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Propagating Uniform Millimeter Wave in Dust and Sand Storm

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Abstract—Recently, researchers have focused on the effect of changes in weather on the operation of wirelessly connected systems. Past researchers studied the impact of rain and snow on propagating electromagnetic waves. These researchers concluded that the millimeter waves are more sensitive to changing weather, and the vertical polarization is the best during rainy and snowy weather. Other studies concluded that the impact of dust and sand storms on the propagating 5G waves is not series when the visibility is greater than 10m. In this research, the normal and oblique incidence of the electrical and magnetic fields are considered during dusty/sandy medium with different forms of polarization to see which polarization is less affected by dust and sand storms. In the case of normal incidence, the proposed mathematical model of linear, circular, and elliptical polarization are used to see the behavior of different polarizations during dusty/sandy region. The transverse electric (TE) and transverse magnetic field (TM) are considered in the case of Oblique incidence uniform plane Wave. Maxwell's equations and the Mie model are used to derive the mathematical model of the electric field and magnetic field in both incident forms. Finally, the numerical results are generated by using MATLAB to show the behavior of different polarization during severe weather.

Index Terms—normal incidence, oblique incidence, TE mode, TM mode, lossy medium.

I. Introduction

THIS paper is an expansion of the previous study published in the 2022 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) [1]. As we have previously stated before, the 5G radio frequency (RF) is considered a connectivity channel to support vehicleto-vehicle ($V2V$) and other newer systems that send and receive discrete packets [2]. It is known that the new digital communication systems aim to send data with a high rate and lower signal-to-noise ratio. Recently the $5G$ frequency band has opened the door to connect different digital systems, but this technology is affected by changes in weather, such as dust storms. For this reason, the impact of dust and sand on the $5G$ channel is important to consider to support these new technologies. The wireless network is used to decrease the installation cost of connected systems between different locations. Different new applications and digital systems are supported by using wireless millimeter radio channels. Previous work stated that the transmitted power of a 5G millimeter wave is attenuated when it is propagating during dusty/sandy regions or rainy weather [3]. Herein, the impact of dust/sand storms on the propagating $5G$ transmitting signal is considered in the normal incident case and oblique incident case. The different forms of normal incident polarization (linear, circular, and elliptical) are considered in the normal incident case, and TE mode and TM mode are considered in the oblique incident case. The amplitude and the phase of propagating electric and magnetic fields are investigated when these fields propagate in the form of linear, circular, and elliptical polarization. In the Oblique Incident Uniform Plane Wave case, the TE and TM polarized waves are investigated during dusty/sandy weather. This research aims to find the optimum polarization that is best used during severe weather. In other words, it focuses on seeing which polarization is more affected by dust/sand storms. During rainy weather, horizontal polarization seriously affects in comparison with vertical polarization. The results of this research will display the impact of dust/sand storms on different forms of polarization. Moreover, simulation results will give a clear meaning of this propagating behavior. Past work [4] showed that the impact of the dusty/sandy medium on a point-to-point connected wireless system signal is computed by knowing the attenuation constant in dB/km. This attenuation is changed when the propagating parameters and properties of the transmitting medium are changed. Also, the effect of dusty/sandy medium on the $V\ 2V$ connectivity channel was investigated because this application is one of the most important recent applications in our life. This previous study mentioned that the attenuation factor of the transmission medium is increased when propagating parameters such as operating frequency are increased. Also, the attenuation is increased when the transmission medium has more dust and sand with high humidity. It is found that the Dedicated Short-Range Communications channel ($DSRC$) is less effect by dust storms in comparison with the 5G mm-wave radio channel [5]. Other research groups conducted studies to see the effect of dust/sand storms on different exciting wireless communication systems such as mobile networks and microwave links [6]–[8]. These researchers summarized that the transmitting power of the propagating signal is attenuated when it passes through a sandy/dusty medium. It is found that the permittivity of a wireless transmitting medium (vacuum) with dust and sand is changed from a real to a complex value. This change affects the attenuation of this transmitting medium because the attenuation constant depends on the complex dielectric constant of the dusty/sandy region. The dielectric constant depends on the chemical composition of the dust and sand particles. Moreover, the Mie model shows that the frequency, visibility, humidity, and particle size

