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Terahertz Window Frequency Signal Attenuation and Dispersion Characteristics in Tropical Climate Zone: An Experimentally Validated Reliability Analysis

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ABSTRACT The propagation of electromagnetic signals through atmosphere is affected by absorptive and dispersive processes present therein. The resulting attenuation increases in adverse weather conditions. The loss of signal power due to scattering of electromagnetic waves in free space, is one of the most common hazards in ultrafast wireless communication systems. The scattering of signal is caused by the suspended atmospheric hydrometeors. Moreover, due to the humidity of the atmosphere, the defocusing of the electromagnetic beam, known as scintillation, may occur. In this paper, the authors, for the first time, have presented a comprehensive analysis of terahertz (THz) signal attenuation along with scintillation effect, in fog-laden atmosphere of Indian subcontinent under tropical climatic belt. The frequency-dependent properties of the signal attenuation have been analysed using an indigenously developed Non Linear Terahertz Attenuation Model (NLTAM)simulator. Moreover, the difference between single and multiple scattering effects of THz signal has also been presented here. The nature of THz signal attenuation spectra in foggy atmosphere, agrees closely with experimental findings, for near THz or IR signal transmission in fog-based aerosols weather scenario in both tropical and non-tropical regions. The experimental study at MMW regime was carried out through radiometric measurement of fog attenuation at Kolkata (22^0N, tropical region) and the results are compared with the NLTAM model data for reliability verification. The signal attenuation is found to be $\sim 16 \times 10^5$ dB/Km around 2.0 THz frequency. By incorporating parametric variations in the present simulator, the authors have estimated the reliable range of THz signal energy, coming out of atmospheric fog-layer. The authors have developed a separate reliability model to address this aspect of study. To initiate a comparative analysis on the prediction of attenuation of THz wave for different types of scattering mechanisms, especially in foggy atmosphere, under tropical climatic region, a novel technique has been developed and reported by the authors for the first time.

INDEX TERMS Terahertz, Mie-theory, extinction coefficient, radiation-fog, absorption, multiple scattering, reliability study.

I. INTRODUCTION

The terahertz (0.1THz-10THz) spectrum is located between conventional electronics and photonics. It has captured a wide area of modern research [1]–[3] in the field of wireless communication, owing to itsversatile applicability. The bandwidth offered by terahertz technology is quite large and the channel capacity is also very high [4]–[6]. THz waves can show a very high sensitivity to adverse weather conditions, when subject to pass through near-surface atmosphere. In clear weather, presence of atmospheric gases and air turbulence may degrade the performance of THz communication [7]–[10]. The atmosphere, works as the medium between THz-Transmitter and Receiver in a particular THz communication system. The prime constraint in THz communication is the high amount of propagation loss, that

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occurs due to atmospheric absorption and signal scattering [11]–[13]. Various gas molecules, like Oxygen, Water-vapor in atmosphere, can absorb the THz signal, while the existence of randomly positioned as well as randomly traversing finite and discrete aerosols may lead to scattering effect in THz transmission [14]. In terrestrial communications, turbulence in fog-laden air leads to scattering as well as scintillation effect in electromagnetic signal, where, the attenuation of electromagnetic wave, subject to propagate through a random medium is frequently calculated using the single scattering method [15], [16]. The effect of single-scattering is almost ideal. The high density of aerosols in atmosphere lead to very poor visibility condition, in which the phenomenon of multiple scattering of electromagnetic signal becomes significant [17]. Fog is the most common weather occurrence in which particles, water droplets or ice crystals are suspended in the air near the ground. Based on visibility and droplet size, it is categorised as haze, heavy fog, thick fog, or mist. Fog is divided as advection fog or radiation fog, depending on the origin and the process involved in its generation.Advection fog arises when warm, wet air flows over a cool sea surface. When the earth emits long wave terrestrial radiation, the air in the vicinity of the ground follows an adiabatic cycle, which initiates radiation fog in saturated atmosphere [18], [19].

In Northern part of India, under tropical climatic belt, the concentration of radiation fog based hydrometeors decreases at a rate of around 1.5×10^5 particles/litre/hour during day-time of Mid-December to January [20]–[24]. The mean temperature level of tropical climate lies around 65^0F. The climatic belt of South-East Asia is largely tropical [20]–[23]. The rate of variation of this concentration increases after sunset. In general, the mode of fog-generation in tropical climatic belt isaccumulation type [24] in which the particle diameter of aerosols plays a very important role. The researchers have found that in most of the cases, the urban-fog under sub-tropical climatic belt, is anthropogenic, where the hydrophilic ions are prevalent [25], [26]. Theestimation of scattering attenuation of the incident THz signal in fog is primarily governed by Mie-Scattering theory [15], [27], as the particle-diameter and the wavelength are almost compatible. For tropical climatic area, fog can extend vertically to an altitude of 500m from ground surface. The presence of liquid water content in fog initiates variation of refractive-index in the medium that in turn leads to attenuation of incoming THz signal [28]–[31]. In sub-tropical continental or radiation fog, discrete temporal variability can be observed [32]–[36], which leads to multipath propagation as well as multiple-scattering of the THz-wave.

Water vapor is a minor gaseous constituent but anotably main contributor for the attenuation. The gaseous attenuation is commonly described as the sum of spectral absorption links of water vapor and oxygen and a water vapor continuum component. The humidity affects the signal attenuation significantly when it changes from 20% to 97%. In strong winter, atmospheric humidity level under tropical-climate region fluctuates. This humidity fluctuation, in addition with air-turbulence can induce a distortion of the wave front of the THz beam, leading to focusing and defocusing effects. Such fluctuations of the beam, called scintillations, would attenuate the beam power and degrade link performance [37]–[46]. The authors, have incorporated the modified radiative transfer equations in the newly developed NLTAM model, by considering the discrete microphysical approach, supported by vector radiative-transfer theory [32]–[36]. In this uniquely developed model the context of geophysical separations and the effect of these separations on atmosphere have also been included. To initiate the temporal variation of aerosol concentration along the path of propagation of THz-wave in the discrete medium, the authors have included the probability statistics and studied the wave-particle interaction more comprehensively. The tropical refractive-index structural variation with temperature and humidity related parameters has been thoroughly studied and simulated to yield the scintillation output. Although, several research works on multiple-scattering of sub-millimeter wave in adverse weather condition under non-tropical climatic belt have been reported so far, no work on the same for Indian tropical-climate has been reported yet.

