_2 = \varepsilon'' + 0.02\,H - 3.71 \times 10^{-4}\,H^2 + 2.76 \times 10^{-6}\,H^3 \quad (4)$$

where H is the air relative humidity in percentage unit. The general formula of the complex permittivity with humidity in the dusty region is written as

$$\varepsilon = \varepsilon_1 + \varepsilon_2 (5)$$

2.2 Attenuation Model

The mathematical model, which is based on the Mie scattering method, is developed to compute the reduction of the propagating mm-wave strength. The ratio of diameter (sand/dust) to the wavelength of the propagating signal is considered when the attenuation factor model is developed to get an accurate effect. This model is valid to use, especially at higher frequencies. The most important parameters that affect the attenuation value are particle radius, operating frequency, humidity, and complex permittivity. The attenuation of the dust and sand A_d is defined by [20], [21] in *dB/km* and presented in (6)

$$\begin{gathered} A_d = \frac{a_e f}{v}\left[C_1 + C_2 a_e^2 f^2 + C_3 a_e^3 f^3\right] \\ C_1 = \frac{6\epsilon_2}{(\epsilon_1 + 2)^2 + \epsilon_2^2} \\ C_2 = \epsilon_2\left[\frac{6\left[7\epsilon_1^2 + 7\epsilon_2^2 + 4\epsilon_1 - 20\right]}{\left[(\epsilon_1+2)^2 + \epsilon_2^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\epsilon_1+3)^2 + 4\epsilon_2^2\right]}\right] \quad (6) \\ C_3 = \frac{4}{3}\left[\frac{(\epsilon_1 - 1)^2(\epsilon_2 + 2) + [2(\epsilon_1 - 1)(\epsilon_1 + 2) - 9] + \epsilon_2^4}{[(\epsilon_1 + 2)^2 + \epsilon_2^2]^2}\right] \end{gathered}$$

where a_e is the equivalent particle radius in meters, v is the visibility in *km*, f is the frequency in GHz, γ = 1.07, and b = 0.28 [13]. The attenuation of dust and sand in *dB* is defined as [1]

$$\alpha_{(dB)} = \int_0^d A_d\,dl \quad (7)$$

where d is the length of the propagation wave.

CHAPTER 3

Link Budget Analysis with Dust and Sand

First of all, the path loss is the loss or attenuation of the power of a propagating wave as it propagates through transmission media. In this study, the free space is considered as a transmission media. According to (6), when the dust and sand particles in the air increase, the path loss increases too. The importance of path loss is that it can be used to find the total received power of signals being transmitted from point to point, such as vehicle to vehicle or vehicle to infrastructure. In the case of V2V connection, there are two possible scenarios that are studied for path loss. These scenarios are Urban condition and Highway condition. These two scenarios were specifically chosen because they are general driving environments regardless of the general locations. The path loss for each case should be calculated differently to derive an accurate value of the signal loss. The path loss of the Urban condition is defined as [6]:

$$L_s = 38.77 + 16.7\log_{10}(d) + 18.2\log_{10}(f) + \chi_a \qquad (8)$$

The path loss of the Highway condition can be written as

$$L_s = 32.4 + 20\log_{10}(d) + 20\log_{10}(f) + \chi_a \qquad (9)$$

where *f* is the signal frequency in GHz, *d* is the distance between vehicles in meters and χ_a represents shadowing (an incremental shadowing term is applied in $NLOS_v$, modeled as a log-normal random variable). According to dust and sand storm conditions, the expression of the path loss for both conditions will be modified to take into account the effect of dust and sand. The modified path loss of Urban condition is

$$L_{sm} = 38.77 + 16.7\log_{10}(d) + 18.2\log_{10}(f) + \alpha + \chi_a \quad (10)$$

and the modified Highway condition is

$$L_{sm} = 32.4 + 20\log_{10}(d) + 20\log_{10}(f) + \alpha + \chi_a \quad (11)$$

where *α* is the attenuation factor of dust and sand that is defined by (7).
The proposed link margin Md is defined as:

$$M_d = \frac{G_t G_r P_t}{k T_s R L_0 L_{sm}\left(\frac{E_b}{N_0}\right)} \qquad (12)$$

where G_r is the receive antenna gain, G_t is transmitted antenna gain, P_t is the transmitted power (*dBm*), *R* is the data rate in *bps*, *L*0 represents circuit losses, *k* is the Boltzmann's constant 1.38 10^{-23} *J/K*, T_s is the effective system noise temperature, E_b/N_o is the required energy per bit to noise spectral density ratio, L_{sm} is the modified free space path loss that is represented by (10) and (11).

CHAPTER 4

Field Sand and Dust Data

The authors had field data from the desert of the southern part of Libya; thus, the region was identified as the study region to investigate the impact of dust and/or sand storms on the wireless communication systems [5], [11]. Moreover, this region was considered because it is characterized as a famous desert climate, and it has a fast wind filled with dust from time to time. Based on the study region information, nine places were chosen to collect the sand and dust carried by the wind. The plastic cans were placed on the tower or on the roof of buildings at a height of 13 m to collect dust and sand through the dust storms of different seasons (summer, fall, winter, and spring).

4.1 Analysis of the Samples

For this study, samples' particle size distribution, average density, and chemical composition are required to compute the dielectric constant and attenuation factors. There are two laboratories available to carry out the analysis of the samples. These two laboratories are the Libyan Petroleum Institute and the Industrial research. The measured density of all samples determined by the Libyan Petroleum Institute is shown in Table 1.

Table 1. Density of Samples

Sample No.	Density (g/m^3)
1	2.5426
2	2.56857
3	2.6138
4	2.62714
5	2.4202
6	2.9232
7	2.4732
8	2.5425
9	2.4764

The average density of all samples from Table I is equal to 2.5764 g/m^3. The size of dust and sand particles is determined using the sieving method. The sieving analysis showed that the major grain size of these samples ranges from less than 90 μm to 600 μm. The complex permittivity of the composite component can be calculated using (2). The complex permittivity of each sample is shown in Table 2. The average complex permittivity of the samples collected in the studied region from Table 2 is equal to 6.3485−j0.0929. The following empirical relation is used for the variation of complex permittivity with relative humidity [5].

Table 2. Complex Permittivity of Each Sample

Sample No.	Complex Permittivity
1	5.0384 - j 0.0509
2	5.4851 - j 0.0562

3	5.4801 - j 0.0694
4	7.5929 - j 0.1140
5	6.7899 - j 0.1296
6	5.4003 - j 0.0787
7	7.4707 - j 0.1344
8	5.5713 - j 0.0704
9	8.3078 - j 0.1329

The average complex permittivity of the samples collected in the studied region from Table II is equal to 6.3485−j0.0929. The following empirical relation is used for the variation of complex permittivity with relative humidity [5]

$$\epsilon_1 = 6.3485 + 0.04H - 7.78 \times 10^{-4}H^2 + 5.56 \times 10^{-6}H^3$$

$$\epsilon_2 = 0.0929 + 0.02H - 3.71 \times 10^{-4}H^2 + 2.76 \times 10^{-6}H^3$$

where H is the air relative humidity (percentage).

CHAPTER 5

Results and Discussion

5.1 Point to Point Link

The Simulink on MATLAB is used to model the 5G mini links as the transmitter, receiver and communication channel. The point A and point B in Fig. 1 are named transmitter and receiver, respectively, in the Simulink model, as shown in Fig8. This figure shows the model of the point-to-point 5G communication link. The simulation has been made using Simulink on MATLAB, and it consists of different blocks models. The three main parts of this Simulink connection are the transmitter, receiver and communication channel. The transmitter block consists of a binary generator source, modulator, high-power amplifier and antenna to transmit the signal through free space. The communication channel consists of the path loss equation (11), implemented in the system as a function block where the signal has input from the transmitter. It is modified based on different parameters such as frequency, distance, visibility and particle size. The last part of the system is the receiver where the signal is being transmitted through the channel and received by the antenna block to deliver to the demodulator.

