IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 7, 2019, accepted June 23, 2019, date of publication July 1, 2019, date of current version July 19, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2925815

The Impact of Atmospheric Turbulence on Terahertz Communication

LEI CANG, HENG-KAI ZHAO, AND GUO-XIN ZHENG
School of Communication and Information Engineering, Shanghai University, Shanghai 200444, China
Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai 200444, China

Corresponding author: Heng-Kai Zhao (zhaohk@shu.edu.cn)

This work was supported by the National Natural Science Foundation of China under Grant 61571282 and Grant 61871261.

ABSTRACT The application prospect of terahertz (THz) has been vastly enriched because it has the advantages of good penetrating power, high security, accurate directionality, and high bandwidth. Moreover, it is found that the atmospheric instability which is caused by fluctuating temperature and humidity has a great influence on THz communication. Therefore, in this paper, we mainly study the atmospheric conditions, focusing on the impact of atmospheric turbulence on THz communication under consideration of inland areas. Initially, we deduce the variances of fluctuating amplitude and fluctuating phase. And afterward, the quantitative analysis is presented for the overall effects of turbulence on THz wave, which offers the standard deviation of the fluctuating waves. The theoretical model reasonably explains the phenomena of signal fluctuations caused by the turbulence, and these fluctuations increase with the increment in the distance discovered by D. Grischkowsky. At last, we consider the atmospheric turbulence as a specific type of additive noise to study the influence on THz communication and to predict the upper limit of bandwidth efficiency influenced by turbulence in different atmospheric conditions.

INDEX TERMS Atmosphere, atmospheric turbulence, bandwidth efficiency, propagation, radio communication, THz communication.

I. INTRODUCTION

The THz wave which combines the advantages of optical communication and microwave communication is one of the most promising techniques in modern communication systems because of its good penetrating power, high security, accurate directionality and large available bandwidth [1], [2]. And it is widely used in communication, physics, chemistry, forensics, biology and medicine [3]. As the communication media, the atmosphere affects THz communication in terms of three aspects: atmospheric attenuation, atmospheric dispersion and atmospheric turbulence [4]. The first aspect typically causes significant energy loss, which can usually be observed as attenuation on amplitude and thus limitations on communication distance. In the vicinity of strong resonant absorption lines of water vapor [5], [6], almost all energy can be absorbed, leading to atmospheric windows [3], [7]–[9]. Previous studies have shown that the resonance lines of water vapor and oxygen are the major factors of THz transmission attenuation in the atmosphere, especially water vapor [10]–[12]. Atmospheric dispersion refers to that the waves in different frequencies have different refractive indexes and different phase velocities resulting in the change of wave package. These waves cannot arrive the receiver simultaneously. And it can be usually seen as the waveform broadening [13]–[17]. Phase shift caused by atmosphere is also analyzed through THz-TDS (terahertz time-domain spectroscopy) in the experimental process [18]–[21]. Because of the asymmetrical temperature, humility, air pressure, and air velocity, atmospheric turbulence is highly unpredictable [22], [23], leading to fluctuations on both amplitude and phase [24]–[27]. THz beams are influenced inevitably by turbulence when propagating through the atmosphere near the ground [28]–[30]. The time variation due to atmospheric turbulence between the two pulses of the 910 m measurement was up to 4 times larger than that between the two pulses of the 186 m measurement [31]. Generally speaking, the effects of atmospheric attenuation and dispersion on THz communication are shown mainly by changing the mean values of amplitude and phase, respectively. While atmospheric turbulence causes the random fluctuations for THz wave. These fluctuations not only

The associate editor coordinating the review of this manuscript and approving it for publication was Ke Guan.

appear on the amplitude, but also exist on the phase [27]. Thus, the effect of turbulence is shown as the variances in amplitude and phase of wave. In case of high humid atmosphere, the attenuation and dispersion effects will be obvious. When the temperature and humidity fluctuate violently and the mean value of temperature is high, the influence of turbulence on communication will be very serious. However, the theoretical research on the impact of atmospheric turbulence on THz communication has never been carried out.

This paper is organized as follows:

1) By combining multiple factors including temperature, humidity, wind velocity, and atmospheric pressure, we derive refractive index structure constant, which can describe the intensity of atmospheric turbulence for inland areas.
2) The fluctuations on amplitude and phase are calculated respectively.
3) We obtain the standard deviations of THz signal fluctuations in different atmospheric conditions. This result is in agreement with the actual measurement mentioned above [31].
4) We consider the signal fluctuations by turbulence as additive noise to accurately forecast the relationship of meteorological factors and bandwidth efficiency in atmospheric turbulence.

II. EFFECTS FROM ATMOSPHERIC TURBELENCE

There are many articles dealing with the impact of atmospheric attenuation and dispersion on THz, so this work concentrates on the effects from turbulence. According to definition, the atmospheric turbulence refers to the fluctuations of refractive index caused by all fluctuations in the air such as humid, temperature, wind velocity, and atmospheric pressure [32], leading to impact on wave propagation. In practice, the atmospheric refractive index structure constant, denoted as C_n^2 [33], which is used to describe the intensity of atmospheric turbulence [34], is actually a function of space and time rather than a constant. Also it is influenced by fluctuation of refractive index. For example, the equation for refractive index is

$$n \approx \left[7.52\times10^{-3}\frac{P_a-e_a}{\lambda^2 T}+72\frac{e_a}{T}+3.75\times10^{5}\frac{e_a}{T^2}\right]\times10^{-6}+1 \qquad (1)$$

in the equation above, P_a and e_a stand for atmospheric pressure and vapor pressure in hPa. λ indicates wavelength. And $e_a = 6.112\cdot RH\cdot e^{\frac{17.67(T-273)}{T-29.5}} = \frac{P_a\cdot q}{0.622+0.378q}$ can be expressed with temperature T and relative humidity RH, and it also can be expressed with atmospheric pressure P_a and specific humidity q. We can take the partial derivative of refractive index respecting to temperature and specific humidity, expressed as $\left(\frac{\partial n}{\partial T}\right)$ and $\left(\frac{\partial n}{\partial q}\right)$, respectively. Refractive index structure constant C_n^2 for inland areas can be denoted with temperature structure constant C_T^2, humidity structure constant C_q^2 and temperature-humidity mixing structure constant C_{Tq} [22], [35].