For the first time, the authors have developed a comprehensive simulator of THz-attenuation spectrum in continental fog-scenario, to simulate the THz attenuation with the effect of different scattering mechanism and scintillation effects. The sensitivity analysis has been performed also to propose the possible range of reliable THz operation in tropical climate. The validity of the model is also established by the authors' group. The outcome of this model would assist defence people

II. NUMERICAL ANALYSIS

The uniquely developed physics-based self-consistent Non-Linear Terahertz Attenuation Model(NLTAM) mainly focusses on the time-varying and turbulent behaviour of atmosphere on the radio-frequency wave passing through it. Different weather-dependent parameters, have been included in the study and corresponding equations are solved subject to appropriate boundary conditions. The variations of refractive-index of the liquid water based absorbent, with incident THz radiation, have been thoroughly investigated by incorporating the modified Millimeter-wave Propagation Model(MPM) [40]. The particle size-parameters play very important role in simulating the atmospheric attenuation of electromagnetic-signal. The terahertz wavelength range has been employed to estimate the fog-based total extinction cross-section of THz signal.

The presentation of this paper is arranged in four steps:

i) The simulation of attenuation spectrum due to single-scattering effect of THz wave and tropical- hydrometeors incorporating necessary weather dependent boundary conditions.
ii) The simulation of attenuation spectrum due to multiple-scattering effect of THz wave and tropical hydrometeors under the appropriate boundary conditions.
iii) Comparison of single versus multiple scattering model.

TABLE 1. List of major parameters incorporated in NLTAM simulator.

Parameter	Physical Significance	Utility
f	Frequency	Terahertz regime
x	Size-parameter	Characterization of scattering
s	Radius	Droplet dimension
r_f	Refractive-index	Signal attenuation
Q_{sca}	Scattering-efficiency	Amount of Signal-Scattering
Q_{ext}	Extinction-efficiency	Amount of Signal-Extinction
v_{rms}	RMS velocity of wind in Tropical Climate	
A_T,S_T	Temperature(Tropical) dependent structural parameter	Signal-scintillation
A_H,S_H	Humidity(Tropical) dependent structural parameter	
h	Tropospheric altitude	
T	Mean temperature	~66^0F in Tropical climate
ϵ_r	Real part of complex permittivity	Permittivity of water-Medium
ϵ_i	Imaginary part of complex permittivity	
R_L	Moist Air Resonance	
R_D	Non-resonant Dry Air Spectrum	Requisite factors to determine the complex refractivity of dispersive medium
R_C	Continuum Spectrum of Water Vapor	
R_W	Refractivity of Suspended water	
R_R	Contribution of falling aerosols	
$E_{inc}(d,t)$	Incident space-time dependent E-field	Electric-field components of THz signal in dispersive medium
$E_{sca}(d,t)$	Scattered space-time dependent E-field	
$G(d,d_1)$	Dyadic Green's function with two points(d,d_1) in the scattering potential	Multiple-scattering of THz Signal in fog-laden Medium
$T(d_1, d_2)$	Lippman-Schwinger Function with another two points(d_1, d_2) in the scattering potential	
ψ_{abs}, ψ_{sca}	space and time dependent fog based absorption and scattering coefficient	THz-Transmission Attenuation Rate
$\xi(d,t,\theta)$	THz Electric Flux-density of E-field	
U	Rate of THz photon capture	
σ	Fitting-parameter	

iv) The simulation of scintillation-effect on signal propagation in tropical weather condition.
v) Experimental verification of the indigenously developed self-consistent physics based non-linear simulator(NLTAM) followed by a reliability analysis of the model.

Table 1 summarizes the parameters used in NLTAM simulator.It is evident from Fig.1 that the amplitude and phase-distortions of THz wave during its propagation through vacuum, are caused by various atmospheric variants. The

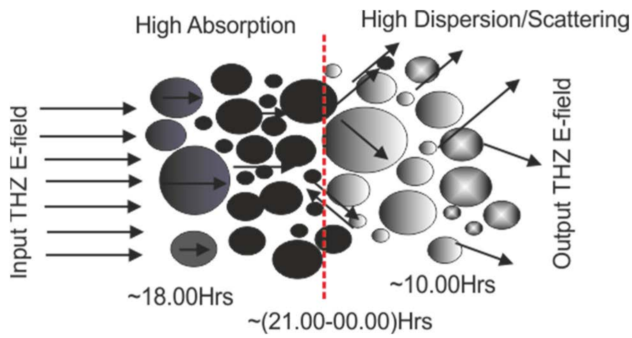

FIGURE 1. Scattering and absorption of THz wave due to fog-based aerosols, depending on the diurnal variation of concentration of liquid water crystalsin tropical climate area.

time-varying dispersion, absorptionand refraction properties of THz signal are controlled by the dielectric characteristics of liquid water droplets present in the fog-laden atmosphere. The frequency domain expression of Electric-field of the THz signal, subject to propagate a distance d in the absence of turbulence of the medium, can be given as [14], [15],

$$E\,(d\,,\theta,\varphi)=E_0(\theta,\varphi)e^{-jk_f d} \tag{1}$$

where, $E_0(\theta,\varphi)$ is the peak intensity of the incident E-field in terms of angles θ,φ. $k_f$is the frequency dependent propagation vector, which can be expressed as

$$k_f=(2\pi f/c)r_f \tag{2}$$

In (2), the complex refractive-index of the medium is denoted by r_f and c is the speed of electromagnetic wave in free-space. Since, the complex refractive index of the medium through which the signal is subject to propagate, is dependent on medium's dielectric properties, therefore, in general, it is expressed as [36]–[46]

$$r_f=\sqrt{\epsilon}_m=\sqrt{\epsilon_r+j\epsilon_i} \tag{3}$$

ϵ_m, ϵ_r, $\epsilon_i$signify the complex permittivity of the medium through which the signal is subject to propagate and the real and imaginary parts of complex permittivity respectively. Equation (3) indicates the relation between the complex refractive-index and permittivity of the medium through which the desired signal is subject to propagate. The complex permittivity of the medium,on the other hand, depends on the frequency of the incident signal. It can be derived by utilising the Double-Debye method [39], [40] as,

$$\epsilon_m=\sum\nolimits_{l=1}^{2}[\{A_l/\left(f_l^2-f^2-j\gamma_l f\right)\}-(A_l/f_l^2)] \tag{4}$$

In (4), the parameters $f_1, f_2, \gamma_1, \gamma_2, A_1$, A_2 can be estimated from Liebe's Millimeter-wave Propagation Model (MPM)[39].