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seriously affect the attenuation factor of the transmitting medium [9]. Again, This study focuses on the impact of dust storms on the power of the $5G$ channel of digital communication systems. This transmitting RF signal is in the linear, circular, and elliptical polarization form. Also, the transmitting RF signal is considered in the form of TE and TM modes to see the behavior of these two modes during dust and sand storms. To compute a real attenuation factor, it is required to measure the complex dielectric constant of different desert regions in the United States. In this research, Maxwell's equations and the Mie scattering model are used together to find the characteristic equation of propagating electric and magnetic fields in the case of different forms of polarization. This work is covered in four important sections. Section II discusses the mathematical model that represents the electric and magnetic fields of the uniform $5G$ wave traveling in an unbounded dusty/sandy region in the normal incident case. In section III, the propagating of the mm-wave in the oblique incident case is investigated. Section IV introduces the numerical results of the computer simulation. The conclusion and future work are inserted in Section V.

II. Normal Incident Uniform $5G$ Wave in Unbounded Lossy Medium

In this section, the expressions of the electric and magnetic fields of the uniform millimeter plane wave traveling in an unbounded dusty/sandy medium are written. It is considered that the time-harmonic uniform millimeter plane wave is traveling in an unbounded dusty and sandy lossy region(ε,μ) in the positive z direction. The real and imaginary parts of the complex dielectric constant are defined as [10]

$$\varepsilon_m = \varepsilon' - j\varepsilon'', \quad (1)$$

where the real part and the imaginary part of the complex dielectric constant of the dusty lossy region are defined respectively as [11]

$$\varepsilon' = 6.3485+0.04H-7.78\times10^{-4}H^2+5.56\times10^{-6}H^3, \quad (2)$$

$$\varepsilon'' = 0.0929+0.02H-3.71\times10^{-4}H^2+2.76\times10^{-6}H^3, \quad (3)$$

where H is the percentage of relative humidity. The general expression for the electric and magnetic fields associated with this wave is written as [1]

$$\tilde{E} = [E_1\hat{a}_1 + E_2\hat{a}_2 e^{j\theta}]e^{-\alpha}e^{-jk_o\cdot d}. \quad (4)$$

$$\tilde{H} = [\frac{E_1}{\eta}\hat{a}_1 + \frac{E_2}{\eta}\hat{a}_2 e^{j\theta}]e^{-\alpha}e^{-jk_o\cdot d}. \quad (5)$$

where θ is the phase angle, E_1 and E_2 are the amplitude of the electric field in $\hat{a}_1$ and $\hat{a}_2$ direction respectively, d is an attenuation length, k_o is the wave number, η is the intrinsic impedance of the free space and α is the attenuation constant of dusty region. The attenuation factor of dust and sand is computed by using the Mie model as [12] and [13]

$$\alpha(\frac{Np}{km}) = \frac{1}{8.68}\frac{a_e f}{v}[C_1 + C_2 + a_e^2 f^2 + C_3 a_e^3 f^3](\frac{dB}{km}), \quad (6)$$

where $C_1(\varepsilon',\varepsilon'')$, $C_2(\varepsilon',\varepsilon'')$ and $C_3(\varepsilon',\varepsilon'')$ are constants and depend on the complex dielectric constant of dusty/ sandy [2], a_e represents the particle ($meter$), v represents the visibility (km), and f represents the frequency (GHz). The directions of $\hat{a}_1$, $\hat{a}_2$, and k_o are determined by Maxwell's equations and presented in table 1.

