Review of Weather Impact on Outdoor Terahertz Wireless Communication Links

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ABSTRACT

As the demand for higher wireless data rates continues to increase, there has been more interest in extending the carrier frequency of wireless links from the millimeter wave range into the terahertz (THz) range. For long distance wireless communications, THz links can suffer significant signal loss due to atmospheric weather effects. Obviously, for evaluating wireless system link budgets, it will be important to estimate the weather impact on high capacity data links and compare the performance degradation of THz links to that of the competing approach of free-space optical wireless. This paper reviews the impact of weather on THz wireless links and emphasizes THz attenuation and channel impairments caused by atmospheric gases (in particular water vapor), airborne particulates (such as dust, fog, clouds, and rain), refractive index inhomogeneities which are driven by air turbulence, and their associated scintillations.

Keywords: Terahertz, wireless, atmospheric propagation, weather

1. INTRODUCTION

The demand for high channel wireless bandwidth is increasing due to the proliferation of broadband wireless communication networks and novel wireless services. Wireless data rates have doubled every eighteen months over the past few decades and multi gigabit-per-second data rates are predicted to appear in the next five to ten years [1, 2]. Wireless communication systems at the lower end of the Terahertz frequency spectrum have seen growing interest in recent years due to their larger atmospheric transmission window compared to millimeter waves (MMWs), which leads to an increasing capacity in links [2-5]. Potential applications[1-6] include machine-to-machine communications among distributed sensors, routing within a data center or factory, transmission of high-definition TV (HDTV) signals from an event to a broadcast studio with low latency, terabit/s personal and local-area networks, secure wireless networks, high speed data kiosks, cellular networks, wireless back-haul for data and voice communications, high speed wireless connections to fiber-optic backbone (ie. the 'last-mile' problem), and nanoscale wireless links. Data rates as high as 100 Gbit/s have been demonstrated below 300GHz while the maximum achieved data rates above 500GHz are limited to below 10Gbit/s primarily due to the lack of high power sources in that frequency range.[7] Moreover, when compared to free-space optical (FSO) or infrared (IR) channels as a competing approach, the lower attenuation of THz radiation in dust, fog, clouds, and atmospheric turbulence (ie. scintillations) constitutes viable advantages of THz communication links as FSO/ IR wireless systems can fail under similar weather conditions [2, 8-10].

Over the past several years, the focus of our research team has been to obtain an extended description of weather impact on THz channels. In this paper, we present a comprehensive description of weather-based measurements and theoretical analysis from several active research groups. In particular,

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this paper emphasizes THz attenuation and channel impairments caused by atmospheric gases (in particular water vapor), airborne particulates (such as dust, fog, clouds, and rain), refractive index inhomogeneities which are driven by air turbulence, and their associated scintillations. For long distance communications, THz links can suffer significant signal loss due to atmospheric weather effects. Obviously, for wireless service providers, it will be important to estimate the weather impact on high capacity links and compare performance degradation of THz and FSO wireless systems especially in respect to weather driven system outages.

In predicting link performance, one typically considers a simple system with a THz transmitter, receiver, with intervening medium between the two. Some of the essential characteristics of THz wireless communication can be explored using the Friis formula [1, 4, 5]. The power supplied to the load of the receiving antenna is given by

$$P_{out} = P_{in} \left(\frac{\lambda}{4\pi d} \right)^2 G_r \cdot G_t \cdot F_r(\theta_r, \phi_r) \cdot F_t(\theta_t, \phi_t) \cdot e^{-\alpha_e d} \cdot \varepsilon_p \quad (1)$$

where P_{in} is the input power to the transmitting antenna, G is the antenna gain, F is the normalized intensity pattern function, $e^{-\alpha_e d}$ is the path power transmission factor, α_e is the extinction or total attenuation coefficient due to both scattering and absorption in the atmosphere, ε_p is the polarization coupling efficiency, λ is the wavelength of the radiation, and d is the distance between the transmitting (t) and receiving (r) antenna. The angles θ and ϕ refer to spherical coordinates at either the receiver or transmitter. While weather-based channel impairments are all fundamentally related to the atmosphere's complex refractive index, at times it is convenient to classify the impairments from the atmosphere as mainly being due to attenuation (from both particle scattering and absorption) and refractive index fluctuations (i.e. scintillation effects).

The free-space loss factor $(\lambda/4\pi d)^2$ in Eq. (1) arises from two effects: (a) The assumption that the receiving antenna is detecting the far-field radiation of the transmitting antenna leads to treating the source as emitting a spherical-like wave whose power decreases as $1/d^2$ with distance. (b) The factor of λ^2 arises from the diffraction limited directivity (D_{max}) or alternatively the solid angle which defines the extent of the diffracting intensity pattern function: $D_{max} = 4\pi/\Omega = 4\pi A_{eff}/\lambda^2$, for which A_{eff} is the effective area of the detector. The antenna gain and directivity are related by

$$G_t = \frac{P_{rad}}{P_{in}} D_t \quad (2)$$

where P_{rad} is the power radiated by the antenna. If the radiation and input powers were matched, then the gain of the antenna would be equal to the directivity so that Eq. (1) could be rewritten as

$$P_{out} = P_{in} \frac{A_t A_r}{d^2 \lambda^2} F_r(\theta_r, \phi_r) \cdot F_t(\theta_t, \phi_t) \cdot e^{-\alpha_e d} \cdot \varepsilon_p \quad (3)$$

where A_t and A_r refer to the effective areas of the transmitter and receiver, respectively. According to Eq. (3), the power received at a detector varies as $1/\lambda^2$ so the efficiency of detection improves as the wavelength decreases or the THz frequency increases. This implies that THz communications are inherently more directional than microwave or MMW links due to less free-space diffraction of the waves. Consequently, THz communication systems will typically be line-of-sight systems with high gain antennas.

The atmospheric conditions directly impact the attenuation factor $e^{-\alpha_e d}$ from the intervening medium. Increased attenuation decreases detected power which can degrade the detected bit-error-rate

(BER) or may require either shorter link distances, higher power sources and/or more sensitive detectors to compensate for the loss through the atmosphere. Moreover, the $1/\lambda^2$ dependence of the received power suggests that decreasing the THz wavelength (or increasing the THz frequency) is advantageous. However, as will be shown in the next section, the atmospheric attenuation due to water vapor increases with increasing THz frequency. Polarization dependent scattering by atmospheric particles can potentially change the polarization of the transmitted THz radiation thereby impacting the polarization coupling efficiency ε_p in Eq. (3). Lastly, real refractive index fluctuations tend to spatially spread out a propagating beam such that the effective area A_r of the receiver restricts the detected power.

In this paper, we will describe the effect of weather on THz wireless links. In Section 2, the theoretical background for attenuation effects of gaseous atmospheric components (eg. water vapor and O₂), airborne particulates, and scintillations will be introduced. Section 3 will describe the various laboratory environmental chambers which are been used to emulate various weather conditions. Section 4 will describe measurements of THz transmission in various weather conditions. Lastly, Section 5 will summarize the effects of weather on THz links.

2. Channel Modelling

In modelling of communication links, one typically starts with an equation similar to the Friis formula Eq. (3) and then makes assumptions concerning the transmitter and receiver characteristics and the attenuation of the intervening medium. The emphasis of this paper is ground-to-ground wireless links. Clearly in the case of ground to space links, the temperature, atmospheric pressure, and water vapor content all vary with altitude resulting in an altitude dependent atmospheric attenuation as well as refractive index for the THz range [4, 5, 11]. Some recent examples of outdoor line-of-sight channel modelling can be found in Refs [1, 12, 13]. In this section, we will focus on the effect of the intervening atmospheric medium under three conditions (a) clear weather in which the attenuation of water vapor and gaseous oxygen dominate (b) airborne particulates such as dust, fog, clouds, and rain (c) localized inhomogeneities in the refractive index of the atmosphere which lead to scintillation effects.