A. SINGLE-SCATTERING OF TERAHERTZ WAVE IN AEROSOLS

As per Liebe's MPM [39], [40], the dispersive complex refractivity of the medium through which the electromagnetic signal of desired frequency is subject to propagate, can be characterized by the summation of frequency-dependent atmospheric constraints. The Fog-based aerosol, is generally enhanced by the condensation of Liquid Water Content (LWC) present in the atmosphere. The amount of relative-humidity as well as density of LWC crystals in tropical climate differ from temperate climatic zone. The authors, in NLTAM, have considered the frequency-dependent complex-refractivity of the dispersive medium as R(f), where,

$$R(f) = R_L + R_D + R_C + R_W + R_R \tag{5}$$

Here, the contribution of moist air resonance is initiated by R_L, the non-resonant spectrum of dry air is denoted by R_D, the continuum spectrum of water vaporis mentioned by R_C, the refractivity of suspended water droplets is given byR_W, and R_R stands for the contribution of rain to refractivity.The solution for Macroscopic Maxwell's Equation in E-field, considering the medium as homogeneous and isotropic, has been given in (1). In general, the presence of an obstacle along the path of electromagnetic signal propagation leads to the scattering of the signal. To simplify the complexity of analysis coming out of decomposition of E-field into innumerable back-waves due to scattering mechanism, the idea of Single-Scattering is generally taken into account [41]–[43]. In NLTAM, the authors have initiated the simulation ofSingle-Scattering mechanism in the presence of fog-based aerosols, by considering the entire E-field vector as,

$$\vec{E}\left(\vec{d}, t\right) = \vec{E}_{inc}\left(\vec{d}, t\right) + \vec{E}_{sca}\left(\vec{d}, t\right) \tag{6}$$

where, $\vec{E}_{inc}\left(\vec{d}, t\right)$ and $\vec{E}_{sca}\left(\vec{d}, t\right)$ represent the incident and scattered vector counterparts of E-field respectively.

Under single-scattering, it has been considered that size of fog-based water droplets in tropical climate, is regular(mainly spherical), with mean diameter around 10micron. In the fog-based medium, when the product of size-parameter(x) and refractive-index at a particular wavelength of incident electromagnetic radiation exceeds 0.5, Mie-scattering becomes predominant [43]. The authors, in this work, have uniquely characterizedboth of the Rayleigh and Mie-Scattering phenomena at THz-regime.The distribution of fog-particles for a particular droplet-size of radius, s, is considered to follow the Modified-Gamma Law [40]–[45] as

$$n(s) = as^p e^{-bs^\gamma} \tag{7}$$

In (7), a, b, p and γ are the parameters that mainly depend on the type of fog(advection or radiation). For tropical-fog, the radii of water-droplets are bound within 20micron. As a consequence of scattering through fog-based medium, the relative degradation of incident E-field after traversing adistance d, can be estimated by using Beer-Lambert Law [41]–[44] as,

$$E(d) = E_0 e^{-\alpha_{ext} Wd} \tag{8}$$

where, $E(r)$ is the difference of incident and scattered E-fields, indicated earlier. $E_0$is the initial field-intensity. The mass extinction coefficient, measured in m^2/g, is denoted by α_{ext} and W is the concentration of LWC, measured in g/m^3.In the measurement of the fog-based attenuation of THz signal due to single-scattering mechanism, the mass-extinction coefficient, as a combination of absorption and scattering coefficients, plays a very important role [41], [42]. Using extinction-efficiency Q_{ext}, the mass-extinction coefficient has been simulated as

$$\alpha_{ext} = [\int s^2 Q_{ext} n(s)\, ds]/[1.34\rho * \int s^3 n(s) ds] \tag{9}$$

The factor ρ, in (9), signifies the aerosol concentration in absorbing medium. To simulate the single-scattering attenuation-loss of THz signal in foggy-atmosphere, the authors have incorporated the expressions of scattering and extinction efficiencies as [41]–[44],

$$Q_{sca} = (2/x^2) * \sum\nolimits_{m=1}^{\infty} (2m+1)(|a_m|^2 + |b_m|^2) \tag{10}$$

and

$$Q_{ext} = (2/x^2) * \sum\nolimits_{m=1}^{\infty} (2m+1)Re(|a_m| + |b_m|) \tag{11}$$

In (10) and (11), x is the size-parameter [41], [42] and a_m, b_m are derived from standard expressions of Mie-abcd parameters as

$$a_m = a_{1,2}/a_{2,2} \tag{12}$$
$$b_m = b_{1,2}/b_{2,2} \tag{13}$$
$$c_m = c_{1,2}/c_{2,2} \tag{14}$$
$$d_m = d_{1,2}/d_{2,2} \tag{15}$$

where, $a_{1,2}, a_{2,2}, b_{1,2}, b_{2,2}, c_{1,2}, c_{2,2}, d_{1,2}, d_{2,2}$ are elaborated elsewhere[15].

The single-scattering based attenuation of THz signal in fog, has been simulated in this model(NLTAM) by using the expression,

$$\text{Attenuation(dB/km)} = \text{C} \int_0^{\infty} Q_{sca} n(s) ds \tag{16}$$

Here, C has the magnitude of about 5×10^3.