$$C_n^2=\left(\frac{\partial n}{\partial T}\right)^2 C_T^2+2\left(\frac{\partial n}{\partial T}\right)\left(\frac{\partial n}{\partial q}\right)C_{Tq}+\left(\frac{\partial n}{\partial q}\right)^2 C_q^2 \qquad (2)$$

Kolmogorov first discovered the 'two thirds law' in turbulent inertial sub-range [36], [37] which describes that the average of the square of differences from two points is proportional to two thirds power of the distance. Later, this relationship has been extended to passive conservative quantity by Oxygen. Temperature structure constant, humidity structure constant and temperature-humidity mixing structure constant can be expressed in the form of 'two thirds law'. The intensity of atmospheric turbulence, which is quantified by the refractive index structure constant, depends on the fluctuations of temperature and humidity. Thus, the refractive index structure constant can be written as

$$\begin{aligned} C_n^2 &= \left(\frac{\partial n}{\partial T}\right)^2\cdot\overline{(T_r-T_0)^2}\cdot r^{-2/3} \\ &\quad +2\left(\frac{\partial n}{\partial T}\right)\left(\frac{\partial n}{\partial q}\right)\cdot\overline{(T_r-T_0)}\cdot\overline{(q_r-q_0)}\cdot r^{-2/3} \\ &\quad +\left(\frac{\partial n}{\partial q}\right)^2\cdot\overline{(q_r-q_0)^2}\cdot r^{-2/3} \end{aligned} \qquad (3)$$

where T_r, T_0 are thermodynamic temperature which are r apart from each other, and q_r, q_0 are specific humidity in kg/kg.

A. INFLUENCE OF TURBULENCE ON TRANSMISSION AMPLITUDE

Assuming the value of C_n^2 keep unchanged over transmission path, mean-square value of log-amplitude of spherical wave propagating through symmetrical turbulence can be captured in the following equation [25]:

$$\langle\chi^2\rangle = 0.124C_n^2k^{7/6}L^{11/6} \qquad (4)$$

where $k=\frac{2\pi f}{c}$ is wave number,f is transmission frequency, and c denotes the speed of light. L is propagating distance, and $\chi = ln\frac{A}{\bar{A}}$ is log-amplitude.

The transmission linear amplitude can be considered as the sum of average value and fluctuating value, which can be expressed as $A=\bar{A}+\tilde{A}$. Then, we can get

$$\chi = ln\frac{A}{\bar{A}} = \ln\left(1+\frac{\tilde{A}}{\bar{A}}\right) \qquad (5)$$

Since the value of $\frac{\tilde{A}}{\bar{A}}$ is close to 0, we can find that χ and $\frac{\tilde{A}}{\bar{A}}$ are equivalent infinitesimal based on limit properties, $\chi\sim\frac{\tilde{A}}{\bar{A}}$. Then we can further derivate this into

Mean-square value of log-amplitude:

$$\left\langle\chi^2\right\rangle=\left\langle\left(\frac{\tilde{A}}{\bar{A}}\right)^2\right\rangle=\frac{\left\langle\tilde{A}^2\right\rangle}{\bar{A}^2} \qquad (6)$$

Variance of logarithmic amplitude:

$$D(\chi)=\left\langle\chi^2\right\rangle-\langle\chi\rangle^2 \qquad (7)$$

Variance of amplitude fluctuating value:

$$D\left(\tilde{A}\right) = D\left(A - \overline{A}\right) = D\left(A\right) - D\left(\overline{A}\right) = D\left(A\right) \tag{8}$$

Mean-square value of amplitude fluctuating value:

$$\left\langle \tilde{A}^2 \right\rangle = D(\tilde{A}) + \langle \tilde{A} \rangle^2 = D(A) + \langle \tilde{A} \rangle^2 = D(A) \tag{9}$$

Amplitude average value:

$$D(A) = \left\langle \tilde{A}^2 \right\rangle = \left\langle \chi^2 \right\rangle \cdot \overline{A}^2 = 0.124 C_n^2 k^{7/6} L^{11/6} \overline{A}^2 \tag{10}$$

Since the calculation of C_n^2 can only be performed in inertial sub-range, which is between inner scale and outer scale, and the range of typical outer scale is from 1 m to 100 m. Since in practice, propagation distance could be much larger, the atmosphere in the model is actually discrete into numbers of layers. And the thickness of each layer is between inner scale and outer scale. In this way, the amplitude structure function throughout transmission can be treated as the summation of amplitude structure function of each layer.

$$D_A = 0.124 k^{7/6} \overline{A}^2 \sum\nolimits_{i=1}^{N} C_n^2(L_i)\, \Delta L_i^{11/6} \tag{11}$$