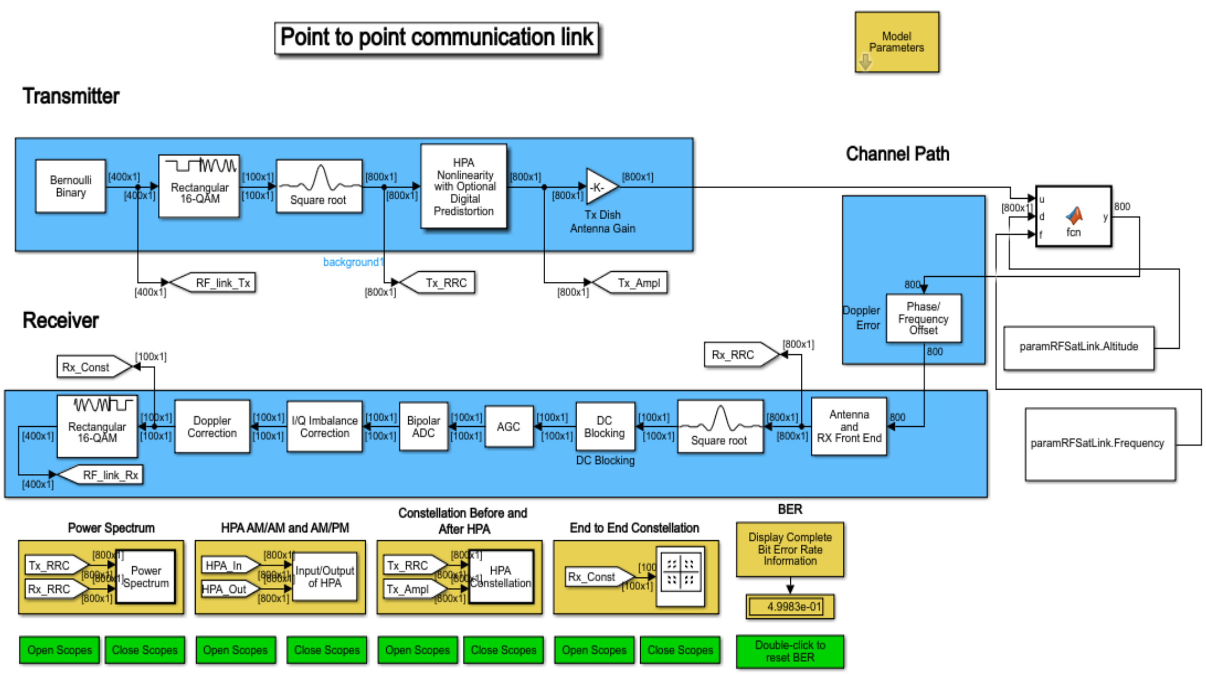

Figure 2. Point to point communication link

Fig. 2 shows the spectrum analyzer screen where the transmit signal is in the blue line and the received signal is in the red line. It is configured that the transmit channel power is 20 dBm and the antenna gain 40.7 dB. The parameters of ML6363 that are shown in TABLE II are considered. It is selected that f = 21.8GHz, d = 1.8km, V = 10m and the humidity is 60%. It is seen that the received channel power is 691 dBm and the BER = 4 ×10−5, so the total loss is 661dBm. When the visibility sets to 0.1m, the receiver loses the signal and the BER = 2.4 ×10−1, but the received channel power is measured to 1496 dBm at dry weather and the BER = 5.7 ×10−5. In the case of ML6352 (73.5GHz), It is found that the received channel power is 1099 dBm and the BER = 5×10−5 when f = 73.5GHz, d = 1.8km, V = 10m and the humidity is 60%. When the visibility sets to 0.1m, the receiver loses the signal and the BER = 4.998×10−1 in both cases 60% and 0% humidity, as shown in Fig.3. In general, both 5G mini links are affected by the sandy weather, especially when the visibility less than 10 m. Also, the ML-6352 is more effect by dust and sand storms than ML-6363.

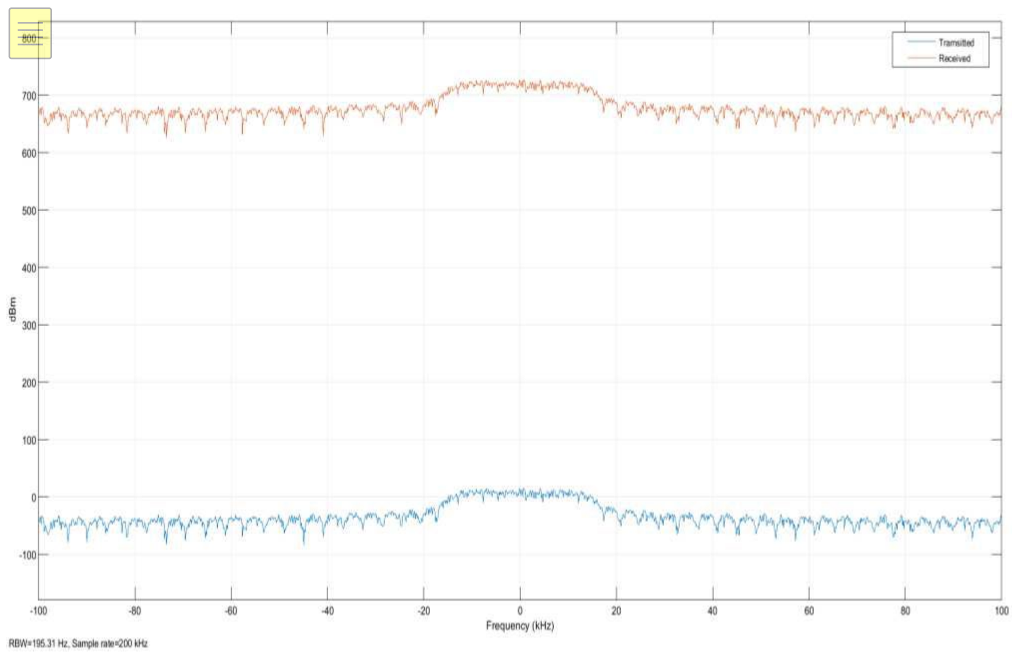

Figure 3. Transmitted and received signal of ML6363 (21.8 GHz)

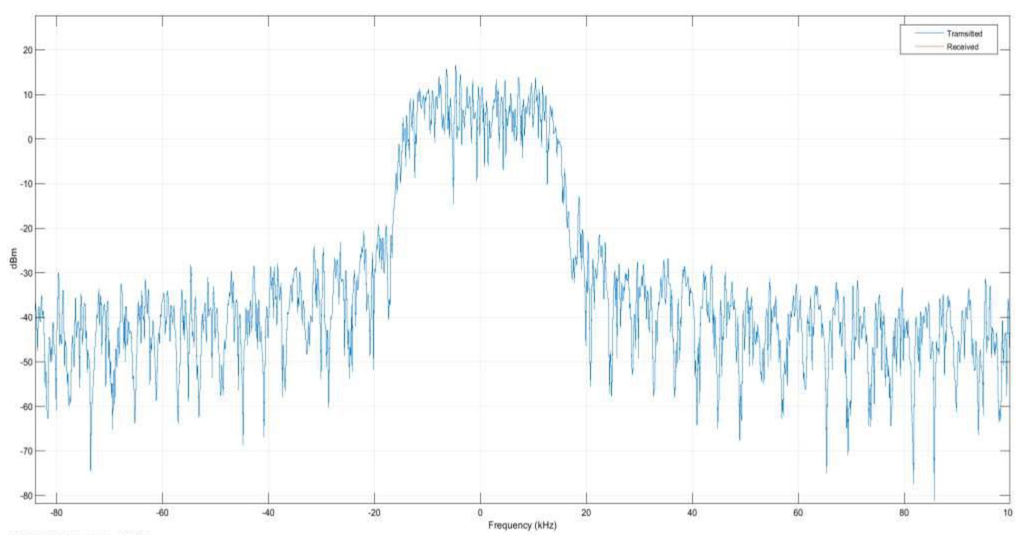

Figure 4. Transmitted and received signal of ML6363 (73.5 GHz)