B. MULTIPLE-SCATTERING OF TERAHERTZ WAVE IN AEROSOLS

The multiple-scattering can be inevitably considered as the most common scattering phenomenon, as the dimension of aerosols present in tropical fog is quite compatible with the wavelength of terahertz radiation. The authors, in their uniquely developed NLTAM simulator, have incorporated the modified Radiative-Transfer theory [35]–[40] along with statistical analysis to study the successive back-scattering of incident THz wave in random-medium. The model analysis has been initiated by employing the FOLDY-LAX Equations in (6) to navigate the effect of local-excitations [35]–[40] within a certain volume in discrete medium. Equation (6) is re-expressed as,

$$\vec{E}\left(\vec{d}\right) = \vec{E}_{inc}\left(\vec{d}\right) + \sum_{i=1}^{N} \vec{E}_i^{sca}\left(\vec{d}\right) \tag{17}$$

The summation term, in (17), signifiesthe entire LWC present in a finite group of aerosols. For numerical-computation with successive iterations, the authors have incorporated the operator-form of (17), which is given as,

$$\vec{E} = \vec{E}_{inc} + \sum_{i=1}^{N} \hat{G}\hat{T}_i\vec{E}_i \tag{18}$$

and

$$\vec{E}_i = \vec{E}_{inc} + \sum_{j(\neq i)=1}^{N} \hat{G}\hat{T}_j\vec{E}_j \tag{19}$$

In both of (18) and (19) $\hat{G}$ is Dyadic-Green operator, which has been incorporated in the simulation in order to specify the partial-scattering effect in between two distinct space vectors, $\vec{d}$ and $\vec{d}_j$ of two different particles(here, aerosols) [47]. $\hat{T}_j$ is the Lippmann-Schwinger operator. The tailor part of (19) can be re-expressed as [35]–[40],

$$\hat{G}\hat{T}_j\vec{E}_j = \int_{V_j} d\vec{d}_1 \overleftrightarrow{G}\left(\vec{d}, \vec{d}_1\right) . \int_{V_j} d\vec{d}_2 \overleftrightarrow{T}_j(\vec{d}_1, \vec{d}_2)\vec{E}_j(\vec{d}_2) \tag{20}$$

Utilising the above equations, the order of entire E-field with its expansion can be iterated as,

$$\vec{E}\left(\vec{d}, t\right) = \vec{E}_{inc}\left(\vec{d}, t\right) + \sum_{j(\neq i)=1}^{N} \hat{G}\hat{T}_j\vec{E}_{inc} + \sum_{\substack{j(\neq i)=1 \\ l(\neq i)=1}}^{N} \hat{G}\hat{T}_j\hat{G}\hat{T}_l\vec{E}_{inc} + .. \tag{21}$$

The computation of the E-field under multiple-scattering effect, based on (21), has been carried out for a finite interval of iteration.

To make the analysis of multiple-scattering more realistic, the authors have incorporated the space and time dependent aerosol distribution statistics in tropical climate area by considering the following equation

$$\frac{1}{u}\nabla_t\xi\left(\vec{d}, t, \theta\right) + \hat{\Theta}\xi\left(\vec{d}, t, \theta\right) + (\psi_{abs} + \psi_{sca})\,\xi\left(\vec{d}, t, \theta\right) = \zeta_T N\left(\vec{d}, t\right) + \psi_{sca}\int \xi\left(\vec{d}, t, \theta\right) d\theta \tag{22}$$

where, u is the velocity of THz-wave in space, $\xi\left(\vec{d}, t, \theta\right)$ is the flux-density of THz Electric-field, $\hat{\Theta}$ is the angular-scattering operator, ψ_{abs} and ψ_{sca} are the space and time dependent fog based absorption and scattering coefficients, ζ_T stands for the transmission coefficient of THz signal through aerosol and $N\left(\vec{d}, t\right)$ represents the space and time-dependent fog-density, especially in tropical-climatic belt. The overall space and time dependent Electric-field under multiple-scattering of THz signal in fog-laden atmosphere is enumerated by solving (22) with appropriate weather dependent boundary conditions. The THz-attenuation rate under multiple-scatteringis calculated by considering the successive collisions from the fog-particles, where the mean free-path between two successive collisions has been assumed to have a finite probability distribution[48], by which the THz-photon capture within a certain limit can be achieved. If the rate of capture be considered as U(no. of THz photons/degree), then the entire attenuation(dB/km) can be expressed as

$$\text{Attenuation(dB/km)} = [-5^{\sigma}/Q_{ext}] \ln U^2 \tag{23}$$

Here, σ is the fitting-parameter which is < 2.

The Transmission Attenuation Rate per unit distance of THz transmission can be found out by taking the logarithm of (23).

C. SCINTILLATION OF TERAHERTZ WAVE IN AEROSOLS

The fluctuation of atmospheric humidity, in addition with air-turbulence, leads to focusing and defocusing effects of THz signal, which is well known as scintillation [37]–[46]. Falling aerosols are also responsible for thescintillation effect. The strength of scintillation is related to the terminal velocity of aerosols, which varies with the water-amount of hydrometeors.The scintillation-coefficient, which is directly related to scintillation-index parameter, can be expressed as

$$\alpha_{scint} = \left|10log\,(1 - \sqrt{\sigma^2_{scint}})\right| \tag{24}$$

where, α_{scint}, σ^2_{scint} are the scintillation-coefficient and scintillation-index parameter respectively. The scintillation index parameter is used to determine the magnitude and effect of scintillation [49-50]. According to ITU Recommendation Sector, the scintillation-index parameter depends on refractive index structure parameter (S_n^2), wavelength of incident signal and the distance-traversedby the signal. Under the turbulent atmospheric condition, the refractive-index structure parameter at a certain height from the ground(h), can be expressed as [45]–[50],

$$S_n^2 = 8.15 * 10^{-56} * v_{rms}^2 * h^{10} * \exp\left(-h/10^3\right) + 2.7 * 10^{-16} * \exp\left(-h/1500\right) + 1.7 * 10^{-14} * \exp\left(-h/100\right) \tag{25}$$

where, v_{rms} is rms wind velocity along the vertical path, which is approximately 20m/s.