TABLE I
DIRECTION OF PROPAGATING WAVE

No.	(E)	(E)	(H)	(H)	(k)
-	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_1$	$\hat{a}_2$	$\hat{k}$
1	x	y	y	-x	+z
2	y	x	-x	y	+z
3	-x	-y	-y	x	+z
4	x	y	-y	x	-z
5	-x	-y	y	-x	-z
6	y	x	x	-y	-z
7	-y	-x	-x	y	-z

Table 1 shows the possible direction of the electric field E and magnetic field H with a specific direction of $\hat{a}_1$ and $\hat{a}_2$. For example, if $\hat{a}_1$ is in x direction and $\hat{a}_2$ is in y, the mm-wave propagates in the z direction as mentioned in No.1 in the table. In the case of the normal incident, the linear, circular, and elliptical polarization are generated by using (5). To generate the linear polarization form of the electric field, it is assumed $E_1 = E_2 = E_0$ and θ=o. The electric is represented by

$$\tilde{E} = [E_0\hat{a}_1 + E_0\hat{a}_2]e^{-\alpha}e^{-jk_o\cdot d}. \quad (7)$$

and the magnetic field is

$$\tilde{H} = [\frac{E_0}{\eta}\hat{a}_1 + \frac{E_0}{\eta}\hat{a}_2 e^{j\theta}]e^{-\alpha}e^{-jk_o\cdot d}. \quad (8)$$

In the circular polarization case, it is assumed $E_1 = E_2 = E_0$ and θ=90. The electric field is written as

$$\tilde{E} = [E_0\hat{a}_1 + E_0\hat{a}_2 e^{j90}]e^{-\alpha}e^{-jk_o\cdot d}. \quad (9)$$

and the magnetic field as

$$\tilde{H} = [\frac{E_0}{\eta}\hat{a}_1 + \frac{E_0}{\eta}\hat{a}_2 e^{j90}]e^{-\alpha}e^{-jk_o\cdot d}. \quad (10)$$

In the case of elliptical polarization, it is assumed $E_1 \neq E_2$ and θ is the phase difference between two components, so the electric field and the magnetic field are presented by (5) and (6).

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III. Oblique Incident Uniform Plane Wave in Unbounded Lossy Medium

In this part, the propagating of the mm-wave in the oblique incident case is considered. The expressions of electric field and magnetic field are written for oblique incident uniform mm-plane waves traveling in a dusty/ sandy unbounded medium. It is assumed the mm-uniform plane wave is propagating in an unbounded dusty/sandy medium in parallel with the x-z plane. Herein, the electric field has two components in the direction of x and z, and the magnetic field has one component in the direction of the y axis, so this mode is called transverse electric (TE). On the other hand, if the magnetic field is traveling in parallel with the $x - z$ plane and the electric field is perpendicular to the plane of the incident, the mode is called transverse magnetic (TM). These two modes are discussed in the coming two sections.

A. TE Mode

In the case of TE, it is assumed the electric field does not have a y component. The electric field has only two components in the direction of the x and z axes. The electric field is propagating in the direction of $\hat{a}_x sin(\theta_i)+\hat{a}_z cos(\theta_i)$, and it lies in the plane of incidence. The electric field is represented by

$$\tilde{E} = E_0[\hat{a}_x cos(\theta_i) - \hat{a}_z sin(\theta_i)]e^{-\alpha}e^{-jk_o \cdot d(sin(\theta_i)+cos(\theta_i))}. \quad (11)$$

The magnetic field has one component that is perpendicular to the plane of incidence as

$$\tilde{H} = \hat{a_y}[\frac{E_0}{\eta}e^{-\alpha}e^{-jk_o \cdot d(sin(\theta_i)+cos(\theta_i))}]. \quad (12)$$

B. TM Mode

In the case of TM, it is assumed the electric field does not have a x and z components. The electric field has only one component in the direction of y axes that is perpendicular to the plane of incidence. The electric field is propagating in the direction of $\hat{a}_x sin(\theta_i)$ + $\hat{a}_z cos(\theta_i)$. The electric field is represented by

$$\tilde{E} = \hat{a}_y[E_0 e^{-\alpha}e^{-jk_o \cdot d(sin(\theta_i)+cos(\theta_i))}]. \quad (13)$$