5.2 Attenuation of Dust and Sand

Equation (6) is used to estimate the attenuation of dust and sand in terms of the concentration of dust, the particle size of sand, and the transmitted signal's frequency. The 5G (28GHz) and DSCR (5.9GHz) are two bands of frequency. The particle size is changed from 0 to 538μm. The maximum height is between 0.75m-2m. The attenuation is computed at different values of humidity (0%, 60%, and 100%). Figure 4 shows the attenuation of dust and sand versus the visibility when the transmitted frequency is 5.9GHz.

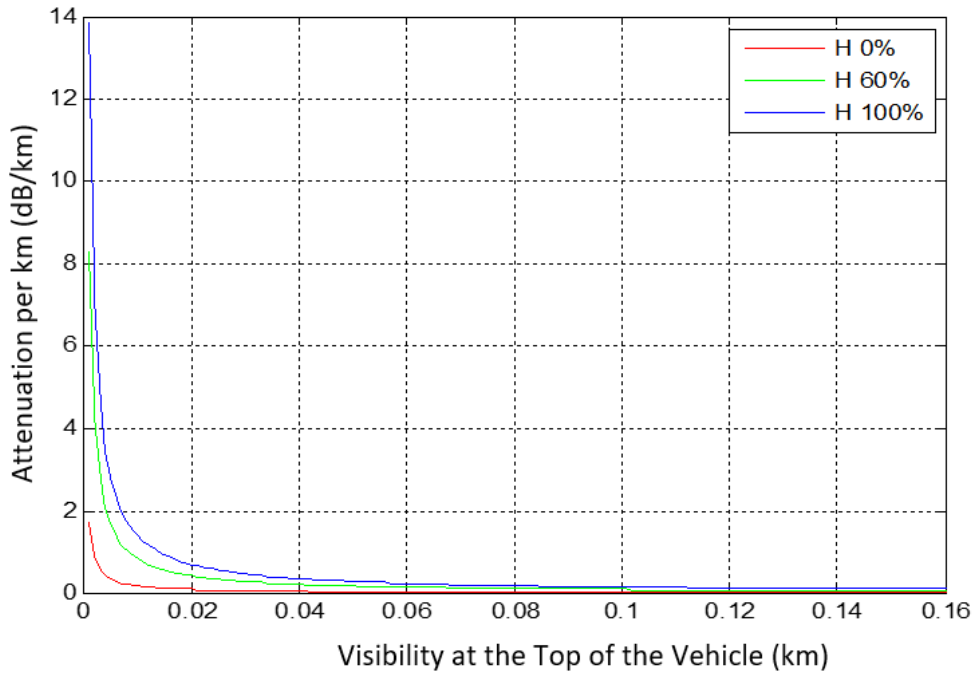

Figure 5. Attenuation versus the visibility at 5.9GHz and h = 1 m

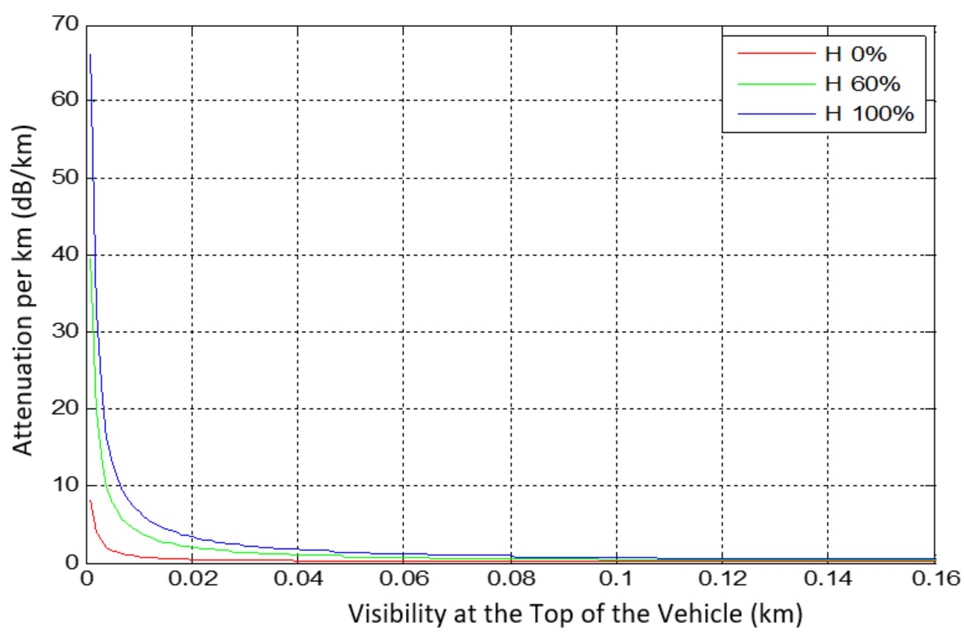

Figure 6. Attenuation versus the visibility at 28GHz and h = 1 m

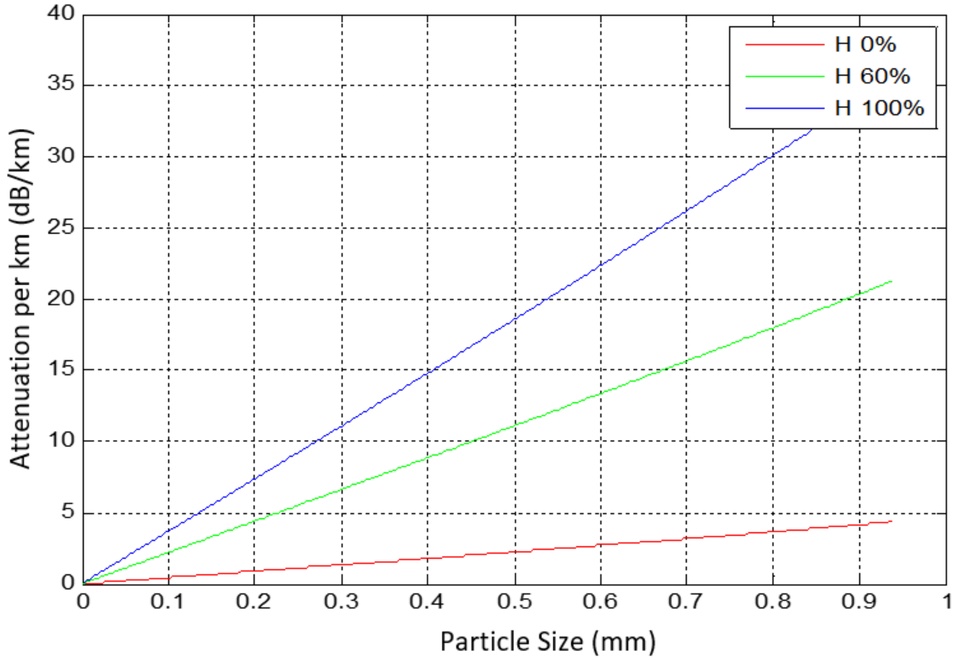

Figure 7. Attenuation versus the particle size (mm) at 5.9GHz and h = 1 m

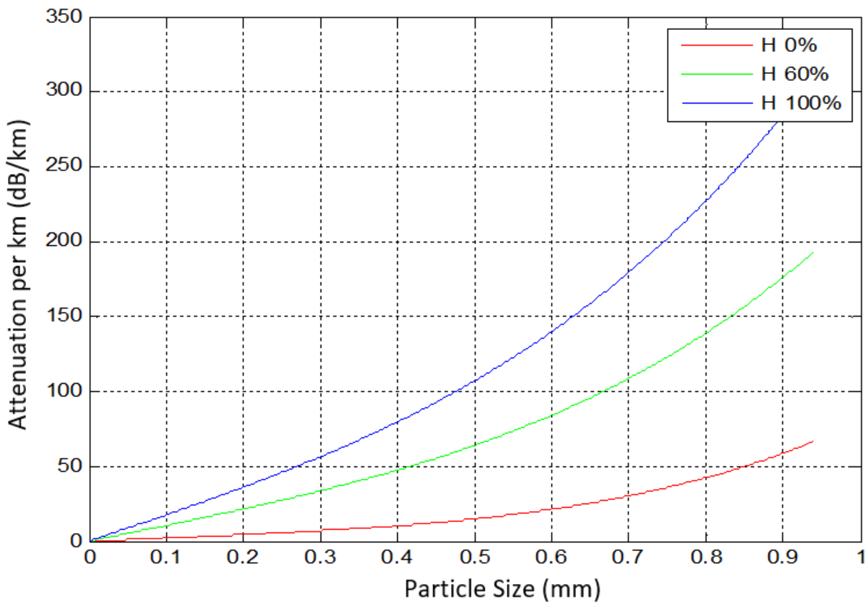

Figure 8. Attenuation versus the particle size (mm) at 28GHz and h = 1 m

The dust and sand attenuation increases as the frequency increases, as shown in Fig. 5. Also, the same attenuation model is used to investigate the effect when the particle size is increased at different values of considered frequency. It is found that the value of the attenuation of 5G is higher than the value of DSCR, as shown in Figs. 6 and 7.

5.3 Link Budget of V2V

The designed system consists of two vehicles. The sensor of every vehicle used a dual-band phased array antenna. This system is proposed and tested by a research team from Florida International University [22]. This dual-band RF front-end for DSRC and 5G V2V operates at 5.9GHz and 28GHz. The modified link budget of the V2V communication link that is presented in (12) is used to estimate the received power signal. If the received energy per bit to noise spectral density ratio is achieving the required bit error rate, the communication between V2V is reliable. On the contrary, if the received energy per bit to noise spectral density ratio is not achieving the required bit error rate, the communication between V2V is disconnected.

Link Budget information of 5.9 GHz and 28GHz is shown in Table 3 [22].

Table 3. Required Link Budget Information

	DSRC 5.9GHz	mm-Wave 28GHz
Transmit Antenna Gain	9.9 dBi	23.4 dBi
Receive Antenna Gain	9.9 dBi	23.4 dBi
Transmit power	27 dBm	27 dBm
EIRP	36.9 dBm	50.4 dBm
Required	18.8 Db	18.8 Db
Data Rate	27 Mbps	1 Gbps

According to the proposed model of Sandhiya Reddy Govindarajulu and Elias A. Alwan [22], it assumed the overall circuit losses L0 = 5dB, receiver front-end noise figure F = 6dB, $T_s = T_A + (F - 1)290$, T_A = 290K, the distance between vehicles d = 390m and E_b/N_0 = 18.8dB that is required to achieve a bit error rate BER equal to 10^{-6}. Moreover, the radio frequency parameters that are presented in Table III are used together to insert into (12) to calculate the value of L_{sm} to maintain the link margin $M_d \geq 10$dB. If the $M_d \geq 10$dB, all the required transmission