Based on the dependence of atmospheric refractive index structure constant on temperature, humidity and pressure,the relationship between the atmospheric refractive-index structure constant of THz-wave in tropical climatic zone and temperaturecan be expressed as,

$$S_n^2 = \left(79p/T^2 * 10^{-6}\right)^2 S_T^2 \tag{26}$$

where, S_T^2 stands for temperature structure constant, p signifies atmospheric pressure in millibar, T stands for absolute temperature(K). Following Rytov model [49], [50], the temperature and humidity dependent refractive-index structure parameter can be re-expressed as

$$S^2_{n,T,H} = (A_T^2/\langle T\rangle^2)S_T^2 + \left(A_H^2 * S_H^2/\langle H\rangle^2\right) + 2A_T A_H (S_{T,H}/\langle T\rangle\langle H\rangle) \tag{27}$$

S_Q^2, in (27), is humidity structure constant, $S_{T,H}$is the joint structure constant of temperature and humidity, H is the

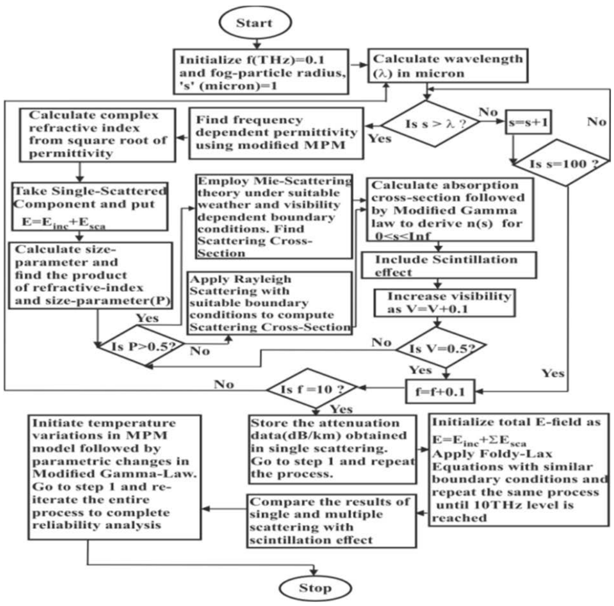

FIGURE 2. Flow-chart of NLTAM Simulator incorporating reliability analysis.

concentration of water vapor in molecules.cm^{-3}. A_T, A_H are the temperature and atmospheric pressure dependent environmental coefficients of tropical weather scenario. Incorporating the scintillation-effect, the total extinction-coefficient in tropical fog-based attenuation model of THz wave can be expressed as

$$\alpha_{total} = \alpha_{scint} + \alpha_{ext} \tag{28}$$

The term α_{ext} is expressed in (9).

D. RELIABILITY ANALYSIS

The propagation of THz signal in atmosphere can be interrupted by several ambient effects which vary with time and geographical coordinates naturally. The environmental temperature is one of the most crucial parameter. Based on the fluctuation of temperature, different atmospheric incidences may occur. The occurrence of hydrometeors and the accumulation of crystal droplets around a specific diameter are examples of such type of incidences. The permittivity of the medium through which the THz signal is subject to propagate, varies with temperature. Using Double-Debye method [39], [40], the real and imaginary parts of complex-permittivity of water can be individually expressed as,

$$\epsilon_r = [\epsilon_0 - \epsilon_1]/[1 + (f/f_x)^2] + [\epsilon_1 - \epsilon_2]/\left[1 + \left(f/f_y\right)^2\right] + \epsilon_2 \tag{29}$$

$$\epsilon_i = f * [\epsilon_0 - \epsilon_1]/[f_x * \{1 + (f/f_x)^2] + f * [\epsilon_1 - \epsilon_2]/[f_y * \{1 + \left(f/f_y\right)^2] \tag{30}$$

where,

$$\epsilon_0 = 77.66 + 103.3 * (300 * T^{-1} - 1) \tag{31}$$

$$f_x = 21 - 143 * \left(300 * T^{-1} - 1\right) + 294 * \left(300 * T^{-1} - 1\right)^2 \tag{32}$$

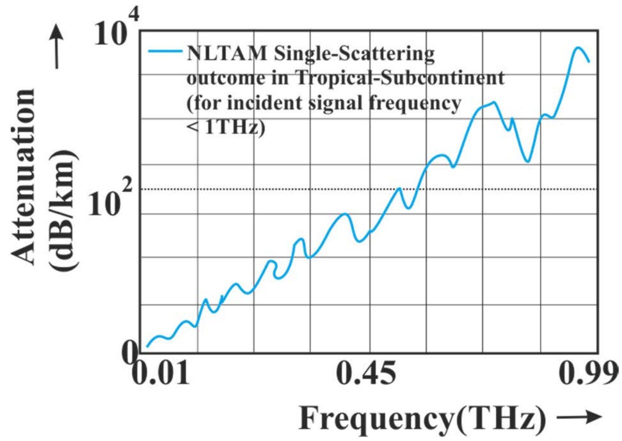

FIGURE 3. Attenuation spectrum of THz wave (below 1THz) due to single-scattering by fog-particles in tropical climate (based on rayleigh scattering).

$$f_y = 590 - 1500 * \left(300 * T^{-1} - 1\right) \tag{33}$$

$\epsilon_{1,2}$ are bounded within 6 [15]–[20]. It is, therefore, clear that the fog-based attenuation of THz signal can be estimated as maximum within a certain temperature range. As discussed earlier, the tropical climate is generally described by a specific mean temperature level. In this weather scenario, the accumulation of aerosols at aspecific particle diameter, is purely statistical [40]–[45]. The maximum accumulationof LWC crystals for a fixed diameter may lead to highest attenuation of incident THz wave at a specific ambient temperature. In their indigenously developed and experimentally verified NLTAM simulator, the authors, for the first time, have incorporated the reliability analysis of THz communicationthrough fog-laden atmosphere of tropical climatic belt. The workflow of reliability analysis within NLTAM simulator has been presented in Fig.2.