The magnetic field has two components that are perpendicular to the incident electric plane as

$$\tilde{H} = \frac{E_0}{\eta}[-\hat{a_x}cos(\theta_i) + \hat{a_z}sin(\theta_i)]e^{-\alpha}e^{-jk_o \cdot d(sin(\theta_i)+cos(\theta_i))}. \quad (14)$$

IV. Results and discussion

In the computer simulation, the wireless system is assumed to operate at $73.5GHz$, and the transmitting power is $15dBm$. The amplitude E_o is $3.5\ v/m$ by using Maxwell's equations and field equations. The measured dielectric constant $\varepsilon = 6.3485 - j0.0929$ is changed when the humidity is changed by using (2) and (3). MATLAB is used to simulate the effect of dust and sand on the propagating electric field in the case of different polarizations. All figures show the change of magnitude of the electric field when the visibility and humidity of the transmission medium are changed. Fig. 1, 2 and 3 show the relationship between visibility (v) in the $x - axis$, the component of electric field (E_x) in $y - axis$, and component of electric field (E_y) in $z - axis$ at different altitudes in the free space with different humidity values. The absolute value of E_x and E_y are $(2.635{,}2.635)$, $(0.9356{,}0.936)$, and $(0.388{,}0.388)$ at 0, 60, and 100 humidity, respectively with visibility $v = 10m$ and particle size $94.43um$, in the linear polarization as shown in Fig.1. In the circular polarization, the E_x and E_y are $(2.635{,}8.7 \times 10^{-10})$, $(0.9356{,}3.09 \times 10^{-10})$, and $(0.388{,}1.28 \times 10^{-10})$ at 0, 60 and 100 humidity respectively with visibility $v = 10m$ and particle size is $94.43um$ as shown in Fig.2. Fig.3 shows that the E_x and E_y are $(2.635{,}0.838)$, $(0.9356{,}0.29767)$, and $(0.388{,}0.1235)$ at 0, 60 and 100 humidity respectively with visibility $v = 10m$ and particle size is $94.43um$, in the elliptical polarization. These three figures show the linear form in the normal incidence case is the best polarization that is recommended using with severe weather.

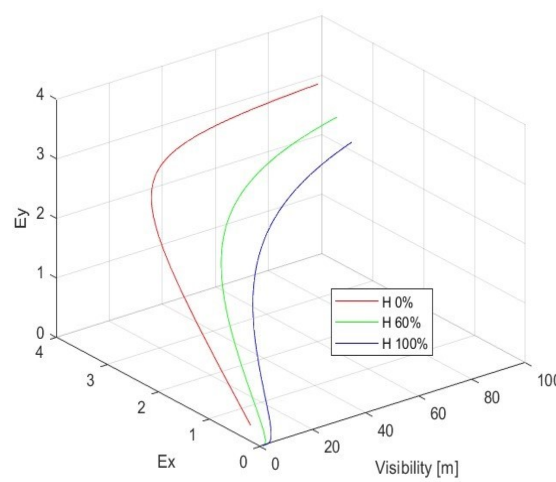

Fig. 1. Linearly polarized millimeter wave f =73.5GHz

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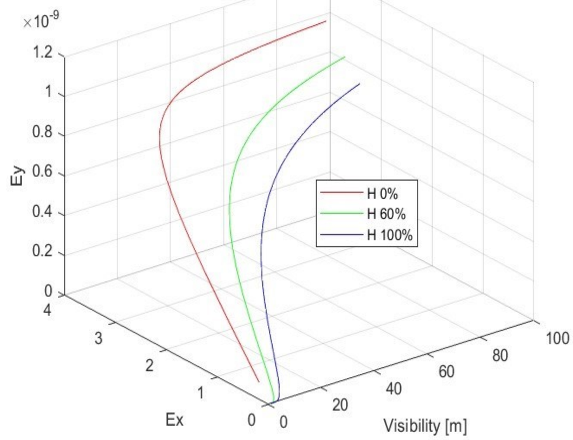