parameters are achieved to avoid any disconnect or loss of communication between autonomous vehicles. Since the attenuation L_{sm} at M_d = 10dB (the threshold value) is computed, Figs. 1-4 are used to identify the minimum equivalent particle radius and visibility (concentration of dust) to avoid communication loss between V2V. In other words, these minimum values of equivalent particle radius and visibility are the threshold value. If the equivalent particle radius increases or the visibility decreases, the communication between V2V will discount. For this reason, this research is important to design a reliable system to support the recent intelligent transportation network. In this simulation, 5G communication channel (28 GHz) and DSRC channel (5.9 GHz) are considered to investigate the effect of dust and sand. The result of this simulation is summarized in Table 4.

Table 4. Simulation Results

Humidity	Frequency	Urban	Highway
0 %	5.9 GHz	V is not affected Particle Size (P S) ≥ 1.48 mm	V is not affected P S ≥ 614 μm
	28 GHz	V is not affected P S ≥ 0.27 mm	V≤ 51m P S ≥ 2 μ m
60 %	5.9 GHz	V is not affected	V≤ 2 m

	 28 GHz	P S ≥ 0.328 mm V≤ 3m P S ≥ 58 μ m	P S ≥ 129 μ m V≤ 120 m P S ≥ 0.39 μ m
100 %	5.9 GHz 28 GHz	V≤ 1m P S ≥ 0.2 mm V≤ 5m P S ≥ 36 μ m	V≤ 3 m P S ≥ 70 μ m V≤ 160 m P S ≥ 0.2 μ m

Table 4 shows that dust and sand affect the 5G communication channel more than the DSRC channel. This effect is logical because the wavelength λ of the propagating 5G mmwave is short compared to the particle size of dust and sand. It is seen that the 5.9 GHz is not affected by the dust in the dry weather (H = 0%) for both scenarios, but the 5G (28 GHz) is affected when visibility is less than 51 m in the highway case. At the H=0%, the 5.9GHz is affected if the particle size is greater than 1.48 mm in the urban case and 614 μm in the highway case. At the H = 0%, the 28 GHz is affected if the particle size is greater than 0.27 mm in the urban case and 2μm in the highway case.

At the H = 60%, the 5.9GHz is affected if the particle size is greater than 0.328 mm in the urban case and 129 μm in the highway case, but it is affected by the concentration of dust if the visibility is less than 2 m in the highway case. At the H = 60%, the 28 GHz is affected if the particle size is greater than 58 μm and the visibility is less than 0.39 μm in the urban case. It is affected when the particle size is greater than and the visibility is less than 120 m in the highway case.

At the H = 100%, the 5.9GHz is affected if the particle size is greater than 0.2 mm in urban case and 70 μm in the highway case. Also, it is affected by the concentration of dust if the visibility is less than 1 m in the urban scenario and 3m in the highway scenario. At the H = 100%, the 28GHz is affected if the particle size is greater than 36 μm and the visibility is less than 5 m in the urban case. Also, it is affected when the particle size is greater than 0.2 μm and the visibility is less than 160 m in the highway case.