2.1 Clear Weather Conditions – Effects of Humidity

Outdoor channel modelling must include the effect of atmospheric water vapor or humidity at THz frequencies. There are several calculations for absorption in the frequency band ranging from 100 GHz to 1000 GHz due to water vapor [14]. Water vapor, due to its polar nature and accompanying rotational and vibrational transitions, dominate atmospheric absorption under clear weather conditions [11]. At lower altitudes water vapor is always present and is one of the major limiting factors in determining the maximum link distance, maximum THz frequency of the link, and link performance.[4, 5, 11] The frequency dependent atmospheric absorption can be calculated by summing the effect of the absorption lines for any species of gases present. To calculate the sum, the center frequency of the absorption line, as well as the line intensity, line width, and lineshape function must be known for each gas species. These parameters can be extracted from several spectroscopic databases [15]. As an example, Figure 1 shows the computed the water vapor absorption coefficient (H₂O density 10 g/m³) using the Millimeter Wave Propagation (MPM) model [16]

$$\alpha = 0.182f \left[\sum_{j=1}^{34} S_j F_j + S_c F_c \right] \quad (4)$$

at atmospheric pressure where f_j is central frequency of spectral lines with line strength S_j and line shape function F_j . The model accounts for 34 water vapor lines spanning the range from 22.235 GHz to 1780 GHz. In addition, under standard ITU-R atmosphere conditions oxygen exhibits two absorption peaks near 60 GHz (resulting from 25 overlapping spectral lines) and 118.7GHz. The atmospheric attenuation

can be calculated using the International Telecommunication Union Radiocommunication Section (ITU-R) standards which are valid from 1-1000 GHz[11]. There are 5 atmospheric transparency windows in the frequency range from 300 – 1000 GHz with attenuation below 100 dB/km. Several tens to around 100GHz of bandwidth can be found in these windows which can realize data channels with 100Bit/s or beyond for wireless communications. Due to the high atmospheric attenuation (>100 dB/km) above 1THz, one would expect practical THz wireless links above 1THz to be very limited in distance. However, in the 100-1000GHz frequency range, several transmission windows between water vapor peaks can be exploited: 70-110GHz, 120-170GHz, 200-310 GHz, 300-370GHz, 390-440GHz, 625-725GHz, and 780-910GHz.

In addition to the sum of the absorption peaks of water vapor as illustrated in Eq. (4), there is also a contribution of the water vapor continuum at THz frequencies. As pointed out by Siles *et al.* [11] and Yang *et al.*[15] the water vapor continuum contribution to the attenuation is empirically defined as the difference between the measured attenuation and theoretical line sum. Consequently, its contribution strongly depends on the absorption line intensities, line widths, and line shapes which are included in the summation method. As illustrated in Eq. (4), the water vapor continuum can be modelled by a fictitious spectral line. In ITU-R P.676-10 Recommendation, this continuum absorption is modeled as an absorption peak at 1780 GHz [11]. As an alternative to using an artificial absorption peak, Yang *et al.*[15] employed a Molecular Response Time theory and demonstrated much closer theoretical match of the spectral dependence to measured attenuation due to humidity.

2.2 Airborne Particulates

It is well-known that granular particles with sizes comparable to the size of the THz wavelength can strongly impact the scattering, polarization, and extinction of propagating THz radiation [17]. The size of atmospheric airborne particulates varies[4, 5, 18]: fog droplets can range from <20 to at most 50 μ m. Particulates from paper mills, forest fires, oil fires, pollution can range from 10-50 μ m. Particles sizes in smog vary from 0.003-6.8 μ m while battlefield oil particulates [19] are typically 0.4 μ m. Rain drops vary in size from ~0.5 to ~4mm in diameter.

The attenuation of radiation in the THz range due to airborne particulates has been modelled using either the Mie scattering theory or the Rayleigh approximation to Mie scattering. The total attenuation or extinction can be expressed in terms of the scattering and absorption cross-sections by $\sigma_e = \sigma_a + \sigma_s$. The atmospheric attenuation coefficient can be calculated by employing Beers - Lambert Law [20] $\exp(-\alpha_e d) = \exp(-\alpha_a + \alpha_s d)$ where the α 's are the extinction coefficients corresponding to the absorption and scattering cross-sections. Generally, the cross-sections are also functions of the size of the airborne particulates.

An important consideration: Under what conditions can either model be used? Using a Mie scattering approach, the extinction, scattering, and absorption cross-sections all can be determined. The attenuation coefficient can be found by integrating over all particle sizes. In the limit of spherical particles with a radial distribution function $p(r)$ the attenuation coefficients α in dB/km of the THz and IR channels can be determined shown to be [21]

$$\alpha = 3.3429 \int_0^{\infty} p(r) \sigma_e(r) \pi r^2 dr \quad (5)$$

where, $\sigma_e(\chi)$ is the extinction efficiency of *e.g.* raindrops which can be derived from Mie scattering theory

$$\sigma_e(\chi) = \frac{2}{\chi^2} \sum_{l=1}^{\infty} (2l+1) \operatorname{Re}\{a_l + b_l\} \quad (6)$$

where $\chi = \frac{2\pi r}{\lambda_0} \sqrt{\epsilon_b}$ is a dimensionless parameter, while λ_0 and ϵ_b stand for the wavelength of the light and the real part of the relative dielectric constant of the background medium, respectively. The Mie coefficients a_l and b_l are functions of χ and the refractive index of the particle [8]. As an example for rain drops, one could use a double-debye dielectric model (D3M) to calculate the dielectric constant of water [21]. Its real and imaginary parts refer to the relative permittivity and its dielectric loss factor for the raindrop, respectively. Consequently, scattering and absorption effects are considered in the extinction efficiency, which are known to be the two main effects for attenuation by rain [22].

If the size distribution function of the particles is known, then Eq. (5) can be integrated to calculate the total attenuation. However, if the distribution is not known, then one needs to resort to microphysical modelling to determine the distribution function. For example, cloud droplets can be modelled by a modified Gamma function[11] $P(r) = a r^\alpha \exp(-b r^\beta)$ for which the parameters a , b , α , and β take on different values depending on the cloud type.

However, if the size of the airborne particles where small enough compared to the electromagnetic wavelength so that scattering cross-section is small compared to the absorption cross-section $\sigma_s \ll \sigma_a$, one can use the Rayleigh approximation of Mie scattering to simplify the calculation of the attenuation coefficient. As an example, Yang *et al.* note that attenuation by fog is due to absorption by the water droplets and not due to scattering which is much smaller in magnitude.[18] In this limit, the Rayleigh absorption approximation[23] of the Mie scattering theory provides a complex refractive index contribution Δn to the clear atmosphere which is independent of the particle size distribution:

$$\Delta n = \frac{3}{2} X_p \frac{(\epsilon - 1)}{(\epsilon + 2)} \quad (7)$$

where X_p is the mass fraction of water droplets in the atmosphere, and ϵ is the complex permittivity function of the particulate material (eg. water of clouds or fog). Note that in this limit, the complex refractive index contribution due to water droplets Δn , and therefore the absorption coefficient of the atmosphere, is proportional to the water mass density in the atmosphere. In general, the Rayleigh approximation can be used [24] when the refractive index of the particle n and the dimensionless Mie parameter χ meet the condition $|n|\chi < 0.5$. For example in their analysis of clouds, Siles *et al.* [11] show that the Rayleigh approximation can be used up to 200-300 GHz. Beyond this limit, accurate evaluation of the total extinction coefficient due to water drops requires complete Mie scattering equations. For fog droplets with diameters less than 20 μm , the Rayleigh absorption approximate is still valid. Rayleigh absorption theory using a double-Debye model for the dielectric properties of water has been employed to calculate attenuation due to fog for frequencies up to 1000 GHz [35].

The Rayleigh absorption approximation can also be derived by assuming that the droplets in the air form an effective medium. Starting from Maxwell-Garnett (MG) theory [25, 26] one can calculate the effective dielectric properties of a material formed by the presence of small (spherical) particles embedded in a host material:

$$\frac{\epsilon_{eff} - \epsilon_h}{\epsilon_{eff} + 2\epsilon_h} = X_p \frac{\epsilon_p - \epsilon_h}{\epsilon_p + 2\epsilon_h} \quad (8)$$

where the subscripts h and p represent the ‘host’ and ‘particle’, and X_p is the volume fraction of the ‘particles’. It is further assumed in the MG model that the volume fraction of the ‘particles’ is small so that the size of the particles is much smaller than the spacing between them. It is assumed that the electromagnetic field averages over spatial scales which are large compared to the particle size. The Maxwell-Garnett model attempts to account for local electric field effects which occur when the presence of the particles perturb the electric field from an electromagnetic wave as it interacts with an individual, isolated particle. Higher order interactions among the particles are neglected.