III. RESULTS AND DISCUSSIONS

A. SCATTERING AND SCINTILLATION OF TERAHERTZ WAVE IN AEROSOLS

In the simulation of single-scattering of THz wave from the continental fog-based aerosols, the authors initiated the NLTAM analysis by considering the regular droplet size of aerosols. Rayleigh and Mie-Scattering analyses are shown in Fig.3 and Fig.4 respectively. It is depicted that the attenuation spectrum of THz signal due to single-scattering by tropical hydrometeors, increases gradually below 1THz and reaches the peak-value $\sim 1.5 \times 10^6$dB/km in between 2-4THz. From Fig.4, it is also clear that the level of attenuation of THz signal within 5THz-10THz bandwidth in tropical fog-laden atmosphere, remains almost invariant at $\sim 8.0 \times 10^5$ dB/km, approximately. This nature of variation may be explained in terms of standard Mie-scattering effect[51]. The gradual decrease in the attenuation spectrum is observed after 10THz.Incorporating the effect of size-irregularity and random nature of medium, the multiple-scattering effect of THz

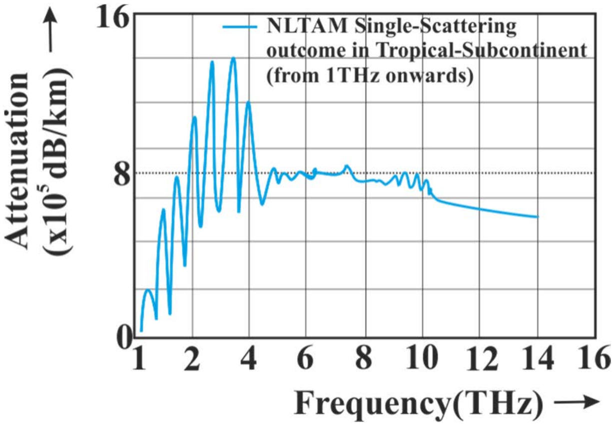

FIGURE 4. Attenuation spectrum of THz wave (above 1THz) due to single-scattering by fog-particles in tropical climate.

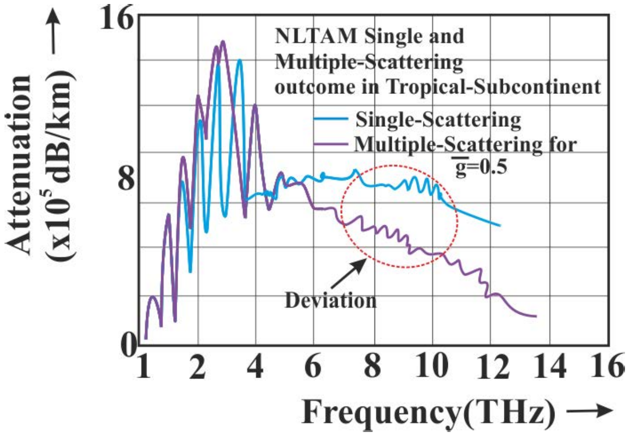

FIGURE 5. Comparison of single and multiple-scattering attenuation spectra of THz signal in tropical climate, obtained from NLTAM simulator.

wave has also been simulated in tropical foggy-atmosphere. The modified Radiative-Transfer Theory, in connection to Foldy-Lax equations have been incorporated to initiate the successive back-scattering mechanism of the incident THz signal, from the fog-laden atmosphere. The authors have presented the comparison of single and multiple-scattering effects in Fig.5. It is clear from this diagram that the slope of decrease of THz-attenuation rate in continental fog-scenario is about 0.5×10^5 dB/km/THz under single-scattering effect from fog-based hydrometeors, which is approximately half of the attenuation rate for multiple scattering effect. This clearly establishes that the multiple-scattering of THzsignal in foggy atmosphere can be treated as more effective than single-scattering in doing attenuation study. In Fig.6, theauthors have presented the Transmission Attenuation Rate per unit distance of THz-attenuation due to multiple-scattering in tropical fog with frequency under 500m visibility constraint. It is clear from this diagram that the level of attenuation approaches the peak value around 3THz, after which the rate of attenuation decreases. This nature of variation of normalised attenuation rate per unit distance can be explained in terms of back-scattering theory [47]. Fig. 7 shows the variation of scintillation index with distance traversed by THz wave in fog-based tropical climate region. It is clearfrom this diagram that the amount of scintillation index increases with decrease in THz-wavelength, which satisfies the proportionality of scintillation index and frequency [53]. Theoutput of the simulator and experimentally measured data [53] are in close-proximity.

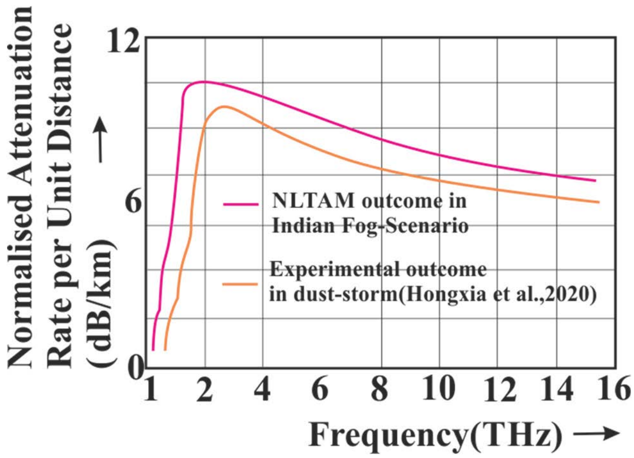

FIGURE 6. Variation of NLTAM simulated Transmission Attenuation rate per unit distance with frequency of THz signal in tropical climate in foggy-atmosphere under 500m visibility Vs the Experimental observation [47] in dust-storm under same visibility.

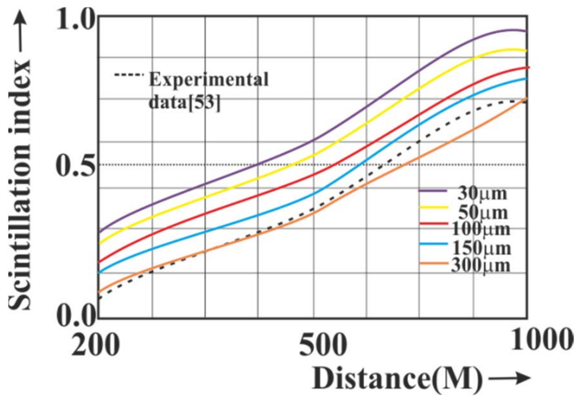

FIGURE 7. Variation of NLTAM simulated Scintillation index of THz signal with distance traversedin fog-laden tropical atmosphere Vs Experimental data [53].