5.4 Factors Affecting Packet Loss in V2V

In order to analyze the impact of dust and sand on received packets among connected vehicles, a simple 2-vehicle communication scenario is simulated. The simulation is developed on NS-3, which is a discrete-event network simulator for Internet systems. An additional NS-3 module Millicar [15] is used to simulate the mm-wave-based V2X networks. This module enables end-to-end, full-stack simulations of vehicular networks with a 3GPP channel model for V2V propagation and fading at mm-waves, and physical and MAC layers redesigned for NR V2X. The Millicar module is redefined, and the weather impact factor Ad is added to quantify the path loss. A simple vehicle-to-vehicle (V2V) scenario is generated with the proposed path loss involving a 5G channel model. In our proposed simulation scenario, two connected vehicles are placed apart at a distance of 10 m and moving at the same speed of 20 m/s in the same direction. The vehicles exchange packets through a UDP application using a wireless channel. The packet size is set to 1024, and bandwidth is 0.1 GHz. In this simulation, we consider LOS condition with no obstacles between vehicles; thus, shadowing effect is not considered.

The path loss function considers the weather impact by involving several parameters, and these parameters are subject to change to demonstrate the weather impact on the communication channels.

In the first series of simulations, all the parameter impacts in weather conditions A_d are tested in the Millicar module. As shown in Table 5, the factors of particle size, visibility, humidity, frequency, vehicle speed, and inter-packet Interval are examined, changing one factor at a time to understand how they affect communications between two vehicles.

Table 5. Simulation Parameters for Platoon Case

Parameters	Value Range
Particle Size (m)	0.0001 -0.0004
Visibility (km)	0.0006-0.003
Humidity (%)	0% -100%
Frequency (GHz)	28, 73.5
Speed (m/s)	1 -40
Inter-packet interval (microseconds)	1-35
V2V Scenarios	Highway, Urban
Vehicle States	Line-of-Sight, Non-Line-of-Sight, Non-Line-of-Sight

5.5 Particle Size, Visibility, Humidity and Frequency

According to Fig. 8, when particle size is greater than 0.2 mm, the received packets between two vehicles decrease drastically as the particle size increases. When the particle size is greater than 0.35 mm, all the packets between two vehicles would be dropped to zero, which means that there would be no communication between the two vehicles.

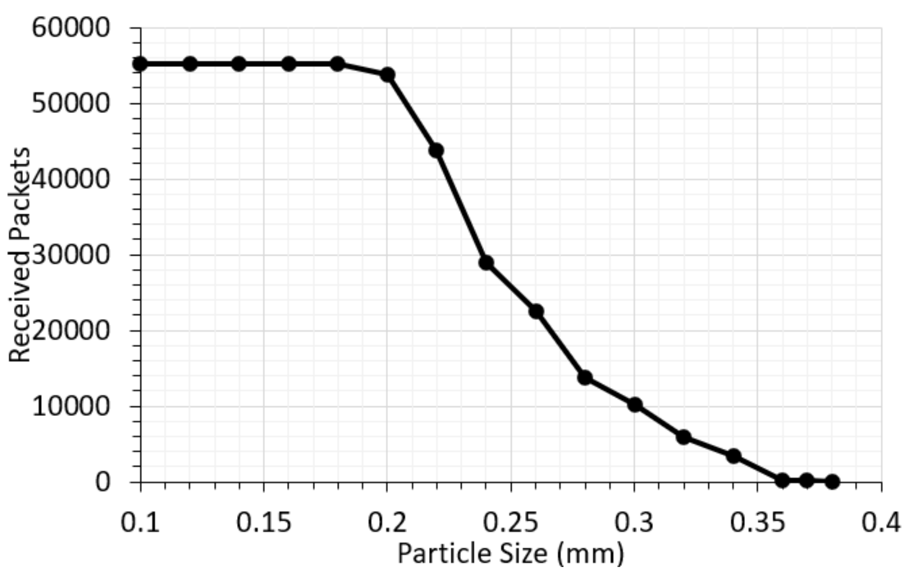

Figure 9. Impact of particle size (mm) on received packets

Figure 9 shows that as visibility increases, the received packets between two vehicles also increase. In more detail, when visibility is less than 1 m, there is no communication between the two vehicles. Starting from a visibility of 1 m, the received packets increase significantly as the visibility increases, and all the packets between two vehicles would be received when visibility increases to 2 m.

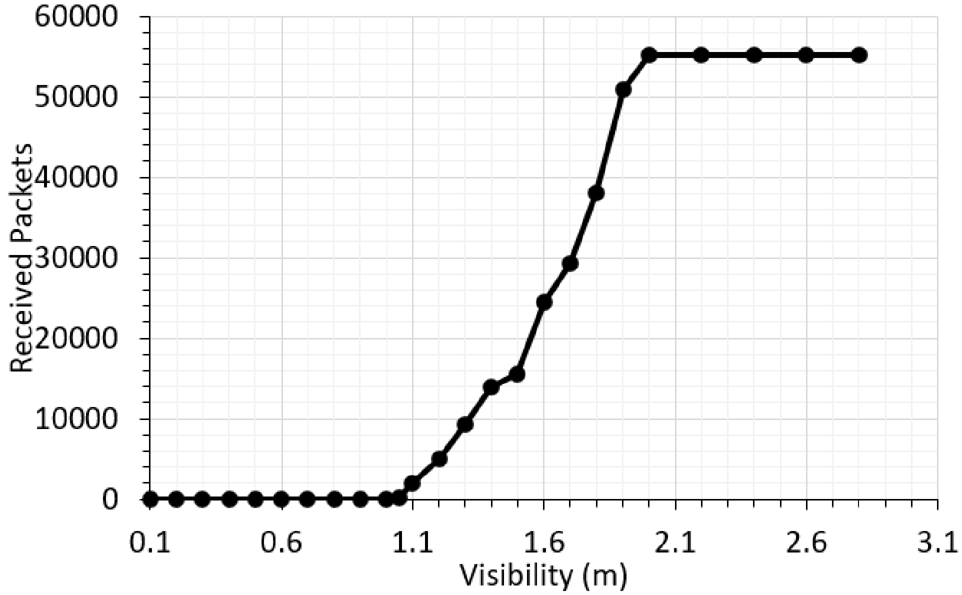

Figure 10 Impact of visibility (m) on received packets

Figure 10 shows the effect of humidity. When humidity is less than 60%, the received packets keep the same level and start to fall rapidly when humidity passes the 60% threshold.

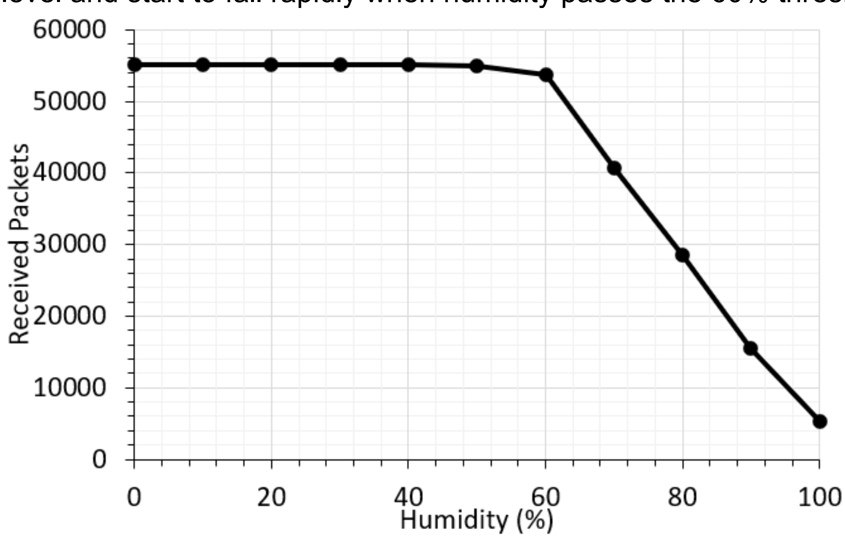

Figure 11. Impact of humidity (%) on received packets

Figure 11 indicates that the received packets between two vehicles will decrease as we increase frequency and 45GHz could be the threshold for no communication under these settings.