Solving Eq. (8) for the effective permittivity yields

$$\epsilon_{eff} = \epsilon_h \left(\frac{1 + 2X_p \left(\frac{\epsilon_p - \epsilon_h}{\epsilon_p + 2\epsilon_h} \right)}{1 - X_p \left(\frac{\epsilon_p - \epsilon_h}{\epsilon_p + 2\epsilon_h} \right)} \right) \quad (9)$$

In the limit of a small volume fraction of particles, the denominator of Eq. (9) can be expanded using the binomial expansion. Then, by taking the square root of both sides and keeping only terms which are linear in X_p one can reformulate the equation as

$$\Delta n = n_{eff} - n_h = \frac{1}{n_h} \frac{3}{2} X_p \left(\frac{\epsilon_p - \epsilon_h}{\epsilon_p + 2\epsilon_h} \right) \quad (10)$$

where the complex refractive index is $n = \sqrt{\epsilon}$. If we consider the ‘host’ material to be atmospheric gases without any water vapor or particles present, we can set both the permittivity and refractive index of the host to be unity in Eq. (10) thereby recovering the Rayleigh absorption formula of Eq. (7).

It should be emphasized that since the efficiency of scattering by airborne particulates is strongly dependent on the size of the particulates relative to the electromagnetic wavelength, there can be a large difference in performance between FSO and THz wireless links under the same airborne particulate atmospheric conditions. For example, theoretically estimated attenuation due to fog and dust particles [8, 9] shows that IR wavelengths are strongly attenuated while THz radiation can propagate well through small airborne particulates. In fact, a direct experimental comparison of a free-space IR and THz links which propagate through the same atmospheric conditions show that the IR signal is completely blocked by dense fog while there is only a very minor impact on the attenuation and Bit-Error-Rate in the THz link [9]. The stronger attenuation in the free-space IR compared to the THz range can be understood as a consequence of Mie Scattering for which visible/IR wavelengths are comparable to or smaller than the particulate size while THz wavelengths (~ 0.3 -1mm) are larger than the size of airborne particulates such as dust and fog. However, for larger particles such as rain drops, the attenuation for FSO and THz are similar. The extinction cross section for THz waves in rain ($\sim 2.35\pi r^2$, r is radius of a raindrop) is slightly larger than for IR waves ($\sim 2\pi r^2$). Consequently, one expects the attenuation in the THz beam due to rain to be slightly larger than in an IR channel [27, 28].

The raindrop-size distribution plays an important role in estimating the channel attenuation by rain. Several types of raindrop-size distributions, such as Laws- Parsons [12], Marshall-Palmer [29], Best [22], Weibull [30] and Polyakova-Shifrin [31] distributions, are known and a specific attenuation model recommended by the ITU-R is usually being applied for attenuation calculation [32]. Calculations based on Weibull distribution and ITU-R shows good agreement with experimental results with rain rate from 1 to 12 mm/hr in Ishii’s study [33]. Also the measured results in the rain rate of 20-60 mm/hr are found to agree well with Laws- Parsons and ITU models [34]. Using temperature dependent refractive

index of water, Ref. [35] concluded temperature has little effect on the attenuation of THz radiation by rain with a maximum variation of about 0.20%.

2.3 Atmospheric Scintillations

In addition to power attenuation effects from absorption or scattering in the atmosphere, another major impairment can be atmospheric scintillations which can be caused by temporal and spatial inhomogeneities in air temperature and pressure, for example, which are generated by thermals and turbulences near ground level. These fluctuations cause small real refractive index fluctuations across the wave front of a beam, thus resulting in deflection and interference between different portions of its wave front (Figure 2) which can destroy the flat phase front of a beam [8, 9] even under clear weather conditions (i.e. no rain, fog, clouds, or dust). Therefore, the beam cross section on the receiver side appears as a speckle pattern with huge local and temporal intensity variations. Scintillation effects are a major limitation to the maximum transmission distance of FSO communication links [36]. In comparison, THz beams are much less susceptible to scintillation.

As an example [8, 9], consider the refraction index of a clear atmosphere. The refractive index of the millimeter wave band up to a few hundred GHz can be well approximated as function of temperature and pressure by:

$$n_{mmW} \approx 1 + \frac{7.76}{T} \left[P_a + 4810 \frac{P_v}{T} \right] \times 10^{-6} \quad (11)$$

where T , P_a , P_v are the temperature (Kelvin) and atmospheric pressures (kPa) for the atmosphere and water vapor [37]. Similarly, for IR wavelengths the refraction index of air can be written as:

$$n_{IR} \approx 1 + 7.76 \times 10^{-6} \left[1 + 7.52 \times 10^{-3} \lambda^{-2} \right] \frac{P_a}{T} \cong 1 + 7.76 \times 10^{-6} \frac{P_a}{T} \quad (12)$$

where λ stands for the wavelength in μm . Equation (12) does not consider humidity as it only insignificantly degrades IR propagation. If one isolates the contribution to the refractive index from atmospheric gases and water vapor

$$\frac{n_{mmW} - 1}{n_{IR} - 1} \approx 1 + \frac{4810}{T} \frac{P_v}{P_a} \quad (13)$$

for relevant atmospheric parameters, evaluation of this ratio gives ~ 1.5 : Even at high levels of water vapor pressure the refraction index changes in both the THz and IR bands due to temperature or pressure changes are comparable. Since scintillation effects are driven by variations in phase, the relevant parameter is the variation in the optical path length relative to the electromagnetic wavelength. Since the variation in the optical path length for both, the IR and THz are comparable, the relative magnitudes of the phase variations are predominately determined by the electromagnetic wavelength. Given that the wavelength at THz frequencies is approximately 1000 times longer than that of visible or IR light, scintillation effects in the THz beam due to atmospheric turbulence are expected to be significantly smaller than for FSO systems.

The distortion of the phase front of an incoming wave can be characterized by the Angle of Arrival (AoA) in which the time (or phase) delay is measured between detectors in an array. For detectors arrayed on a line, equal arrival times at all detectors indicates an AoA of zero degrees. Non-equal arrival times indicates a distortion of an initially planar wavefront and consequential spreading of the incoming beam due to turbulence.

Several models have been developed to describe wave propagation through turbulence. Here, we emphasize Andrews' method, which takes into account the size of the receiving optical aperture [38]. The turbulence induced attenuation of a laser beam through atmosphere can be approximated [38, 39] by

$$\alpha = 10 \cdot \lg \left| 1 - \sqrt{\sigma_I^2(D)} \right| \quad (14)$$

where D is the diameter of the receiver aperture and the theoretical mean variance of optical intensity is characterized by the scintillation index. The scintillation index depends on various parameters including details of the turbulence as denoted by the Rytov variance, which is given by [40]

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (15)$$

where k represents the wavenumber of the propagating beam, L is the path length through the turbulence, and C_n^2 is the structure factor for fluctuations in the refractive index. It is customary to distinguish between weak and strong turbulence via values of the Rytov variance. Weak fluctuation theories are denoted by $\sigma_R^2 < 1$ while $\sigma_R^2 > 1$ denotes strong fluctuations [41]. The structure factor characterizes the effect of temperature, pressure, and/or humidity induced turbulence on a propagating electromagnetic wave. As a simple example, the temperature structure constant C_T^2 in the atmosphere may be evaluated as

$$C_T^2 = \left\langle \left(T_i - T_j \right)^2 \right\rangle L_P^{-2/3} \quad (16)$$

where the term in brackets is the spatially averaged square of the temperature difference and L_P is the characteristic spatial scale of the fluctuations.

In the millimeter range, the structure factor can be written as [41, 42]

$$C_n^2(\lambda) = \frac{A_T^2(\lambda)}{T^2} C_T^2 + \frac{A_Q^2(\lambda)}{Q^2} C_Q^2 + \frac{2 A_T(\lambda) A_Q(\lambda)}{T Q} C_{TQ} \quad (17)$$

where T is the temperature, and Q is the absolute humidity. C_T , C_Q , and C_{TQ} are the structure factors for temperature, humidity, the temperature-humidity cross structure, respectively and the A coefficients are the derivatives of the real part of the refractive index with respect to the logarithm of either T or Q . Relating the humidity and temperature-humidity cross structure factors to the temperature structure factors, Ref. [41] simplifies the refractive index structure factor in the THz range to be

$$C_n^2(\lambda) = \frac{C_T^2}{T^2} \left(A_T^2 + 10^4 A_Q^2 \pm 200 A_T A_Q \right) \quad (18)$$

The aperture dependent scintillation index can be written as [43]

$$\sigma_I^2(D) = \exp \left[\frac{0.49 \sigma_R^2}{\left(1 + 0.65 d^2 + 1.11 \sigma_R^{12/5} \right)^{7/6}} + \frac{0.51 \sigma_R^2 \left(1 + 0.69 \sigma_R^{12/5} \right)^{-5/6}}{1 + 0.90 d^2 + 0.62 d^2 \sigma_R^{12/5}} \right] - 1 \quad (19)$$

with $d = \sqrt{k D^2 / 4 L}$ for which D is the diameter of receiver aperture.