After being transferred into integral form, we get

$$D_A = 0.124 k^{7/6} \overline{A}^2 \int_0^L C_n^2(l)\, dl^{11/6} \tag{12}$$

B. INFLUENCE OF TURBULENCE ON TRANSMISSION PHASE

Based on the foundation of Tatarskii's analysis of wave propagation in asymmetrical media, for electromagnetic waves, fluctuations always exist in transmission path. This effect can be seen as propagation through a series of lens, where each of them causes slight shift on amplitude and phase. During this process, power spectrum can be calculated as [26], [38]

$$F_\chi\left(\kappa_t, L\right) = \pi \kappa^2 L \left(1 - \frac{\overline{\kappa}}{\kappa_t^2} \sin \frac{\kappa_t^2 L}{\kappa}\right) \Phi_n\left(\kappa_t\right) \tag{13}$$

$$F_\varphi\left(\kappa_t, L\right) = \pi \kappa^2 L \left(1 + \frac{\overline{\kappa}}{\kappa_t^2} \sin \frac{\kappa_t^2 L}{\kappa}\right) \Phi_n\left(\kappa_t\right) \tag{14}$$

in the equation above, $\kappa = \frac{2\pi}{\lambda}$ is the wavenumber, $\overline{\kappa}$ is average wavenumber, κ_x, κ_y, and κ_z are the wavenumber vectors in three dimensions, $\kappa_t = \sqrt{\kappa_x^2 + \kappa_z^2}$ denotes the radial function (κ_x, κ_z), z stands for effective characteristic height of troposphere, and Φ_n is energy density function. The overall structural function can be generalized as

$$D_\psi\left(\rho\right) = D_\chi\left(\rho\right) + D_\phi\left(\rho\right) = 2.91 \overline{\kappa}^2 L C_n^2 \rho^{5/3} \tag{15}$$

Based on the relationship between amplitude and phase given in (14) (15), assuming that for one specific type of electromagnetic ($\overline{\kappa} = \kappa$) and transmitting along y direction, κ_t is close to 0 infinitely, and we can derive that

$$\begin{aligned} D_\phi(\rho) &= \lim_{\kappa_t \to 0} \frac{1 + \frac{\overline{\kappa}}{\kappa_t^2 L} \sin \frac{\kappa_t^2 L}{\kappa}}{2} 2.91 \overline{\kappa}^2 L C_n^2 \rho^{5/3} \\ &= 2.91 \overline{\kappa}^2 L C_n^2 \rho^{5/3} \end{aligned} \tag{16}$$

After transferring this into the form of path integrals, just like we did in (12) and (13), we get

$$D_\phi\left(\rho\right) = 2.91 \overline{\kappa}^2 \rho^{5/3} \int_0^L C_n^2\left(l\right) dl \tag{17}$$

III. THE IMPACT OF TURBULENCE ON THZ COMMINICATION IN DIFFERENT ATMOSPHERIC CONDITIONS

The variations of temperature and relative humidity are set to ± 0.1°C and ± 0.6% for calm weather conditions (weak turbulence), and they are set to ± 1.0°C and ± 2.7% for unstable weather conditions (strong turbulence) [31]. Under standard atmospheric pressure the average temperatures are set to 10°C and 30°C, and the average relative humidity is set to 40% and 80%. Based on (3), we can get the intensity of turbulence at different temperatures and humidity, as presented in Table 1.

In table 1, $\overline{T}$ is average temperature, and $\overline{RH}$ is average relative humidity. T_r and T_0 refer to the thermodynamic temperatures of two points over a distance of 50 m. RH_r and RH_0 refer to the relative humidity of that as well. As can be seen from the data in Table 1, the impact of average temperature on C_n^2 is greater than that of average relative humidity for inland areas. The more violent the fluctuations in temperature and relative humidity are, the higher the intensity of turbulence is.

TABLE 1. **The intensity of turbulence at different temperatures and relative humidity.**

	$T_r - T_0 = 0.2$°C $RH_r - RH_0 = 1.2\%$	$T_r - T_0 = 2$°C $RH_r - RH_0 = 5.4\%$
$\overline{T} = 10$°C $\overline{RH} = 40\%$	6.162×10^{-14}	2.125×10^{-12}
$\overline{T} = 10$°C $\overline{RH} = 80\%$	6.602×10^{-14}	2.389×10^{-12}
$\overline{T} = 30$°C $\overline{RH} = 40\%$	4.006×10^{-13}	1.050×10^{-11}
$\overline{T} = 30$°C $\overline{RH} = 80\%$	4.326×10^{-13}	1.216×10^{-11}

According to (12) and (17), we can easily deduce the variances of amplitude and phase, and their mean values are $\overline{A}$ and 0, respectively. After considering normally distributed 10000 values of amplitude A_i and phase S_i, each signal can be write as $x_i = A_i \cdot e^{iS_i}$. And the relation $\overline{x} = \frac{1}{10000} \sum_{i=1}^{10000} x_i \overline{x}$ refers to the mean value of x_i. Afterwards, the standard

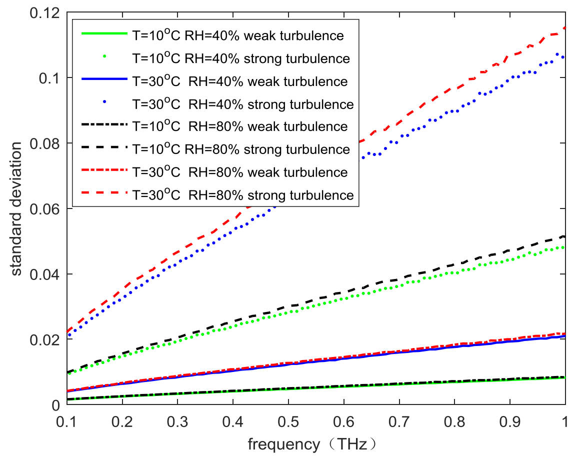


FIGURE 1. **Standard deviation caused by turbulence.**

deviation is as follows.