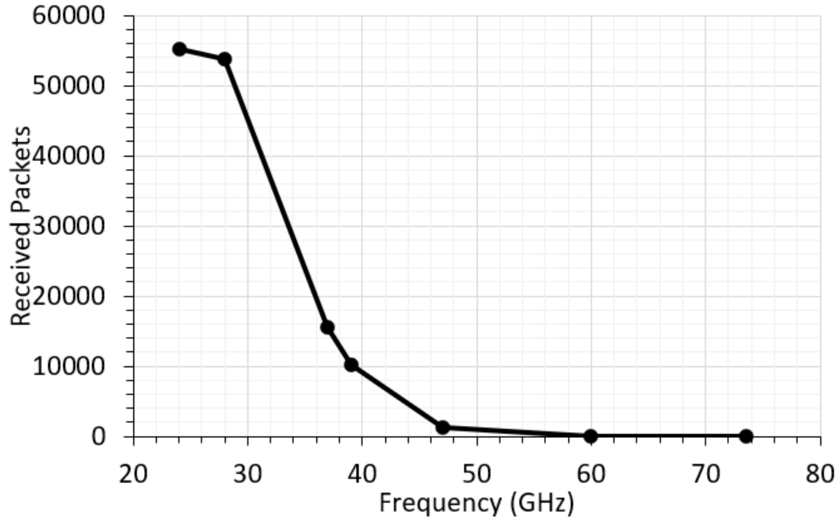

Figure 12. Impact of frequency on received packets

5.6 Vehicle speed and inter-packet interval

Figures 12 and 13 reveal the impact of vehicle speed and inter-packet interval, which are two important parameters in the Millicar module. Based on the results, these two parameters do not have considerable influence on the mm-wave communications between two vehicles and thus are ignored in future sections.

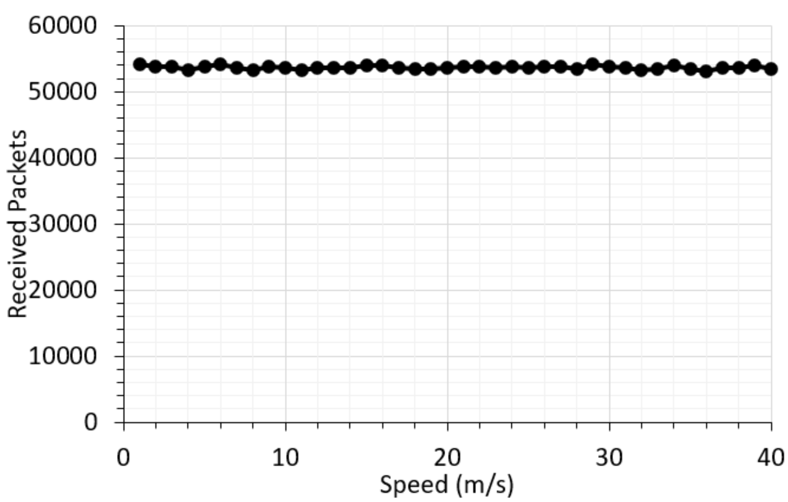

Figure 13. Impact of vehicle speed (m/s) on received packets

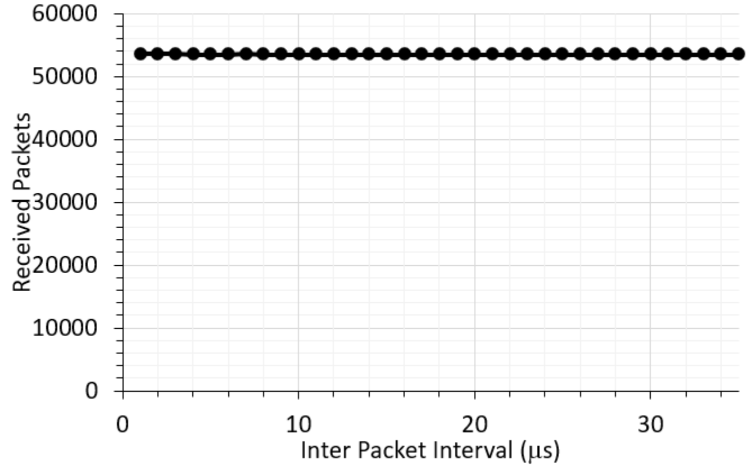

Figure 14. Impact of inter packet times (μs) on received packets

5.7 Compare packets loss with free space path loss

This section is to check the relationship between simulation results and calculated free space path loss introduced in Chapter III. Received packets and path loss are shown in the same graph to identify the trend change.

According to the results, there exists a threshold for the path loss such that no packets would be received if the path loss is larger than this threshold (in this case, visibility reaches a small enough value in Fig. 14, or particle size reaches a large enough value in Fig. 15). And this threshold value changes under different operating frequency and humidity conditions. In Fig. 14, as visibility increases, the received packets increases, whereas the path loss decreases.

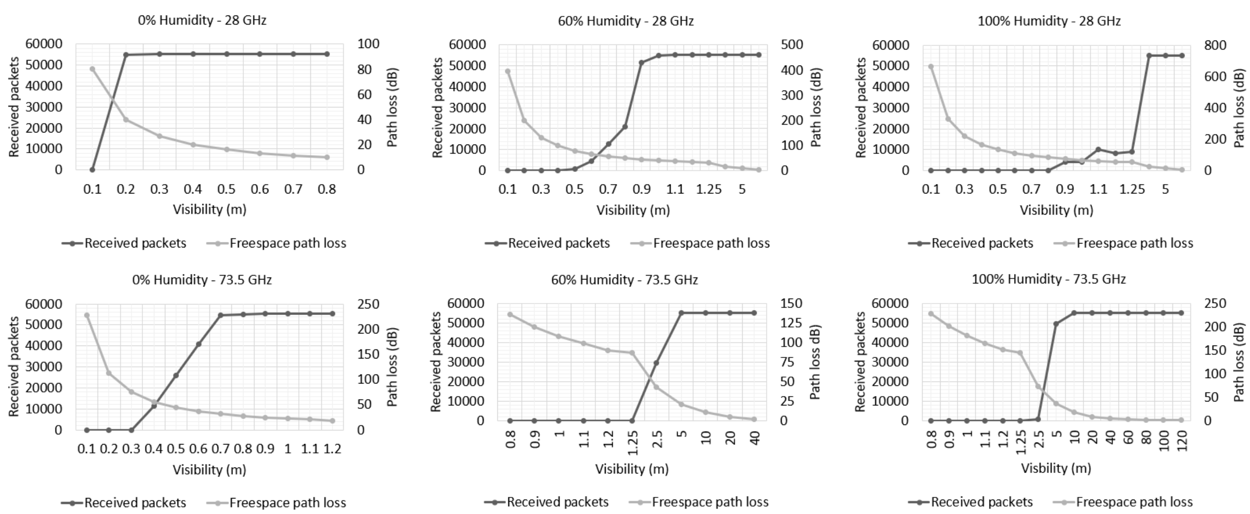

Figure 15. Impact of visibility on the received packets and path loss under different humidity conditions and operating frequency

On the contrary, the particle size shows the opposite effect in Fig. 15. Specifically, as the particle size increases, the received packets decrease, whereas the path loss increases.