In addition to the phase variations induced by scintillations, the spot size of a propagating beam will increase beyond what one would expect purely caused by free-space diffraction. The spot width of a laser beam propagating through turbulences can be related to the Rytov variance σ_R^2 [40]. The relationship between the mean intensity over time of the beam propagating through the turbulence can be expressed as [44]

$$\langle I(r, L) \rangle = \frac{w_0^2}{w_e^2} \exp \left(- \frac{2 r^2}{w_e^2} \right) \quad (20)$$

where w_0 is beam radius at the transmitter, r is the distance from the spot center, and w_θ is the effective long-term averaged beam radius in free space at the receiver given by

$$w_\theta = w_0 \sqrt{1 + 1.33 \sigma_R^2 \Lambda^{5/6}} \quad (21)$$

where w_0 is the beam radius at the receiver for an unperturbed channel, and Λ is the Fresnel ratio of beam at the receiver. Note that in the limit of weak turbulence $\sigma_R^2 \ll 1$, Eq. (21) shows that the spot size of a beam is proportional to the structure factor via Eq. (15).

3. EMULATED WEATHER

Under outside weather conditions it is challenging to measure and analyze an impact of weather on communication channels due to the required long observation times and the difficulty in obtaining recurrence of similar atmospheric conditions to verify results of independent measurements. For example, uncontrollable rain rates and varying rain-drop size distributions under ‘natural’ outdoor conditions present challenges in determining and analyzing the attenuation by rain on communication channels: hence the need for multiple rain drop distribution models (Section 2.2). Therefore it would be advantageous if weather conditions could be repeatable under controlled experimental conditions. Using this motivation, several groups have opted to develop or adapt weather emulating chambers into a controlled laboratory environment. In many cases, the weather conditions (eg. rain drop size distribution) can be reproducibly generated in order to compare measurements to predictions: important parameters such as particulate size distribution functions and particle densities can be independently measured and integrated into the Mie scattering formulation of Eqs. (5)-(6). It is also advantageous if the experimental chambers can accommodate co-propagating THz as well as FSO optical or IR beams. The co-propagating beams enable direct comparison of the degradations observed in two competing wireless solutions since they pass through the same weather conditions.

Of course there are drawbacks to emulated weather conditions: they may be close to but not the same as ‘natural’ weather conditions. Hence there is limited value in deciding, for example, which is best rain drop model (Section 2.2) for emulated rain. Moreover, since the effects of weather on THz propagation are generally a relatively weak effect, long interaction lengths may be needed for effective characterization. But long interaction lengths may be difficult to achieve within a laboratory environment. For example, an accurate characterization of the attenuation of THz pulses through a fog environment required a chamber 137m long. Even for this long interaction length, the time delay between pulses without and with fog present is only ~ 0.6 ps [18]. As an alternative for long path lengths, Ref. [9] used a much lower visibility fog than Ref. [18] to compensate for a much shorter path length.

In this section, a variety of weather chambers for emulated humidity, fog, dust, and air turbulence are described which have been used to characterize THz atmospheric propagation. Details of the chambers’ experimental designs can be found in the various citations.

3.1 Water Vapor Chamber

As THz waves propagate under clear atmospheric conditions, water vapor plays a dominant role in the power attenuation for frequencies above 100 GHz (Section 2.1). A sample chamber used for water vapor generation has been designed by Yang *et al.* [45]. The chamber is a room with a path length of 137 m. The air-vents, lights and lab doors are sealed with plastic sheet and tape to isolate the effect from outside. The chamber can realized controllable and stable water vapor by employing 8 humidifiers and four 16 liter water heaters distributed uniformly along the hallway. Water vapor is produced from the humidifiers with hot water supply by the heaters, and the circulated by two large fans during the measurements. The chamber humidity is stabilized by an initial adjustment of the locations and humidifier settings to obtain similar hydrometer readings throughout the chamber, and then letting the

system run for approximately 30 minutes to reach a stable condition. Hygrometers, located at both ends of the chamber and on the optical table, measure humidity and temperature. Humidity inside can be increased to 30% above the ambient laboratory value. The THz beam is focused into and reflected out of this chamber through a thin plastic film window in the lab doorway.

3.2 Fog Chambers

Fog consists of small water droplets near the earth's surface with diameters smaller than 20 μm . Fog forms when the relative humidity is close to 100% and water vapor condenses to small water droplets. The mechanism of condensation is used to distinguish the types of fog. In the outdoors, only two of them are mostly encountered [46]: (1) Radiation fog is generated in inland at night during autumn and early winter when air temperature reaches the dew point due to the cooling of land by thermal radiation. (2) Advection fog forms in coastal regions throughout the day when warm moist air moves over colder water by advection. For radiation fog, its water content ranges from 0.01 to 0.1 g/m^3 with diameter of water droplets smaller than 20 μm [47]. Diameters for advection fog can be near 20 μm with water content being higher than 0.2 g/m^3 .

In an experimental comparison between the BER performance of THz and free-space IR links, Su *et al.* developed a fog chamber with a 62cm length. Fog is generated by dripping liquid nitrogen into a cup filled with hot water (temperature about $\sim 80^\circ\text{C}$) which is placed inside the fog chamber containing the propagating IR and THz beams [9]. The fog density, controlled by the amounts of liquid nitrogen spilled into the cup, can be fluctuating over a large visibility range. Typical visibilities varying between a few centimeters to several hundreds of meters are observed. The fog droplets are collected on slides covered with a thin layer of mineral oil. Measurements of the fog particles using a microscope suggest an average diameter of the fog drops in a range of 8 μm . The fog diffuses into the chamber flooding it typically in a few 10s of seconds. The THz and IR beam enter the chamber via windows made of 15 μm polyethylene foil which attenuates the beams only weakly.

Z. Ghassemlooy *et al.* generated fog in a designed chamber with a length of 50 cm by employing a commercial water steamer. The fog can be controlled by fans and ventilation systems [48]. The water content of the fog reaches to $0.5 \times 10^3 \text{ g/m}^3$ with droplet diameter up to 40 μm . A much longer fog chamber with a length of 137m is used by Yang *et al.*, who employed a Hurricane 901 fog machine to generate a uniformly distributed fog (visibility $\sim 7\text{m}$) with water content of 0.58 g/m^3 and a particle size of 5 μm [18], for measurements of attenuation using THz time-domain spectroscopy.

3.3 Dust Chamber

Minimal THz attenuation in dust is expected due to their relatively small particle size compared to the THz wavelength (Section 2.2) [49]. Dust consists of small, solid and dry particles in the range from 1 to 100 μm in diameter. Natural sources of dust include volcanic eruptions and soil. Volcanic ash particles with diameters less than 30 μm can be carried for hundreds to thousands of kilometers while soil particles with diameters smaller than 20 μm can be suspended in air for a much longer period of time. Human activities, such as pollution [50], forest fires [51] and large paper mills [52], are responsible for the generation of dust with diameters ranging from 10 μm to 50 μm .

The performance of a THz and IR wireless links was compared in a small dust chamber [8] shown in Figure 3a. The chamber is shaped like a cylinder with 30 cm diameter, 30 cm height, and enclosed with top and bottom plates. A known total mass of dust particles is placed inside the hopper, which sits above the dust holder. An electronic pulse switch controls an air valve and the released air removes the dust from the dust holder and ejects it at a high speed into the chamber from the top plate of the dust chamber. The hopper can be easily refilled and it produces a fairly constant and reproducible feed of dust. Air flows into the chamber with constant volume speed through the holes from the bottom plate. The holes, all with the same 0.18 cm diameter, are placed on 5 concentric set of circles with

diameters 2.22, 4.76, 7.30, 9.84, and 12.38 cm. The constant air volume flow is regulated by an air flow controller to achieve specific flow rates. Two Picarin windows, which are highly transparent to both THz and IR radiation, are mounted at the input and output of the chamber. Bentonite powder, a mixture of clay formed from volcanic ash decomposition and largely composed of montmorillonite and beidellite, is used for dust particles. The average particle diameter is 8.6 μm . The particle concentration evolution with respect to time is plotted in Figure 3b, which varies from $4 \times 10^9/\text{m}^3$ to almost 0 within 300s.