Fig. 2. Circular polarized millimeter wave f =73.5GHz

In the case of TE polarization, the E_x and E_z are (1.247,2.16), (0.443,0.767), and (0.183,0.318) at 0, 60, and 100 humidity respectively, with visibility v = 10m and particle size is 94.43um as shown in Fig.4. The magnitude of the electric field (E_y) is 2.635, 0.935 and 0.388 at 0, 60 and 100 humidity respectively with visibility v = 10m

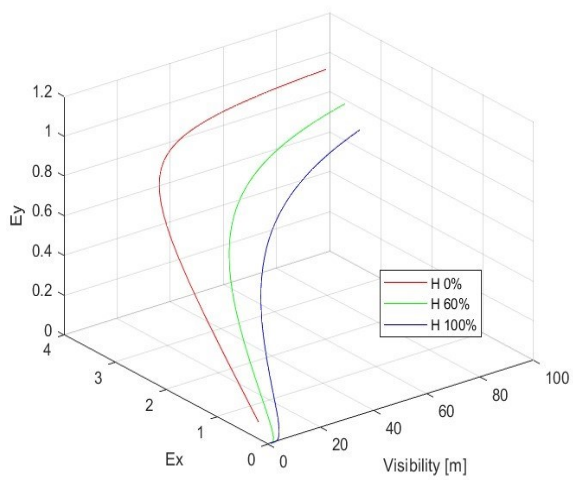


Fig. 3. Elliptical polarized millimeter wave f =73.5GHz

and particle size is 94.43um, in the TM polarization case as shown in Fig.5. These results show that the TM polarization in the Oblique Incident case is the best polarization that is used during severe weather. The electric field of linear polarization and TM mode are less affected by dust storms than other polarization, as shown in Fig.1 and Fig.5. Also, the attenuation of a transmission medium with dust and sand increases when the visibility decreases, and the radius of particle size and humidity increase, as shown in Fig.6 and Fig.7.

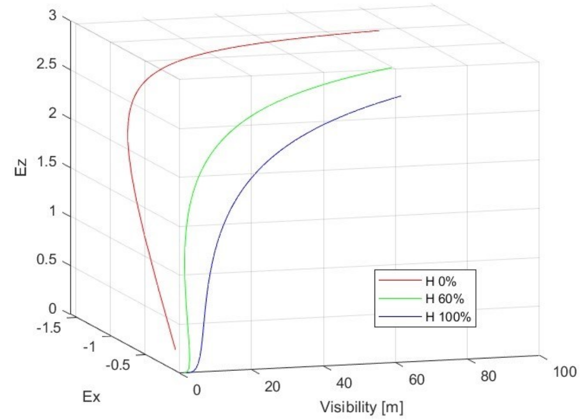


Fig. 4. TE mode polarized millimeter wave f =73.5GHz

The propagating 5G wave during a dusty region is investigated when the radius of the particle size is increased. It is assumed the particle size a_e = 538.04um and other transmission parameters are the same. Fig. 7, 8, 9, 10, 11 and 12 show that the electric field is zero when the visibility is less than 17m, 38m, 60m at 0, 60, and 100 humidity, respectively. Moreover, the magnitude of the electric field in the circular, elliptical, and TM polarization is impacted more by the dust and sand storms. In the linear and TM polarization, dust and sand are still less effect on the magnitude of a propagating plane wave as shown in Figs.1 and 5.