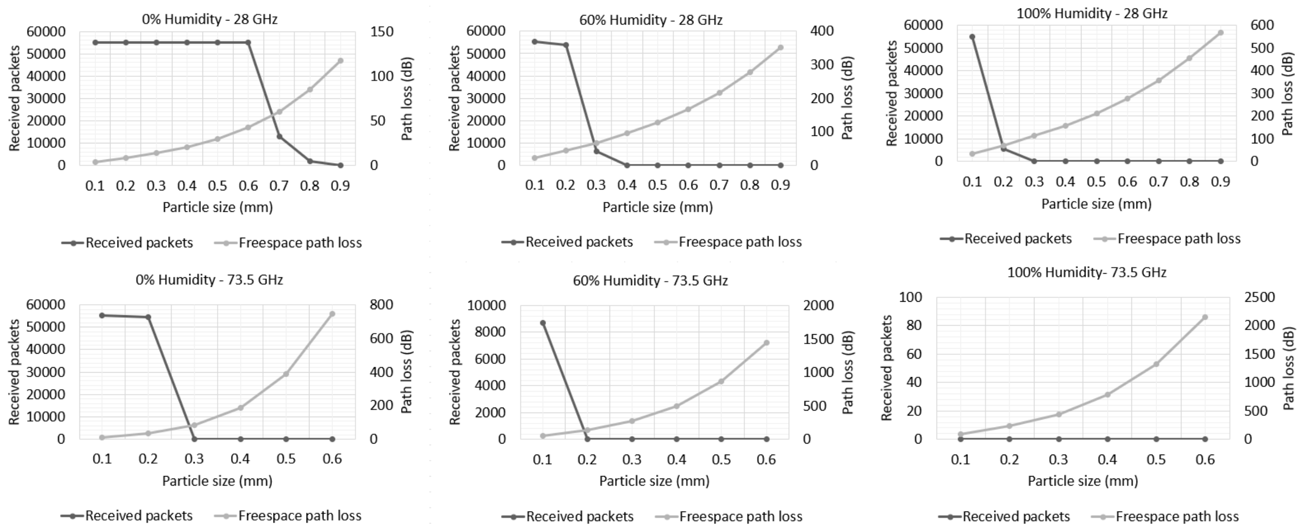

Figure 16. Impact of particle size on the received packets and path loss under different humidity conditions and operating frequency.

5.8 Vehicle collision avoiding in the intersection

As dust and sand have been shown to be able to affect the received packets in section 5.3, a more realistic scenario is created in NS-3 to analyze their actual impact on the behavior of the connected vehicles. In this intersection collision warning scenario, 2-vehicle are placed at their own starting point in the four-way intersection (Fig. 16). The initial distance between each vehicle and the crossing is 40 m and the initial speed is set to 20 m/s for each. Without the intersection collision warning system, the 2-vehicle would arrive at the crossing simultaneously and there is a possibility of collision. After enabling the intersection collision warning system, one vehicle would receive the estimated time-to-collision information from the other vehicle and would thus reduce its speed to avoid the collision. The vehicles exchange packets through a UDP application using a wireless channel. The packet size is set to 1024 and bandwidth is 0.1 GHz. The details of the selection of parameters are shown in Table 6. In this simulation, we consider LOS condition with no obstacles between vehicles; thus, the shadowing effect is not considered.

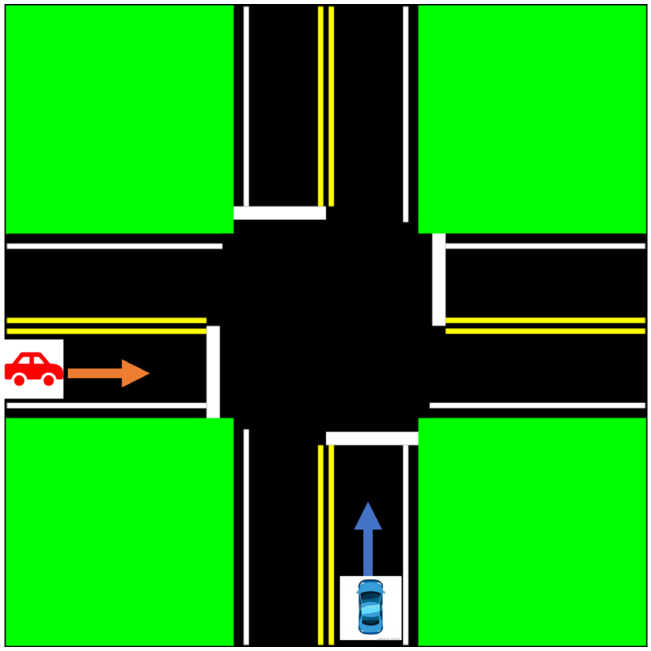

Figure 17. Snapshot of the intersection simulated

Table 6. Simulation Parameters for the Intersection Case

Parameters	Value Range
Particle Size (m)	0.0001 -0.00009
Visibility (km)	0.002
Humidity (%)	0 ,60,100
Frequency (GHz)	28, 73.5
Speed (m/s)	20 (15 after receiving signals)
Inter-packet interval (microseconds)	30
V2V Scenarios	Highway
Vehicle States	Line-of-Sight

As shown in Fig. 17, compared with 0% and 60% humidity, when humidity is 100%, the collision distance starts to decline rapidly at a smaller particle size of 0.18 mm. The corresponding particle size is 0.28 mm for 60% humidity and 7 mm for 0% humidity.

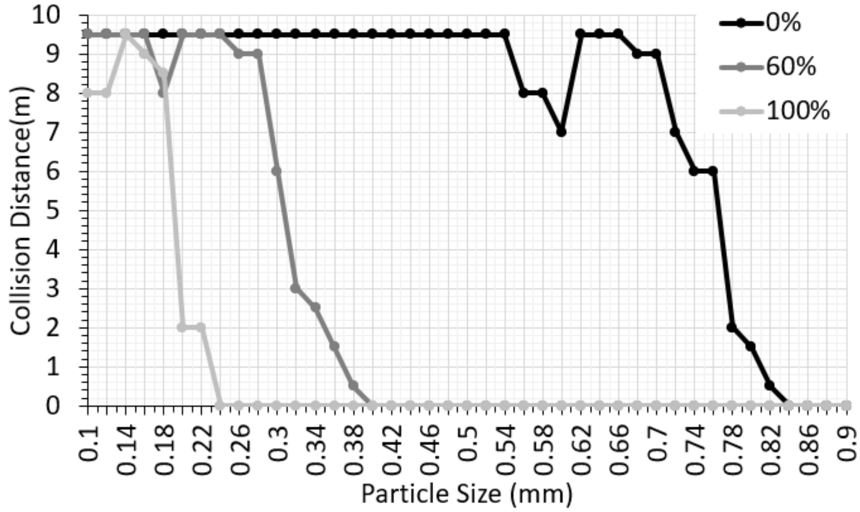

Figure 18. Relationship between particle size and distance under different humidity for 28GHz

As shown in Fig. 18, under a higher frequency of 73.5GHz, when the humidity is 100%, the two vehicles would always collide at the intersection, regardless of particle size changes. Similarly, under a 60% humidity level, when the particle size is greater than 0.14 mm, the two vehicles will crash as well. Under 0% humidity, the two vehicles would be safe until particle size is increased to 0.3 mm.