3.4 Rain Chamber

Rain is formed due to the precipitation of water vapor in atmosphere with droplet sizes comparable to the THz wavelength. Consequently, significant attenuation might be expected at sufficiently high rain rates (Section 2.3). The rain chamber [27, 28] developed at NJIT has a dimension of $100 \times 20 \times 20 \text{cm}^3$ (L $\times$ W $\times$ H) as shown in Figure 4a. Air and water valves on its top are used to fill and pressurize the chamber. Its bottom plate is machined with 3264 holes and 31-gauge needles are epoxied into each hole. The chamber is initially filled with distilled water. Pressurizing the chamber with air forces water release through the needles which generates raindrops. In the rain chamber, the raindrop size follows approximately a Gaussian distribution with an average diameter of 1.9 mm and a variance of 0.08mm^2 . The chamber rain rate is proportional to the pressure applied to the water reservoir as shown in Figure 4b and controllably varied from 0 to 500 mm/hr by changing the air pressure in the chamber. The rain rate, used to classify the rain speed, is less than 3.8 mm/hr for light rain and more than 7.6 mm/hr for heavy rain. We observed some variability in the rain rate at different locations along the beams in the rain chamber. To characterize the average rain rate of the chamber, five beakers (opening area of 56.7cm^2) are positioned underneath the chamber and collect rain for a minimum of 60 s. The total volume of water from the beakers is measured to determine the average rain rate. By reflecting a THz beam from multiple mirrors several times through the chamber, the effective path length through the rain is 4m.

3.5 Air Turbulence (Scintillation) Chamber

While the previously described chambers introduce various particulates into the air which attenuate and produce scintillations of the propagating beams, one can isolate the contribution of scintillations to signal degradation by only introducing air turbulence into the weather chamber. Air turbulence is formed by the temperature inhomogeneities in the atmosphere because of the mixing between warmer and cooler air. Air turbulence can be understood as multiple air pockets of different sizes moving in the atmosphere with changing temperature [43]. These air pockets can act like prisms with changing refractive indices to alter the propagation of laser beams. On the receiver side, the perturbed path of the beam can lead to lower power detection (since the beam spreads out beyond what is expected from diffraction) as well as phase distortion. For optical paths near the ground with path lengths longer than 1 km, scintillation effects are significant and can result in a time-varying fading effect in the order of milliseconds.

The turbulence chamber designed by Ma *et al.* [10] consists of an enclosed chamber (L $\times$ H $\times$ W $\sim 90 \times 40 \times 30 \text{cm}^3$) in which air is blown in through two holes in the top of the chamber using industrial heat guns. The air exits horizontally from the bottom of one side of the chamber. The temperature of the air launched into the chamber can be set to 32°C (cold), 55°C (warm), and 70°C (hot) and airspeeds of 28.6 m/s (low) and 41.6 m/s (high) can be independently adjusted. This parameter set enables the generation of air turbulence that is strong enough to obtain minimal-detectable degradations in the THz channel and weak enough to cause medium-strong scintillation effects in the IR signal. The effects of temperature variations in the chamber can be separated into two contributions which occur on significantly different time-scales: a slowly spatially and temporally changing temperature increase ($\sim$ seconds) and relatively fast temporally and spatially varying temperature gradients ($\sim$ kHz).

Since the refractive index changes in air are similar in the visible, near-infrared, and THz wavelength bands (Section 2.3 [4, 5]), measuring them at visible wavelengths enables an estimation of the cumulative refractive index fluctuations inside the turbulent air for the THz and IR signals. To characterize the turbulence, visible light from a Mach-Zehnder Interferometer is co-propagated with the THz and IR beams. A He-Ne laser beam (632.8nm) with a diameter of 2 mm is first split into two parts by a beam splitter and then recombined by a second beam splitter. The combined beams form localized interference fringes. Refractive index changes are characterized by measuring the change in the fringe pattern. One part of the visible beam co-propagates with the THz and IR beams while the other part of the visible beam propagates through ambient air which is isolated from the turbulence chamber. Lastly, three thermistors are positioned inside the chamber which allows measurement of the temperature evolution with a thermal response time of $\tau \sim 3s$. The thermistors are used to estimate the structure factors for turbulent-induced refractive index variations.

4. CHANNEL MEASUREMENTS

4.1 Water Vapor/ Humidity

To characterize the frequency dependent phase and amplitude of THz wave through water vapor, Ref. [45] used a THz time-domain spectroscopy (THz-TDS) system. THz-TDS uses the pulse train from a mode-locked near-infrared laser (pulse duration ~ 80 fs) to generate and detect broad-banded pulsed THz radiation using typically photoconductive antenna structures. The pulse train from the mode-locked laser is split into two beams. One beam is focused onto a biased photoconductive antenna to generate freely propagating THz pulses using while the second beam ‘gates’ or detects the THz pulse at a detector. Typically the optical path delay between the two beams of the split optical pulse train is adjusted such that the optical pulse from one beam detects the THz waveform which its partner pulse generated. However, since the path length of the humidity/ fog chamber is so long, rather than delaying the ‘detection’ optical pulse also by $\sim 137m$ of optical path length, the simpler solution is to use a latter optical pulse from the pulse train to detect the THz pulse; for Ref. [45], the first optical pulse which generates the THz waveform is detected by the 51st pulse in the pulse train.

Using this THz-TDS long path length system, Yang *et al.* were able to record the attenuation in the 100 to 1000 GHz band through a controlled humidity atmosphere. Figure 5 shows the transmitted THz pulses under relative humidity of 22 %, 43 % and 58 %. Note that as the humidity increases, the boundaries of the transmission bands in the atmosphere are fixed in frequency, but the transmission in the atmospheric transmission windows decreases. Furthermore, they determined the refractivity of water vapor to be $(n_0 - 1) = 70 \times 10^{-6} \pm 10\%$ and essentially frequency independent [45]. The experimental results are summarized and compared with the results in Ref. [14]. Recent measurements of THz pulse propagation under outdoor weather conditions showed that pulse time delays are proportional to the water vapor density in agreement with indoor measurements [53].

4.2 Co-Propagating THz and Free-Space Infrared Link Test-bed

The block diagram of a THz and free-space IR testbed is shown in Figure 6 and its detailed description is given elsewhere [8-10, 28, 54]. The output of a horn antenna from a THz transmitter is collimated to a beam with ~ 15 mm diameter by a lens with 32 mm focal length. The beam propagates over 3 m distance and is then collected by a THz receiver horn similar to the transmitter antenna. A duobinary modulation technique, which enables signaling at high data rate with relatively compact spectrum compared to regular NRZ modulation is utilized in the system to drive a THz source, which is based on a Frequency-Multiplier-Chain with about 1mW output power when operating in a CW mode. An iris is inserted concentrically into the beam to limit the total received power level to an amount that leads to a bit error rate (BER) of about 10^{-6} for an unloaded rain chamber. The initial BER is adjusted to this level so that

stochastic BER fluctuations do not significantly impact conclusions inferred from measurement results. Moreover, a 10^{-6} BER is a typical threshold for forward error correction technology used in light wave communication systems.

The IR transmitter is driven by the same 2.5 Gb/s data pattern as the THz source and outputs a beam with a diameter similar to that of the THz link. The collimated IR beam is superimposed with the THz beam using a thin pellicle beamsplitter with 55% reflection ratio at 45° incident angle. After passing through a weather chamber, the beam is deflected with a similar beamsplitter. A fraction of the deflected beam is launched towards a large area free space photodetector with an effective area of 19.6 mm^2 . The remaining power is coupled into a 1×2 multimode fiber (MMF) coupler via a fiber collimator. One output port of the coupler is connected to a DC-coupled IR lightwave convertor (Agilent 81495A) with large bandwidth that serves as a data receiver. The other output is launched to a second 1×2 MMF coupler whose output ports are connected to low bandwidth photodetector via a standard single mode fiber (SSMF) and to a photodetector via MMF. The purpose of the multiple IR detectors with varying effective apertures is to detect the presence of scintillations in the IR channel. If scintillations were present, power fluctuations would increase as the effect detector aperture size decreased.