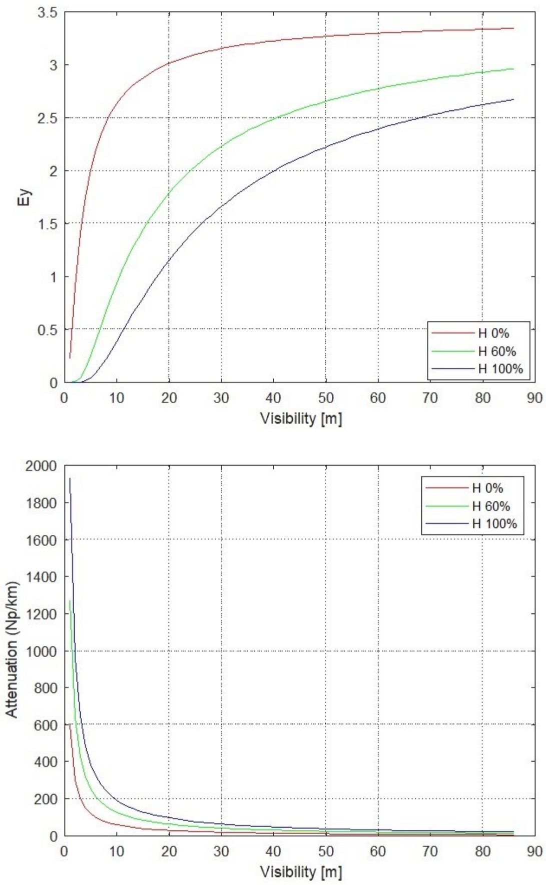


Fig. 5. TM mode polarized millimeter wave f =73.5GHz

Fig. 6. Attenuation constant

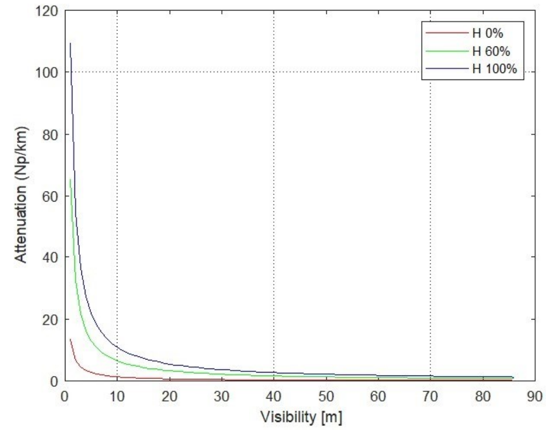


Fig. 7. Attenuation constant

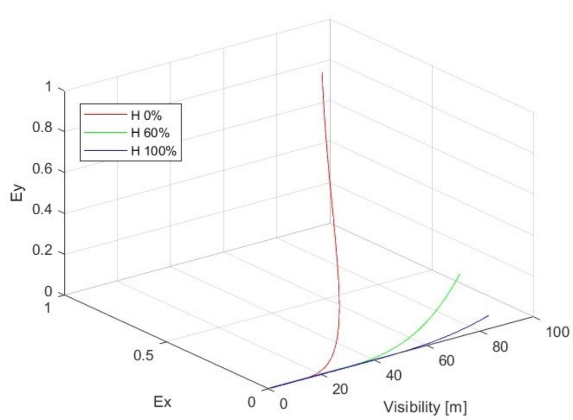


Fig. 8. Linearly polarized millimeter wave f =73.5GHz

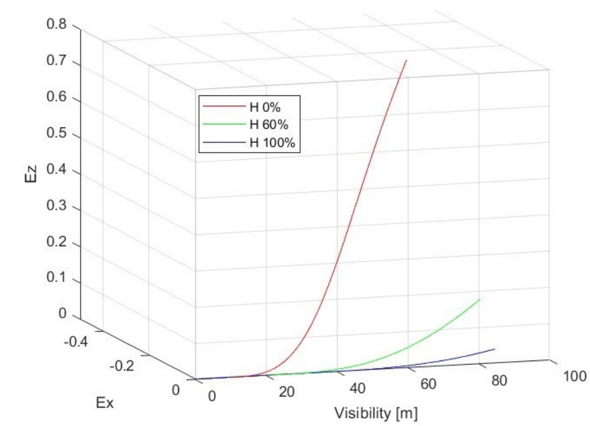
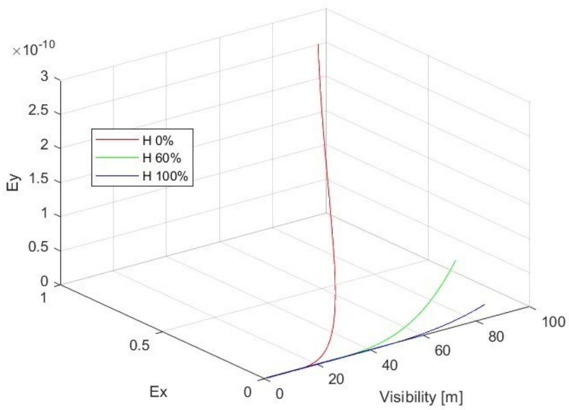