$$\sigma(x) = \sqrt{\frac{1}{10000}\sum_{i=1}^{10000}(x_i - \overline{x})^2} \tag{18}$$

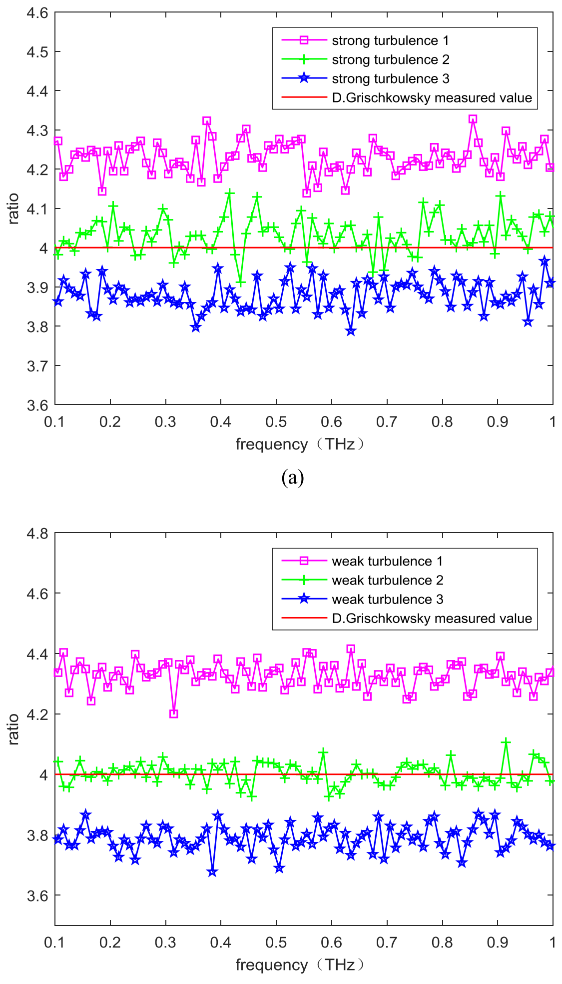
To determine the impact of atmospheric turbulence on THz wave propagation clearly, the standard deviations over the transmitting distance of 1 km in atmospheric turbulence at different temperatures and relative humidity are illustrated in Fig. 1.

When the average relative humidity is 40%, 80% and the average temperatures are 10°C, 30°C, the curves of the standard deviations in different turbulence against frequency are shown in Fig. 1. As can be seen from Fig. 1, for inland areas, with the same fluctuation in temperature and the same fluctuation in humidity, the higher temperature and relative humidity are, the greater signal fluctuations caused by turbulence are. The influence of average temperature on signal transmission is greater than that of average relative humidity.

IV. THE CONTRAST BETWEEN THEORY AND MEASUREMENT

In the measurement by D. Grischkowsky, the temperature and relative humidity in Transceiver Building 1 were 22°C and 40%. The outside temperature and relative humidity between Transceiver Building 1 and Target Building 2 were 6.3°C and 25.7%. These two parts comprised the transmission path of 186 m. In the rest transmission path of 724 m over the water, the temperature and relative humidity were 3.9°C and 32.5%. It was found in the measurement that the time variation due to atmospheric turbulence in the transmission path of 910 m measurement was up to 4 times larger than that in the transmission path of 186 m measurement [31]. For the sake of clarity, we use Path 1, Path 2 and Path 3 to indicate these three parts of transmission path.

It is assumed that the turbulence intensity remains constant throughout the whole transmission path. In Fig. 2, the red dotted line represents the radios of standard deviation in the transmission path of 910 m to that of 186 m measured by D. Grischkowsky. The atmospheric conditions represented by each solid line are shown in Table 2 and Table 3.



(a)

(b)

FIGURE 2. **The ratio of fluctuating standard deviation of 910 m to that of 186 m. (a) The ratio in weak turbulence. (b) The ratio in strong turbulence.**

In these six cases, the calculated results of our theoretical model differ from the measured results by 8.2%, 0.3%, 5.3%, 5.7%, 0.9%, and 2.7%. The green solid line is closer to the red dotted line in each figure. Therefore, our theoretical models is in good agreement with the actual measurement by D.Grischkowsky.

V. THE BANDWIDTH EFFICIENCY IN ATMOSPHERIC TURBULENCE

A. THE EXPRESSION FOR THE CHANNEL CAPACITY IN ATMOSPHERIC TURBULENCE

Conventional thermal noise is produced by the thermal motion of electrons in all resistive components, and it is everywhere. Even if there is no turbulence, it inevitably exists in all electronic equipment. Atmospheric turbulence can be described as the fluctuation of the refractive index caused by irregular atmospheric motion. From this we can know,

TABLE 2. The atmospheric conditions represented in figure 2(a).

	Purple solid line	Green solid line	Blue solid line
Path A Temperature variations	±0.03°C	±0.03°C	±0.03°C
Path A Relative humidity variations	±0.09%	±0.09%	±0.09%
Path B Temperature variations	±0.095°C	±0.1°C	±0.1°C
Path B Relative humidity variations	±0.5%	±0.55%	±0.6%
Path C Temperature variations	±0.1°C	±0.1°C	±0.1°C
Path C Relative humidity variations	±0.6%	±0.6%	±0.6%

TABLE 3. The atmospheric conditions represented in figure 2(b).