B. OUTCOME OF RELIABILITY ANALYSIS

The authors have gone through a comprehensive reliability analysis on the propagation of THz signal through fog-laden tropical climate and the results are presented in Fig. 8 to Fig. 12. It is clear from Fig.8 that amount of absorption of THz signal in foggy-weather would be maximum within tropical hydrometeors of (10-20) micron particle radii. Therefore, thesignal attenuation in this range increases drastically. From Fig. 9 and Fig. 10 it is clear that the droplet distribution statistics of fog based aerosols shows the peak level of particle accumulation in the range of (10-20)micron diameter considering tropical atmosphere. It again indicates that the particle-based interaction of THz signal in tropicalatmosphere will be maximized in this particular range. In Fig. 11, the shift of THz window frequencies for two different droplet distribution statistics have been presented,

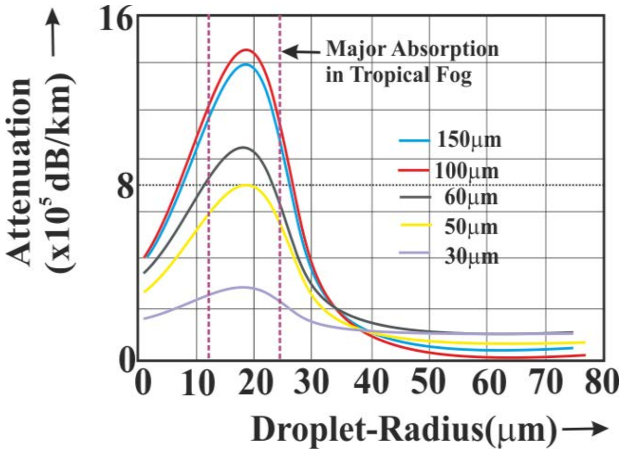

FIGURE 8. Variation of THz signal attenuation in fog-ladentropical atmosphere with droplet radius.

where one frame, located in the approximate range of 4.5THz to 6THz for mean particle diameter of 9.5micron, shifts approximately to 6.5THz to 10THz regime for 12micron centre diameter. It is evident that when the droplet radii increases, the probability of reliable communication also increases. Experiment carried out by Yang *et al.* in 2015 [13], clearly indicates that for constant water density, the optical Mie-scattering is inversely proportional to droplet diameter. The physics behind this observation may be explained in terms of Earth's acceleration due to gravity. Considering the constant density of the droplets, the increasing the diameter of these particles, would enhance their mass, which, in turn, would create the natural downfall of these particles, instead of suspended condition. As a consequence, the composite atmospheric aerosol chamber, consisting of liquid water droplets, would become thinner/less-dense, which will ease the THz signal propagation. However, this effect would become prominent when the gravitational pull will overcome the upward buoyant force/upward drag force. In this study the authors have made the studyfor two different mean diameters: 9.5micron and 12micron, which are considerably higher to consider the effect of gravity. The authors have made a reliability study to assess the effect of increasing temperature on electromagnetic signal attenuation and the graph is presented in Fig.12. Fig.12 corresponds to study in tropical climate condition with special emphasis in Indian subcontinent. Experimental study on atmospheric influences on millimeter wave propagation through atmosphere was carried out by a research group in 2010 under similar climatic conditions[54]. The study has reflected that the variation of attenuation(in dB/km) with increasing temperature is inversely proportional at lower millimeter wave(Microwave) as well as in higher millimeter wave(around 100GHz) regime. It is also interesting to observe from the experimental study that with increasing frequency the rate of decrease of signal attenuation with temperature is more sharp. In this paper, the authors have extended the study from 100GHz to 10THz and similar trend is noticed as obtained through real-field experiment [54].

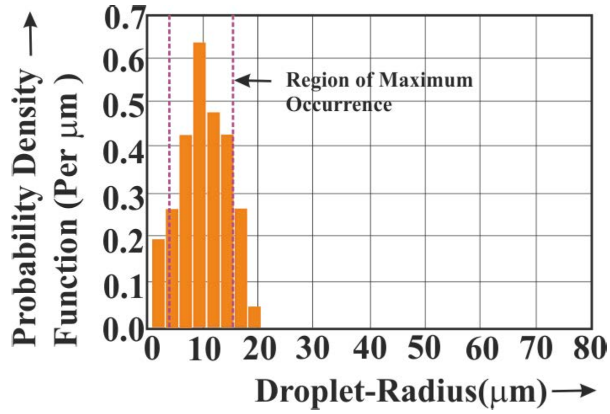

FIGURE 9. Variation of probability density function in tropical fog distribution statistics with droplet radius.

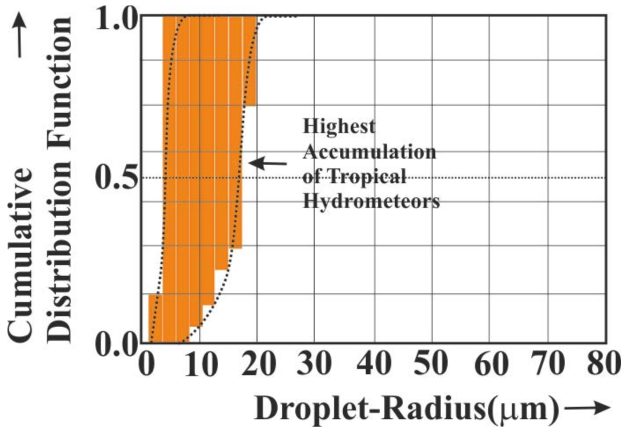

FIGURE 10. Variation of cumulative distribution function in tropical fog distribution statistics with droplet radius.

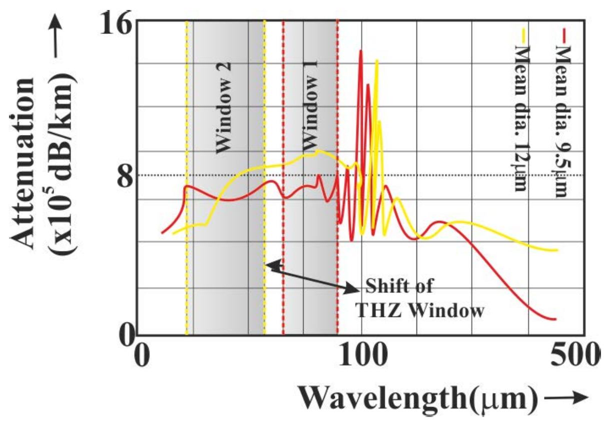

FIGURE 11. Variation of THz attenuation in fog-laden tropical atmosphere with wavelength of the incident signal.