4.3 Fog

While THz links suffer significantly more attenuation through humid air compared to FSO links, the polar opposite is true with atmospheric fog. By co-propagating THz and IR wireless links through a fog chamber with a minimum visibility of a few centimeters [9] the attenuation of the IR light is so high ($>40\text{dB}$) that it is essentially blocked by the fog while the THz signal exhibits only a minor but measurable decrease ($\sim 0.6 \text{ dB}$ attenuation) in power. Figure 7a shows a typical evolution of the attenuation in both channels. At $t=5 \text{ s}$ the fog is introduced into the chamber. By $t=30 \text{ s}$, the fog has dissipated. The actual IR power level cannot be shown from $t=7\text{-}12 \text{ s}$ due to the limited dynamic range of 42 dB . Usually, even ‘small’ amounts of fog are sufficient to block the IR beam after a few seconds of fog diffusion and when reaching an attenuation of about 140 dB , the BER measurement of the IR signal collapses as shown in Figure 7b while the THz channel experiences only a relatively small increase in the BER. After some 10s of seconds the fog disappears into the lab environment or is converted into humidity thus both links regain or approach their original performance, respectively. A similar effect of fog evaporation which increases the water vapor content has been observed in a longer 137 m fog chamber [18]. Measurements of THz time-domain pulses through a much longer 137 m of fog show that the THz transmission windows are essentially the same as a reference THz spectrum scan in the absence of fog with a small 0.6ps shift in the time delay between the two pulses [18].

4.4 Dust

As with fog, attenuation of THz waves due to dust is much smaller than the attenuation for FSO propagation. As discussed in Section 2.2, this difference can be understood simply as a consequence of Mie scattering and the relatively small size of the airborne particles relative to the THz wavelength. Under conditions of low visibility when multi-scattering events are more probable, Ref. [55] used Monte Carlo methods to simulate the multiple scattering of terahertz wave in high particle density sand-dust conditions.

Using the dust chamber described in Section 3.3 in conjunction with co-propagating free-space optical and THz links (Section 4.2), attenuation of the IR beam is $\sim 4.5 \text{ dB}$ for dust particle densities of $4 \times 10^9 \text{ m}^{-3}$ compared to an attenuation of 0.045 dB in the THz range [8]. Dust with different concentrations of $2.5 \times 10^9/\text{m}^3$, $4 \times 10^9/\text{m}^3$, and $6.5 \times 10^9/\text{m}^3$ is loaded into the dust chamber to analyze the effect of varying particle concentration. The attenuation decreases with time since dust particles start falling down to the bottom of the chamber. After 400 seconds, the IR transmitted power recovers and the

channel approaches its original performance as shown in Figure 8. Using the measured time-dependent dust particle concentration, the THz attenuation as a function of time is simulated by using Mie scattering theory. Based on the dust particle concentration evolution curve, the THz attenuation due to dust as a function of time is calculated and compared with the experimental results as shown in Figure 9. The good agreement between experiments and theory suggests that the THz attenuation is consistent with the slow time-dependent change in the average particle density of dust.

The attenuation varies significantly with changing concentrations: larger concentration leads to higher attenuation and larger BER. For the IR channel, the observed change in attenuation produces a sizable initial change in the recorded BERs: The $\log(\text{BER})$ changes from -5.2 to -1.2 upon the introduction of dust particles. The recorded BERs for the THz link ($\log(\text{BER})$ changes by 0.06) verify again that dust particles at these concentration levels have little impact on the THz signal compared to the IR signal across the limited propagation length. The significantly more stable BER performance of the THz compared to FSO link confirms that THz can be a good candidate for wireless communications even in regions of intense smog, dust, and other airborne particulates.

4.5 Rain

Outdoor THz channel measurements in rain are much more common than emulated rain measurements. Attenuation due to rain by a 120 GHz wireless link was measured in Japan to be 9.5, 17, and 23 dB/km corresponding to rain rates of 20, 40, and 60 mm/h, respectively [34]. A maximum attenuation of 8 dB/km for a 300 GHz link is measured under rain rates up to 12 mm/hr [33]. However, there is still a lack of experimental studies on THz attenuation due to rain above 300 GHz. Consequently, Ma *et al.* developed a small rain chamber as described in Section 3.4 to generate controllable and reproducible rain. Moreover, since the drop size distribution is determined by the needle size of the chamber and does not change with rain rate, one can easily measure the static rain drop distribution and model the attenuation using Mie scattering theory in order to compare with experimental results.

By reflecting a THz beam from multiple mirrors, the effective path length through the rain chamber is 4 m [27]. In order to compensate for the relatively short path length through the rain and accumulate a measureable attenuation in the THz range, the water reservoir for the rain chamber can be pressurized to produce rain rates up to ~450 mm/hr. After pressurizing the rain chamber, raindrops are randomly squeezed out from the needles and partially block the beam path as the drop falls through the beam diameter. In order to characterize the spectral properties of rain attenuation by THz-TDS, one uses the same trick as with the long path length through a humidity/ fog chamber (Section 3.1) to detect the THz time-domain waveform: The extra path length through the medium is a integer multiple of the round trip time in the mode-locked laser so that the THz waveform at the receiver is detected by a succeeding pulse from the laser pulse train.

Figure 10b shows the calculated frequency dependence of attenuation due to rain. For this calculation, Mie scattering from spherical rain drops is assumed as well as a double Debye model for the refractive index of water [27]. The attenuation for frequencies below 10 GHz is about 2 dB/km which is negligible. In the range of 0 to 80 GHz, the attenuation increases with frequency. It decreases slowly for frequencies ranging from 80 to 1000 GHz. The strong frequency dependence is due to Mie scattering and the changing ratio of the electromagnetic wavelength relative to the size of the rain drop. For a worse case, a rain rate of 100 mm/hr is assumed in the plot, which leads to a stronger attenuation of 80dB/km for 300GHz. The predicted frequency dependent attenuation from Mie scattering is consistent with the experimental results taken with THz-TDS [27]. In Figure 10a, the attenuation spectrum as measured by THz-TDS is shown for a rain rate of 226 mm/hr along with the predicted attenuation. The two strong peaks at 0.557 and 0.763 THz are caused by water vapor absorptions lines found in [45]. The attenuation

is slightly decreasing in the region of 0.1 – 1THz with respect to frequency as theoretically predicted. Normalizing the measured attenuation to the path length through the rain chamber gives an approximate attenuation coefficient of 250 dB/km at 226 mm/hr rain rate.

Using the same rain chamber, co-propagating THz and free-space optical links are sent through the same weather conditions [28]. At a rain rate of 213 mm/hr the THz link suffers a little bit higher attenuation (~ 0.1 dB) compared to the IR link, which is due to the slightly larger extinction cross section of rain drops at THz frequencies. A typical evolution of the resulting BERs in the THz and IR links due to rain is shown in Figure 11. After 80 seconds recording time, the rain stops, and the transmitted THz and IR signal power approach their original level. For both channels, a strong correlation between their attenuation and their time-averaged (integration time 1s) BER (Figure 11) is observed. The THz link suffers slightly higher power attenuation, but the IR link suffers higher increase of the BER during the rain fall. For an ideal channel, the BER performance should only depend on the received signal power and equal attenuation in the THz and IR channels should result in an equal BER degradation for both links. In testbed setup of Figure 6, the slightly larger BER in the IR is attributed to slightly different receiver sensitivity curves for the THz and IR signals. The same amount of attenuation increases the BER of the THz channel less than the BER of the IR signal [28].

The predicted attenuation of THz and IR channels can be calculated by means of the Mie scattering equations of Eqs.(5)-(6) using the measured rain drop distribution function. A double Debye dielectric model is used to calculate the dielectric function of water. Figure 12 shows a comparison between the theoretical calculated attenuation and the corresponding experimental value for different rain rates. The experimental attenuations are roughly consistent with the theory. The small discrepancy between them can likely be attributed to a measurement error of rain rate and drop size.