	Purple solid line	Green solid line	Blue solid line
Path A Temperature variations	±0.3°C	±0.3°C	±0.3°C
Path A Relative humidity variations	±1%	±1%	±1%
Path B Temperature variations	±0.9°C	±1°C	±1°C
Path B Relative humidity variations	±2.5%	±2.5%	±2.7%
Path C Temperature variations	±1°C	±1°C	±1°C
Path C Relative humidity variations	±2.7%	±2.7%	±2.7%

the signal fluctuation caused by turbulence and thermal noise are uncorrelated. We can consider the turbulence as another additive noise with an average value of 0 which is independent of conventional thermal noise. The power of the turbulent noise is given by

$$N_T = \sigma^2 \tag{19}$$

Based on Shannon formula, channel capacity in turbulent environment is

$$C = B\log_2\left(1+\frac{P_{Rx}}{N_0+N_T}\right) = B\log_2\left(1+\frac{P_{tx}\cdot e^{-\alpha L}}{FK_BTB+\sigma^2}\right) \tag{20}$$

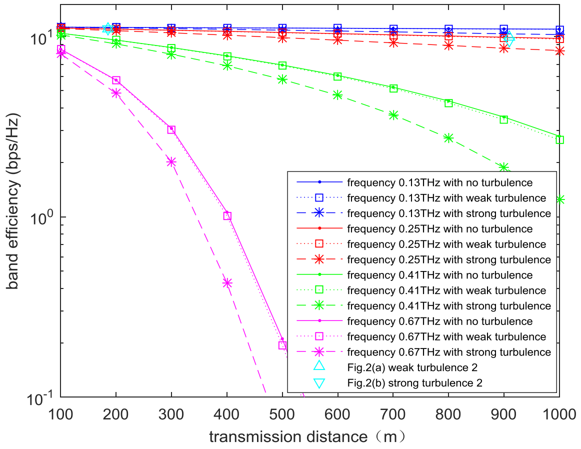


FIGURE 3. Band efficiency in different frequencies.

where B is the bandwidth. $P_{Rx} = P_{tx}\cdot e^{-\alpha L}$ is the received power which can be obtained by transmitting power P_{tx} and attenuation factor α [10], [19]. $N_0 = FK_BTB$ stands for the power of conventional thermal noise [39], [40]. F is noise factor, and the value is taken as 40 dB. T stands for thermodynamic temperature. $K_B = 1.3806488\times10^{-23}W\cdot s/K$ is Boltzmann constant.

So the bandwidth efficiency can be calculated as follows:

$$\eta = \frac{C}{B} = \log_2\left(1+\frac{P_{tx}\cdot e^{-\alpha L}}{FK_BTB+\sigma^2}\right) \tag{21}$$

B. THE INFLUENCE OF TURBULENCE ON BANDWIDTH EFFICIENCY AT DIFFERENT FREQUENCIES

When the attenuation coefficient caused by atmospheric attenuation effect and the dispersion coefficient caused by atmospheric dispersion effect are also considered, the selected frequencies less affected are 0.13 THz, 0.25 THz, 0.41 THz, and 0.67 THz, respectively. Three cases are discussed at each frequency, namely, no turbulence environment, weak turbulence environment and strong turbulence environment. The temperature difference and the relative humidity difference between two points that are 50 m apart from each other in weak turbulence environment are set to 0.1°C and 0.6%, and those in strong turbulence environment are set to 1.0°C and 2.7%. Assume that the antenna gain is 0, and the transmitted power is 0.01 W. Also the temperature and relative humidity are 20°C and 60%. The curves of bandwidth efficiency varied with propagation distance are shown in Fig. 3.

As can be seen from Fig. 3:

1) The higher the transmission frequency is, the lower the bandwidth efficiency is. If the propagation distance is 800 m, with no turbulence, the bandwidth efficiency in the 0.13 THz is 11.02 bps/Hz. The bandwidth efficiency in the 0.25 THz frequency is 10.04 bps/Hz. And the bandwidth efficiency in the 0.41 THz is 4.383 bps/Hz.
2) Under the impact of the atmospheric turbulence, the channel capacity is reduced. In the turbulence of the same intensity, the higher the frequency is, the greater the influence of turbulence on bandwidth efficiency is. If the propagation distance is 800 m, the bandwidth

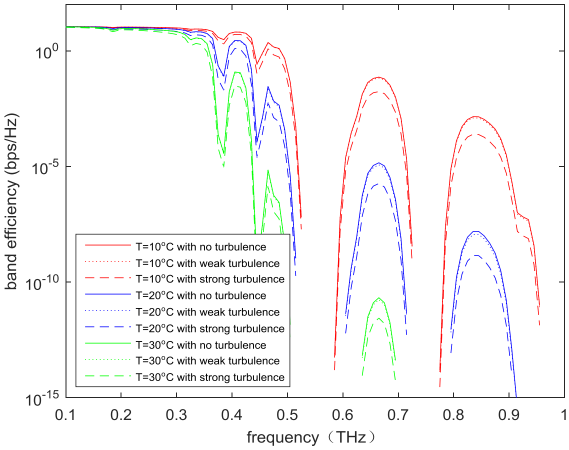


FIGURE 4. **Band efficiency in different temperatures.**

efficiency in the 0.13 THz frequency in weak turbulence is reduced to 99.81%, and that in strong turbulence is reduced to 94.83%. The bandwidth efficiency in the 0.25 THz frequency in weak turbulence is reduced to 99.46%, and that in strong turbulence is reduced to 88.68%. The bandwidth efficiency in the 0.41 THz frequency in weak turbulence is reduced to 97.56%, and that in strong turbulence is reduced to 62.24%.