IV. EXPERIMENTAL VALIDATION

Initially the authors have developed the simulator by incorporating various atmospheric parameters suitable for non-tropical climate zone. This model has been compared with experimental outcome under similar condition as reported by Federici *et al.* in their recent publication [20]. It has been observed that, the nature of THz attenuation spectrum in fog-laden atmosphere, as well as the peak level of attenuation obtained from the simulator, are in close

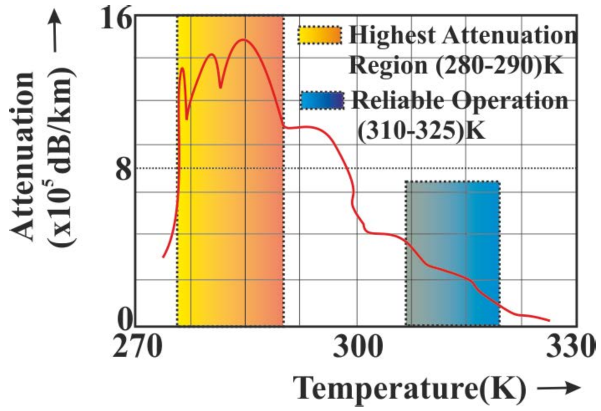

FIGURE 12. Variation of THz attenuation in fog-laden tropical atmosphere with ambient temperature.

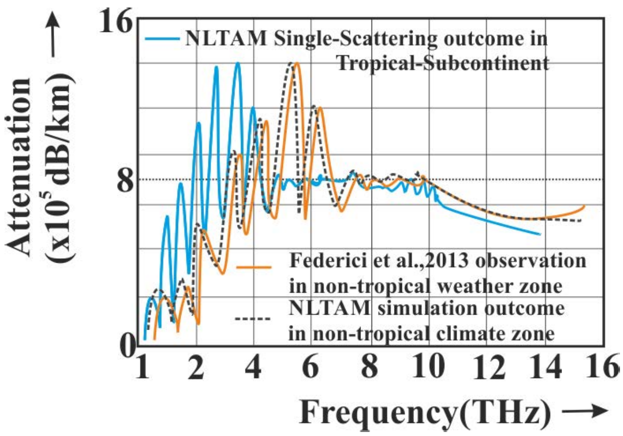

FIGURE 13. Attenuation spectrum of THz signal due to single-scattering by fog-particles in tropical and non-tropical climate zones, compared with experimental observation[20].

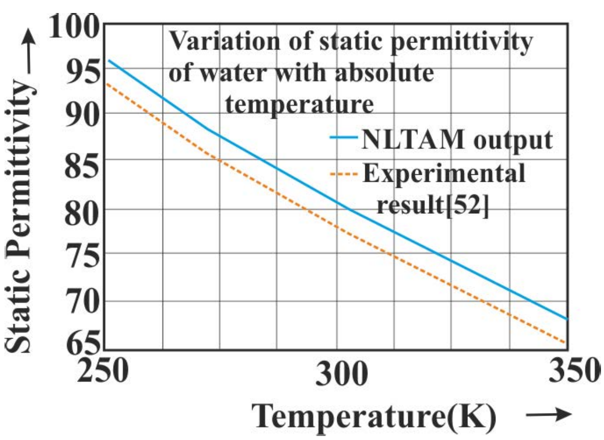

FIGURE 14. NLTAM simulated outcome on temperature dependent variation of static permittivity of water Vs Experimental observations [52].

agreement with the experimental observations in reality. This is shown in Fig.13.After validating the model under non-tropical conditions, the authors have made an attempt to develop the model suitable for tropical climate zone. This has been done by making necessary changes in the vital atmospheric parameters appropriate for tropical climate zone. In Fig.14, the authors have shown the variation of temperature dependent static permittivity of water obtained from the simulator under tropical climate scenario. The outcome is in close-proximity with the experimental observation by Zhou et al [52]. To the best of authors' knowledge, no experimental work is done till date in Indian Sub-continent. The available experimental data under tropical weather condition is for South-Asian countries and climate zones, not in Indian scenario. This project is doing the virtual experiment by developing a self-consistent physics based Non Linear Terahertz Attenuation Model(NLTAM) to estimate the THz signal attenuation in Indian Sub-continent. Based on this a real time experiment would be carried out in future in India and that is scope of another research paper. However, as explained before, the validation of the newly model is done through 2-stage verification: (a) By comparing with the experimental data under tropical climate condition, (b) By comparing with the experiment under non-tropical climate condition. The validity of the model is thusestablished in the manuscript. Moreover, the authors havealso shown the variation of NLTAM simulated Transmission Attenuation rate per unit distance with frequency of THz signal in fog-laden tropical climate under 500m visibility, which is in close-proximitywith the experimental observation [47] in dust-storm under same visibility.

V. CONCLUSION

In most of the research works related to the computation ofadverse weather effects on atmospheric propagation of electromagnetic signal, the single-scattering mechanism has been prioritized. The authors, through this uniquely developed and experimentally validated simulator, haveshown the effect of fog-particle based multiple scattering ofTHz signal in the Indian subcontinent, which has not beenpredicted by any other research-group till date. It has beenclearly established in this work that, in Indian Scenario, which is categorized under tropical climatic area, the peak-attenuation level of THz signal due to single-scattering fromfog-based hydrometeors decreases when the multiple-scattering effect is considered. Although the highest attenuation level is localized within 2THz to 4THz regime for both of the scattering types, the rate of decrease of attenuation spectra is quite faster for multiple-scatteringphenomenon. The outcome of scintillation index simulationalso reveals that the suitable frequency range in fog-laden atmosphere under Indian tropical climate scenario can be centred around 4THz. For the first time, the authors have performed the reliability study around THz window frequency, by which an estimate of secure THz link establishment through suspended tropical aerosols has beenpredicted. In future, the research outcome may find its utility predicted. In future, the research outcome may find its utility to build secure link, useful for defence sector of India.

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