Fig. 11. TE mode polarized millimeter wave f =73.5GHz



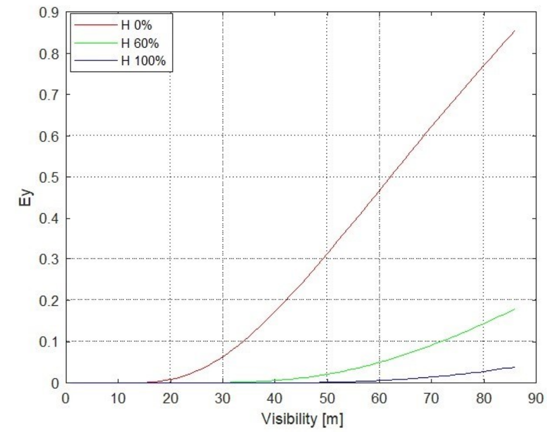


Fig. 12.

TM mode polarized millimeter wave $f = 73.5 GHz$

Fig. 9. Circular polarized millimeter wave $f = 73.5 GHz$

V. Conclusion

The propagating $5G$ mm-wave during dusty/sandy region is investigated in the case of normal and oblique incidence uniform plane wave. The linear, circular, and elliptical polarization are considered in the case of normal incidence. In the case of oblique incidence, TE and TM are considered wave polarization. Maxwell's equation and the Mie model are used to derive the mathematical expressions that represent the different polarizations of the electric fields and magnetic fields. The simulation results show that the linear polarization in the normal incidence case and the TM polarization in the oblique incidence case are less affected by dust and sand storms in comparison with circular and elliptical and TE polarization. In these two recommended polarizations, the components of the electric field are perpendicular (vertical) to the plane of the incidence wave. Results show that circular polarization is the worst transmitting form during dusty and sandy weather. The recommended future work is recording actual data of different weather factors, distributed dust, and the radius of sand in desert areas in the United States to compute the accurate real attenuation factor for these specific regions.

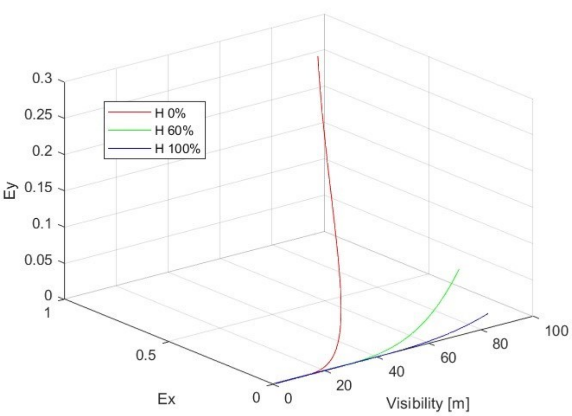


Fig. 10. Elliptical polarized millimeter wave $f = 73.5 GHz$

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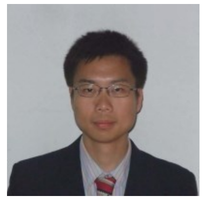

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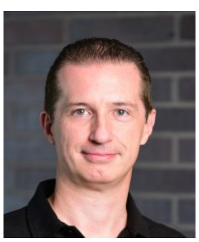

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