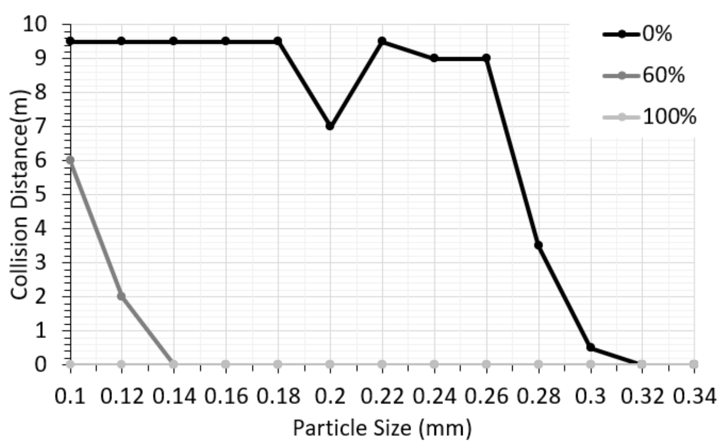

Figure 19. Relationship between particle size and distance under different humidity for 73.5GHz

Comparing results in Figs. 19 and 20, under all three humidity conditions, the corresponding visibility of collision distance increases at 0.2 m, 1 m, 2 m for 28GHz and 0.9 m, 3.5 m, 6 m for 73.5GHz. Higher frequency increases the weather impact, which results in better visibility to enable our collision warning system.

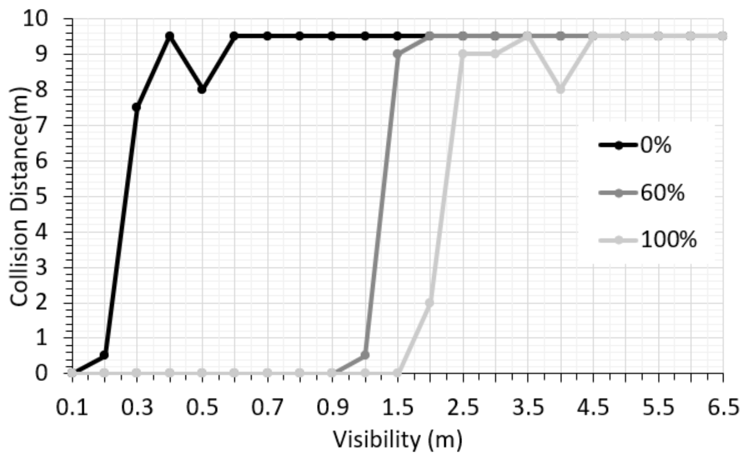

Figure 20. Relationship between visibility and collision distance under different humidity for 28GHz

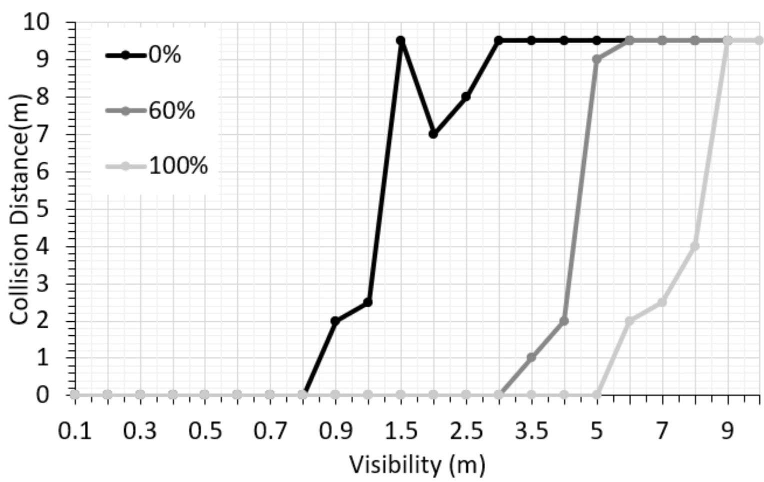

Figure 21. Relationship between visibility and collision distance under different humidity for 73.5GHz

In order to derive quick distance-related thresholds, Fig. 21 shows the impact of humidity, particle size, and visibility together with distance on packets received. From the figure, it can be seen that at 0% humidity, there is no loss for 0.1 mm particle size. When the particle size is 0.2 mm, received packets start to lose at about 200 m. When the particle size is 0.3 mm, received packets start to decline after 150 m. It can also be seen that more than 50% of the packets are lost when humidity is 60% and particle size is 0.1 mm for more than or equal to 100 m. Similarly, for 0.3 mm, half of the packets are lost at 300 m. For lower visibility of 2 m, for particle size of 0.2 mm and humidity of 60%, received packets are reduced by 91%. Thus, this can impact the reliability of safety and time-critical applications.

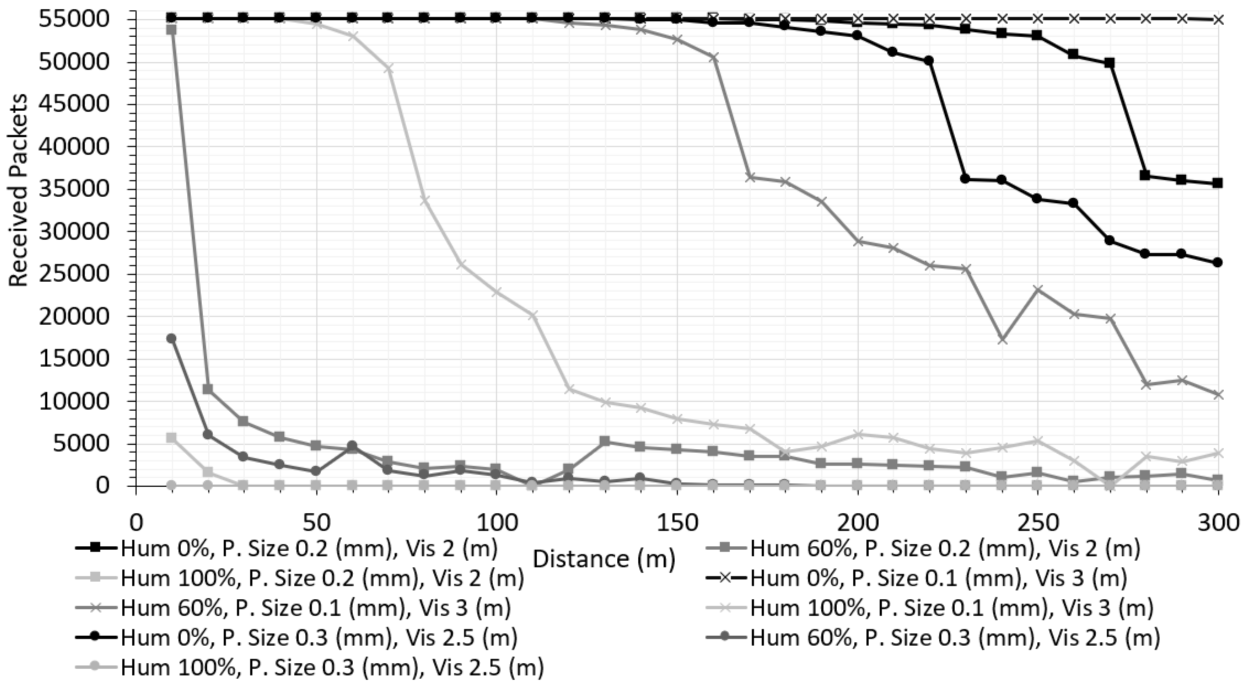

Figure 22. Received packets versus distance at certain humidity (Hum), particle size (P.Size), and visibility (Vis)

CHAPTER 6

Conclusions

In this research, the effect of dust and sand storms on the 5G wireless communication channel between connected vehicles was investigated. The proposed margin link model is used to simulate the effect of dust and sand. The main object point of this work is to find the threshold value of the particle size of sand and the concentration to avoid the loss of communication between autonomous vehicles. The simulation results show that the attenuation of the 5G propagating signal increases when the operating frequency, the concentration of the dust, and the particle size of the sand are increased. Also, it is seen that the 5G mm-wave communication channel is more affected by dust and sand storms than the DSRC channel. We extend NS-3 Millicar module and publish all the code and results on GitHub (https://github.com/ericliujian/ns3-mmwave-weather).

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