3) According to the weak turbulence 2 and strong turbulence 2 in Fig. 2, the bandwidth efficiency in the 0.25 THz frequency over the transmitting distance of 186 m is 10.99 bps/Hz and 10.95 bps/Hz, respectively. And the bandwidth efficiency over the transmitting distance of 910 m is 9.86 bps/Hz and 9.42 bps/Hz, respectively.

C. THE IMPACT OF TURBULENCE ON BANDWIDTH EFFICIENCY AT DIFFERENT TEMPEARATURES AND HUMIDITY

Assume that the relative humidity is 60%, and the propagation distance is 1 km. Three cases are discussed at each temperature, namely, no turbulence environment, weak turbulence environment and strong turbulence environment. The temperature difference and the relative humidity difference between two points that are 50 m apart from each other in weak turbulence environment are 0.1°C and 0.6%, and those in strong turbulence environment are 1.0°C and 2.7%. Assume that the antenna gain is 0, and the transmitted power is 0.01 W. The curves of the bandwidth efficiency varied with frequency in different temperatures are shown in Fig. 4.

As can be seen from Fig. 4:

1) The higher the temperature is, the lower the bandwidth efficiency is. If the transmission frequency is 0.41 THz, with no turbulence, the bandwidth efficiency at the temperature of 10°C is 6.472 bps/Hz. The bandwidth efficiency at the temperature of 20°C is 2.797 bps/Hz. And the bandwidth efficiency at the temperature of 30°C is 0.1215 bps/Hz.

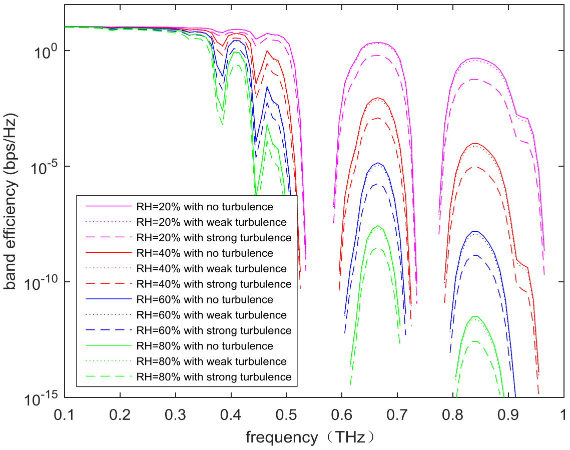


FIGURE 5. **Band efficiency in different relative humidity.**

2) In the turbulence of the same intensity, the higher the temperature is, the greater the influence of turbulence on bandwidth efficiency is. If the transmission frequency is 0.41 THz, the bandwidth efficiency at the temperature of 10°C in weak turbulence is reduced to 99.02%, and that in strong turbulence is reduced to 78.99%. The bandwidth efficiency at the temperature of 20°C in weak turbulence is reduced to 95.39%, and that in strong turbulence is reduced to 44.58%. The bandwidth efficiency at the temperature of 30°C in weak turbulence is reduced to 90.86%, and that in strong turbulence is reduced to 24.73%.

Assume that the temperature is 20°C, and the propagation distance is 1 km. Three cases are discussed at each relative humidity, namely, no turbulence environment, weak turbulence environment and strong turbulence environment. The temperature difference and the relative humidity difference between two points that are 50 m apart from each other in weak turbulence environment are 0.1°C and 0.6%, and those in strong turbulence environment are 1.0°C and 2.7%. Assume that the antenna gain is 0, and the transmitted power is 0.01 W. The curves of the bandwidth efficiency varied with frequency in different relative humidity are shown in Fig. 5.

As can be seen from Fig. 5:

1) The higher the relative humidity is, the lower the bandwidth efficiency is. If the transmission frequency is 0.41 THz, with no turbulence, the bandwidth efficiency at the relative humidity of 20% is 8.373 bps/Hz. The bandwidth efficiency at the relative humidity of 40% is 5.520 bps/Hz. The bandwidth efficiency at the relative humidity of 60% is 2.797 bps/Hz. And the bandwidth efficiency at the relative humidity of 80% is 0.8824 bps/Hz

2) In the turbulence of the same intensity, the higher the relative humidity is, the greater the influence of turbulence on bandwidth efficiency is. If the transmission frequency is 0.41 THz, the bandwidth efficiency at the relative humidity of 20% in weak turbulence is reduced to 98.33%, and that in strong turbulence

is reduced to 76.58%. The bandwidth efficiency at the relative humidity of 40% in weak turbulence is reduced to 97.41%, and that in strong turbulence is reduced to 64.76%. The bandwidth efficiency at the relative humidity of 60% in weak turbulence is reduced to 95.39%, and that in strong turbulence is reduced to 44.58%. The bandwidth efficiency at the relative humidity of 80% in weak turbulence is reduced to 92.10%, and that in strong turbulence is reduced to 28.28%.