4.6 Air Turbulence and Scintillations

As described in Section 2.3, local refraction index inhomogeneities lead to phase front distortions and spatial spreading of the propagating beam. Local refractive index inhomogeneities can be due to air turbulence as well as the presence of airborne particulates such as fog, dust, and rain. Using an effective medium approximation such as the Maxwell-Garnet model of Eq. (8), one could calculate the effective permittivity or refractive index of airborne particulates in air (as the host medium). Clearly localized inhomogeneities in the airborne particle density will be manifested in localized refractive index fluctuations of the effective medium.

As described in Ref. [8, 9, 28] scintillation effects are readily observable in free-space IR channels in the presence of fog, dust, and rain. The key to detecting scintillations in the IR channel is to split the transmitted IR beam into three different detectors with three different effective aperture sizes. As illustrated in Figure 2, as the effective aperture of the detector decreases, the relative size of the detected power fluctuations should increase. As an example, Figure 13d shows the measured power fluctuations for three different aperture sizes. For the smallest effective aperture the transmitted IR radiation is coupled into a single mode fiber prior to the IR detector. The next largest effective aperture results from coupling the light into a larger multi-mode fiber. For the largest effective aperture, the IR beam is directly incident upon a large area IR detector without any fiber optic coupling. Note that as the size of the effective aperture decreases, the power fluctuations increase indicating the presence of scintillations on the IR channel.

In comparison, as described in Section 2.3, the effect of scintillations in the THz band is orders of magnitude smaller than in the IR band. In fog, dust, and rain, the reduction of THz link performance can be explained based purely on the additional attenuation in the beam path due to the particulates; scintillation effects in the THz band are negligible compared to the effects of attenuation [8, 9, 28]. In order to suppress the attenuation effects so that scintillation effects in the THz range are measurable,

Ma *et al.* focused on experiments of the THz link performance in the presence of air turbulence without any airborne particulates. By using the air turbulence chamber described in Section 3.5, Ma *et al.* were able to remove the stronger attenuation effects from particulates and focus exclusively on scintillation effects due to real refractive index fluctuations.

There have been some reported observations of scintillations in the THz and millimeter wave bands under outdoor conditions. For example, scintillations due to wind velocities of 6 m/s led to 8 dB power attenuation. These scintillations caused power degradation in the THz range were observed in a 100Gbit/s wireless link over a distance of 800 m [56]. Metrological measurements of structure factors from temperature and humidity and measured phase and amplitude fluctuations in the millimeter wave range correspond reasonably well with theoretical predictions [42]. Using a theoretical model which describes the THz scintillations due to atmospheric turbulence, Ref. [57] studied the effect of the scintillations on the BER of a THz link. Their modelling shows that for a fixed BER, the effective transmission distance decreases as the THz frequency increases. This effect can be easily explained (Section 2.3). Since scintillation effects are driven by variations in phase, the relevant parameter is the variation in the optical path length relative to the electromagnetic wavelength. Given that the refractive index does not change appreciably with THz frequency (See Section 4.1 – in the absence of airborne particulates, the refractive index of a humid atmosphere is roughly constant in the THz range), the relative magnitudes of the phase variations are predominately determined by the electromagnetic wavelength. As the THz frequency increases and the wavelength decreases, the phase fluctuations should increase.

Using the turbulence chamber described in Section 3.5, Ma *et al.* were able to observe scintillation effects in both the IR and THz channel. After launching heated air into the turbulence chamber, a typical evolution of the attenuations in the THz and IR channels became visible as shown in Figure 13 [10]. Ten seconds after initiating the recording, hot air is launched with high speed into the propagation path of the beams. The IR beam breaks up into a speckle pattern at the receiver side. Depending on the receiver aperture these speckle effects become more or less visible by the fluctuation strength of the detected IR power. For the IR channel, the time-averaged (500 ms) maximum attenuation of the IR light (around 1 dB) is clearly evident while the impact on the THz signal is small (0.015 dB). After the air-supply is powered off at 20 seconds recording time, the transmitted IR power recovers and approaches its original level. For the IR channel, a strong correlation between its attenuation and the recorded BER is clearly visible. The recorded BERs for the THz link verify that air turbulence has little impact on the THz compared to the IR channel. Figure 13c shows the corresponding temperature evolution in the chamber. Our plots include the de-convoluted recordings in order to partially compensate for slow response time of the temperature sensors. Obviously, the attenuation in the IR channel reduces immediately when the air flow stops. But the temperature inside the chamber decays significantly more slowly.

Experiments were conducted in which air at high speed but with different temperatures is induced into the chamber. The attenuation and BER change significantly with air temperature; a strong correlation between the air temperature and BER is apparent in the IR link. In another series of experiments, warm air at different velocities is launched into the chamber. As expected, the attenuation and BER increase with increasing air speed.

The IR attenuation effects can solely be attributed to scintillations in the turbulence chamber since absorption phenomena are too small to cause such power variations. The constantly changing turbulence pattern causes the scintillations, which leads to speckle effects in the receiver plane. The smaller the receiver aperture the more likely that spatial averaging is less effective resulting in the detection of relatively large power level fluctuations. If scintillation effects were to occur, we would expect (and experimentally observed Figure 13d) more pronounced variations in the power coupled into

IR detector with the smallest aperture compared to the output of the IR detector with the largest aperture. Clearly visible is the sharp drop off of the fluctuations compared to the air temperature decay (Figure 13c). This observation suggests that the link attenuation is mainly caused by a constant flow of air pockets with different temperatures into the chamber that relatively quickly mix and achieve a thermal equilibrium once the air flow stops. We observe further that the temperature of the launched air has a stronger impact on the spectra than the airspeed, which correlates with pressure variations inside the airflow. This leads us to the conclusion that the scintillation effects in our setup are mainly caused by temperature fluctuations which fits to a fundamental assumption made for outdoor scintillation models for the IR.

Several statistical models can be used to characterize atmospheric turbulence with different strengths, such as log-normal distribution, gamma-gamma, K-distribution and negative exponential distribution models. Here, Log-normal distribution, which is suitable for weak turbulence, is employed to simulate the air turbulence for comparison with experimental results [28]. Using Andrews' method together with Eqs. (14)-(16), and (19) one can calculate the expected attenuation of a THz beam through turbulence by taking into account the size of the receiving optical aperture. The refractive index structure parameter is given by $C_n^2 = (dn/dT)^2 C_T^2$ where n is the temperature dependent refractive index of air

and the temperature structure constant is given by $C_T^2 = \left\langle \left(T_i - T_j \right)^2 \right\rangle L_P^{-2/3}$ where T_i and T_j are the

temperatures at two adjacent sensors in the turbulence chamber separated by a distance $L_P=15\text{cm}$. Calculations using the experimental parameters and a length for the turbulence chamber of $L=90\text{cm}$ show that the experimentally and theoretically determined attenuations become comparable [28]. Likely, the uncertainty in the effective turbulence length is the dominant factor that causes the discrepancy between simulations and experimental data.

5. CONCLUSION

Table 1 summarizes the dominant physical effects and applicable models under various weather conditions. Under clear weather conditions, the main limitation to THz propagation over 100 GHz in the atmosphere is water vapor. The impact of airborne particulates on THz and FSO wireless systems depends fundamentally on the size of the particulates relative to the electromagnetic wavelength. While a complete description is given by Mie scattering theory, one could use the Rayleigh approximation if the scattering were much smaller than the absorption due to the particulates. In this limit, one can treat the particles 'embedded' in air as an effective medium whose effective permittivity is given by Maxwell-Garnett theory. A comparison of THz and free-space IR links through the same atmospheric conditions is summarized in the last column of Table 1. Free-space IR links should exhibit longer link distances in clear weather compared to THz links due to strong influence of water vapor on THz absorbance. Clearly, the impact on the two different channels depends on the relative size of the particulates compared to the electromagnetic wavelength. Fog and dust have minimal impact in the THz range compared to the FSO range since these particulates are typically much smaller than the THz wavelength. Under identical rain rates, the THz signal suffers slightly higher attenuation compared to the IR signal due to the slightly larger extinction cross section of raindrops in the THz band. While scintillations are clearly observable from fog, dust, and rain in the IR band, scintillations are difficult to observe in the THz band. Under identical turbulence conditions the IR signal is significantly more attenuated than the THz signal which shows almost no degradation. As the air temperature and speed become higher, the attenuation becomes more severe in the IR range. However, the impact on THz signals remains minimal. Experimental observations demonstrate that the observed scintillation effects for the IR and THz channels are mainly

caused by temperature fluctuations in the turbulence. For airflows comparable to the speed of hurricanes and temperature enhancements of several tens of degrees Kelvin the attenuation of the THz signal stays below a tenth of a dB/m. Compared to IR wireless links, THz links within an atmospheric transmission windows are generally much less susceptible to weather conditions such as fog, dust, clouds and air turbulence. This makes THz links a promising candidate as reliable communication technology under most weather conditions.