VI. CONCLUSION

According to Kolmogorov's 'two thirds law', we take the fluctuations of temperature, humidity, wind velocity and atmospheric pressure into consideration and obtain the atmospheric refractive index structure constant which can be used to describe the intensity of atmospheric turbulence. The variances of fluctuating amplitude and fluctuating phase in the transmission path are deduced. We quantitatively analyze the fluctuation of THz signal caused by turbulence for inland areas. And the result is in agreement with the actual measurement by D.Grischkowsky. At last, the atmospheric turbulence is considered as a kind of additive noise to derive the expression of the channel capacity in atmospheric turbulence. Also this paper analyzes the impact of turbulence on bandwidth efficiency in different atmospheric conditions and predicts the upper limit of bandwidth efficiency at different frequencies, temperatures and humidity.

The results are shown below:

1) The influence of average temperature on signal transmission is greater than that of average relative humidity. The higher temperature and relative humidity are, the greater signal fluctuations caused by turbulence are.
2) The higher the transmission frequency is, the lower the bandwidth efficiency is.
3) Under the impact of the atmospheric turbulence, the channel capacity is reduced. In the turbulence of the same intensity, the higher the frequency is, the greater the influence of turbulence on bandwidth efficiency becomes. In strong turbulence environment, the temperature difference and the relative humidity difference between two points that are 50 m apart from each other are set to 1.0°C and 2.7%.The average temperature and relative humidity are 20°C and 60%, and the propagation distance is 800 m. In this case, the bandwidth efficiency influenced by strong turbulence in the 0.13 THz, 0.25 THz, and 0.41 THz frequency is reduced to 94.83%, 88.68%, and 62.24%, respectively.
4) The higher the temperature is, the lower the bandwidth efficiency is.
5) In the turbulence of the same intensity, the higher the temperature is, the greater the influence of turbulence on bandwidth efficiency becomes. The relative humidity is 60%, and the propagation distance is 1 km. If the transmission frequency is 0.41 THz, the bandwidth efficiency influenced by strong turbulence at the temperature of 10°C, 20°C and 30°C is reduced to 78.99%, 44.58%, and 24.73%, respectively.
6) The higher the relative humidity is, the lower the bandwidth efficiency is.
7) In the turbulence of the same intensity, the higher the relative humidity is, the greater the influence of turbulence on bandwidth efficiency becomes. The temperature is 20°C, and the propagation distance is 1 km. If the transmission frequency is 0.41 THz, the bandwidth efficiency influenced by strong turbulence at the relative humidity of 20%, 40%, 60%, and 80% is reduced to 76.58%, 64.76%, 44.58%, and 28.28%, respectively.

REFERENCES

[1] N. Khalid and O. B. Akan, "Experimental throughput analysis of low-THz MIMO communication channel in 5G wireless networks," *IEEE Wireless Commun. Lett.*, vol. 5, no. 6, pp. 616–619, Dec. 2016.

[2] A. Seeds and H. Shams, "Photonics, fiber and THz wireless communication," *Opt. Photon. News*, vol. 28, no. 3, pp. 24–31, 2017.

[3] M. A. Akkaş, "Terahertz wireless data communication," *Wireless Netw.*, vol. 25, no. 1, pp. 145–155, Jun. 2017.

[4] A. Prokes, "Atmospheric effects on availability of free space optics systems," *Opt. Eng.*, vol. 48, no. 6, 2009, Art. no. 066001.

[5] M. J. Weber, B. B. Yang, and M. S. Kulie, R. Bennartz, and J. H. Booske, "Atmospheric attenuation of 400 GHz radiation due to water vapor," *IEEE Trans. THz Sci. Technol.*, vol. 20, no. 3, pp. 355–360, May 2012.

[6] E.-B. Moon, T.-I. Jeon, and D. R. Grischkowsky, "Long-path THz-TDS atmospheric measurements between buildings," *IEEE Trans. THz Sci. Technol.*, vol. 5, no. 5, pp. 742–750, Sep. 2015.

[7] D. M. Slocum, E. J. Slingerland, R. H. Giles, and T. M. Goyette, "Atmospheric absorption of terahertz radiation and water vapor continuum effects," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 127, no. 1, pp. 49–63, 2013.

[8] J. F. O'Hara and D. R. Grischkowsky, "Comment on the veracity of the ITU-R recommendation for atmospheric attenuation at terahertz frequencies," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 3, pp. 372–375, May 2018.

[9] L. Changsheng, L. Leke, Z. Xin, L. Zhaofeng, L. Haiying, W. Zhensen, and H. Chunzhi, "THz atmospheric propagation measurement system of CRIRP," in *Proc. IEEE 9th UK-Eur.-China Workshop Millimetre Waves THz Technol. (UCMMT)*, Sep. 2017, pp. 100–103.

[10] J. R. Pardo, E. Serabyn, and J. Cernicharo, "Submillimeter atmospheric transmission measurements on Mauna Kea during extremely dry El Niño conditions: Implications for broadband opacity contributions," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 68, no. 4, pp. 419–433, 2001.

[11] *Attenuation by Atmospheric Gases*, document ITU-R P. 676-11, 2016.

[12] G. A. Siles, J. M. Riera, and P. García-del-Pino, "Atmospheric attenuation in wireless communication systems at millimeter and THz frequencies," *IEEE Antennas Propag. Mag.*, vol. 57, no. 1, pp. 48–61, Feb. 2015.

[13] G. P. Agrawal, *Fiber-Optic Communication Systems*, 3rd ed. Hoboken, NJ, USA: Wiley, 2002, pp. 37–39.

[14] L. S. Rothman, I. E. Gordon, Y. Babikov, A. Barbe, D. C. Benner, P. F. Bernath, M. Birk, L. Bizzocchi, V. Boudon, L. R. Brown, and A. Campargue, "The HITRAN2012 molecular spectroscopic database," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 130, pp. 4–50, Nov. 2013.