While Mie scattering (or under the appropriate conditions the Rayleigh approximation to Mie Scattering), gives accurate predictions of THz attenuation due to airborne particulates in warm weather conditions, there has been relatively little experimental or theoretical work performed for cold weather conditions of hail, sleet/freezing rain, and snow. Upon first glance, for example, one would expect the THz attenuation of freezing rain to be determined by Mie scattering with the refractive index of the particle being that of ice rather than the Double Debye model of water. On the other hand, the aggregation of ice crystals into larger snowflakes is strongly affected by the humidity level. Consequently, even in the presence of snow as airborne particulates, the dominate attenuation mechanism for a THz link under snow conditions may be the accompanying humidity level rather than Mie scattering by the airborne particulates. The coupling of humidity levels to the formation and size of wintery particulates may require accurate THz attenuation models to simultaneously consider humidity as well its impact on the size and density of wintery particulates.

6. ACKNOWLEDGMENTS

Some of the authors' work presented in this paper was supported by the National Science Foundation under Grant No. ECCS-1102222.

LIST OF FIGURES

Figure 1: Attenuation due to water vapor for 0 - 1000GHz (H_2O density 10 g/m^3 , Pressure 1013mbar, Temperature 20°C).

Figure 2: Air turbulence causes refractive index fluctuations resulting into speckle (intensity variations at receiver) that increases the effective size of the propagating beam. Reprinted from J. Federici, L. Moeller, 'Review of terahertz and subterahertz wireless communications', *Journal of Applied Physics*, 107 (2010) 111101 [5] with the permission of AIP Publishing.

Figure 3: (a) Photo of dust chamber at NJIT. The Dust Chamber and exhaust hosing is indicated in the figure as well as the optical path of the infrared (solid arrow) and THz (dashed arrow) beams. (b) The particle density with respect to time. From [8] K. Su, L. Moeller, R. B. Barat and J.F. Federici, 'Experimental comparison of terahertz and infrared data signal attenuation in dust clouds', *Journal of the Optical Society of America A* 29 (11), pp. 2360-2366 (2012). (©OSA 2012).

Figure 4: (a) Photo of rain chamber at NJIT from Ref. [28] *Journal of Infrared, Millimeter, and Terahertz Waves*, 'Experimental Comparison of Terahertz and Infrared Signaling in Laboratory-Controlled Rain', 36 (2015) 856-865, J. Ma, F. Vorrius, L. Lamb, L. Moeller, J.F. Federici, © Springer Science with permission of Springer. (b) Rain rate in mm/h from the rain chamber with respect to the air pressure in the chamber. The vertical error bars with 95 % confidence interval shown in the plot represent the standard deviation of recorded rain rates. From Ref. [27] *Journal of Infrared, Millimeter, and Terahertz Waves*, 'Comparison of Experimental and Theoretical Determined Terahertz Attenuation in Controlled Rain', 36 (2015) 1195-1202, J. Ma, F. Vorrius, L. Lamb, L. Moeller, J.F. Federici, © Springer Science with permission of Springer.

Figure 5: Amplitude spectrum of the transmitted THz-TDS pulse from [45] Y. Yang, M. Mandehgar, and D. Grischkowsky, 'Time domain measurement of the THz refractivity of water vapor', *Optics Express* 20 (24), pp. 26208-26218 (2012). (©OSA 2012).

Figure 6: Schematic diagram of the THz and IR wireless communications testbed [8-10, 28, 54].

Figure 7: (a) Attenuation of THz link and IR link through dense fog as the function of time; (b) Log(BER) of THz and IR links with respect to time. From [9] K. Su, L. Moeller, R. B. Barat and J.F. Federici, 'Experimental comparison of terahertz and infrared data signal attenuation in dust clouds', *Journal of the Optical Society of America A* 29 (2), pp. 179-184 (2012). (©OSA 2012).

Figure 8: (a) Attenuation of IR link for different dust concentrations; (b) Attenuation of THz link for different dust concentrations. From [8] K. Su, L. Moeller, R. B. Barat and J.F. Federici, 'Experimental comparison of terahertz and infrared data signal attenuation in dust clouds', *Journal of the Optical Society of America A* 29 (11), pp. 2360-2366 (2012). (©OSA 2012).

Figure 9: Experimental and simulated THz attenuation due to dust as a function of time from [8] K. Su, L. Moeller, R. B. Barat and J.F. Federici, 'Experimental comparison of terahertz and infrared data signal attenuation in dust clouds', *Journal of the Optical Society of America A* 29 (11), pp. 2360-2366 (2012). (©OSA 2012).

Figure 10: (a) THz power attenuation spectrum under rain rates of a 226 mm/hr with a path length of 4 m. Dashed line is a theoretical plot based on Mie scattering theory. From Ref. [27] Journal of Infrared, Millimeter, and Terahertz Waves, 'Comparison of Experimental and Theoretical Determined Terahertz Attenuation in Controlled Rain', 36 (2015) 1195-1202, J. Ma, F. Vorrius, L. Lamb, L. Moeller, J.F. Federici, © Springer Science with permission of Springer. (b) Attenuation of THz due to rain with respect to frequency under different rain rates.

Figure 11: Log(BER) of THz link (solid) and IR link (dash) in rain chamber as functions of time. Rain starts at a rate of 213 mm/hr at ~20 s and stops at ~80 s. From Ref. [28] Journal of Infrared, Millimeter, and Terahertz Waves, 'Experimental Comparison of Terahertz and Infrared Signaling in Laboratory-Controlled Rain', 36 (2015) 856-865, J. Ma, F. Vorrius, L. Lamb, L. Moeller, J.F. Federici, © Springer Science with permission of Springer.

Figure 12: Measured (symbols) and simulated (lines) attenuations of the THz (circles, solid line) and IR link (squares, dashed line) for different rain rates. From Ref. [28] Journal of Infrared, Millimeter, and Terahertz Waves, 'Experimental Comparison of Terahertz and Infrared Signaling in Laboratory-Controlled Rain', 36 (2015) 856-865, J. Ma, F. Vorrius, L. Lamb, L. Moeller, J.F. Federici, © Springer Science with permission of Springer.

Figure 13: (a) Attenuation of THz link (solid) and IR link (dashed, PD_MMF) in turbulence chamber as the function of time, for warm air at high speed (b) corresponding Log(BER) of THz link (solid) and IR link (dashed) as the function of time, (c) De-convoluted temperature evolution in turbulence chamber, (d) Normalized output power of the smallest (black), medium (gray), and largest (light gray) effective aperture IR detectors when warm air with high speed enters the chamber [10]. Journal of Infrared, Millimeter, and Terahertz Waves, 'Experimental Comparison of Terahertz and Infrared Signaling in Controlled Atmospheric Turbulence', 36 (2015) 130-143, J. Ma, L. Moeller, J.F. Federici, © Springer Science with permission of Springer.

LIST OF TABLES

Table 1: Comparison of predominate physics effects, applicable models in the THz range, and references for various weather conditions. The last column indicates which link performs better in a direct comparison of THz and FSO links under identical weather conditions.

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Table

Weather Condition	Dominate Effect	Applicable Models	References	THz or FSO?
Clear Weather	Water Vapor	Millimeter Wave Propagation (MPM) model Molecular Response Time Theory	11, 14, 15, 16, 45 15, 45	FSO
Fog	Scattering by small particles ($< \lambda_{THz}$)	Mie Scattering/ Rayleigh absorption approximation (first order limit of EMM) Effective Medium Model (EMM)	9, 11, 18, 23, 24, 35 25, 26	THz
Dust	Scattering by small particles ($< \lambda_{THz}$)	Mie Scattering Effective Medium Model (EMM) Rayleigh absorption approximation (first order limit of EMM)	8, 55	THz
Rain	Scattering by large particles ($\geq \lambda_{THz}$)	Mie Scattering	27, 28, 32, 33, 34	Comparable
Air Turbulence (Scintillations only)	Real refractive index variations	Andrew's method	4, 5, 10, 38, 39, 44	THz

Table 1

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