[15] H. M. Pickett, R. L. Poynter, E. A. Cohen, M. L. Delitsky, J. C. Pearson, and H. S. P. Müller, "Submillimeter, millimeter, and microwave spectral line catalog," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 60, no. 5, pp. 883–890, 1998.

[16] H. Cui, J. Yao, and C. Wan, "The study on THz wave propagation feature in atmosphere," *J. Phys., Conf. Ser.*, vol. 276, no. 1, pp. 12225–12231, 2011.

[17] D. Grischkowsky, Y. Yang, and M. Mandehgar, "Digital THz communication links in the atmosphere," in *Proc. 38th Int. Conf. Infr., Millim., THz Waves (IRMMW-THz)*, Sep. 2013, pp. 1–2.

[18] Y. Yang, M. Mandehgar, and D. R. Grischkowsky, "Understanding THz pulse propagation in the atmosphere," *IEEE Trans. THz Sci. Technol.*, vol. 2, no. 4, pp. 406–415, Jul. 2012.

[19] Y. Yang, M. Mandehgar, and D. Grischkowsky, "Determination of the water vapor continuum absorption by THz-TDS and molecular response theory," *Opt. Express*, vol. 22, no. 4, pp. 4388–4403, Feb. 2014.

[20] Y. Yang, M. Mandehgar, and D. Grischkowsky, "Time domain measurement of the THz refractivity of water vapor," *Opt. Express*, vol. 20, no. 24, pp. 26208–26218, 2012.

[21] Y. Yang, M. Mandehgar, and D. Grischkowsky, "THz-TDS characterization of the digital communication channels of the atmosphere and the enabled applications," *J. Infr., Millim., THz Waves*, vol. 36, no. 2, pp. 97–129, 2015.

[22] D. L. Hutt, "Modeling and measurement of atmospheric optical turbulence over land," *Opt. Eng.*, vol. 38, no. 8, pp. 1288–1295, 1999.

[23] R. J. Hill, "Spectra of fluctuations in refractivity, temperature, humidity, and the temperature-humidity cospectrum in the inertial and dissipation ranges," *Radio Sci.*, vol. 13, no. 6, pp. 953–961, 1978.

[24] X. Zhu and J. M. Kahn, "Free-space optical communication through atmospheric turbulence channels," *IEEE Trans. Commun.*, vol. 59, no. 8, pp. 1293–1300, Aug. 2002.

[25] G. R. Ochs, S. F. Clifford, and T. Wang, "Wind and refractive-turbulence sensing using crossed laser beams," *Appl. Opt.*, vol. 13, no. 11, pp. 2602–2612, 1974.

[26] V. I. Tatarskii, "The effects of the turbulent atmosphere on wave propagation," in *Israel Program for Scientific Translation*. Jerusalem, Israel: NOAA, 1971, pp. 225–232.

[27] G. A. Daigle, J. E. Piercy, and T. F. W. Embleton, "Line-of-sight propagation through atmospheric turbulence near the ground," *J. Acoust. Soc. Amer.*, vol. 74, no. 5, pp. 1505–1513, 1983.

[28] J. Ma, L. Moeller, and J. F. Federici, "Experimental comparison of terahertz and infrared signaling in controlled atmospheric turbulence," *J. Infr., Millim., THz Waves*, vol. 36, no. 2, pp. 130–143, 2015.

[29] J. F. Federici, J. Ma, and L. Moeller, "Review of weather impact on outdoor terahertz wireless communication links," *Nano Commun. Netw.*, vol. 10, pp. 13–16, Dec. 2016.

[30] C. Liu, C. Wang, and J.-C. Cao, "Performance analysis of LDPC codes on OOK terahertz wireless channels," *Chin. Phys. B*, vol. 25, no. 2, 2016, Art. no. 028702.

[31] G.-R. Kim, T.-I. Jeon, and D. Grischkowsky, "910-m propagation of THz ps pulses through the Atmosphere," *Opt. Express*, vol. 25, no. 21, pp. 25422–25434, 2017.

[32] d. G. Pérez and G. Funes, "On a quasi-wavelet model of refractive index fluctuations due to atmospheric turbulence," *Opt. Express*, vol. 23, no. 25, pp. 31627–31639, 2015.

[33] C. Qing, X. Wu, X. Li, Q. Tian, D. Liu, R. Rao, and W. Zhu, "Simulating the refractive index structure constant $(C^{2}{}_{n})$in the surface layer at antarctica with a mesoscale model," *Astron. J.*, vol. 155, no. 1, p. 37, 2017.

[34] N. Anand, S. K. Satheesh, and K. K. Moorthy, "Dependence of atmospheric refractive index structure parameter $(C^{2}{}_{n})$ on the residence time and vertical distribution of aerosols," *Opt. Lett.*, vol. 42, no. 14, pp. 2714–2717, 2017.

[35] M. Braam, A. F. Moene, and F. Beyrich, "Variability of the structure parameters of temperature and humidity observed in the atmospheric surface layer under unstable conditions," *Boundary-Layer Meteorol.*, vol. 150, no. 3, pp. 399–422, 2014.

[36] T. S. Lundgren, "Kolmogorov two-thirds law by matched asymptotic expansion," *Phys. Fluids*, vol. 14, no. 2, pp. 638–642, 2002.

[37] Y. A. Gostintsev, Y. V. Shatskikh, Y. V. Shulenin, and V. E. Fortov, "The evolution of free turbulent spherical gas flames and the generalized Kolmogorov-Obukhov laws," *Russian J. Phys. Chem. B*, vol. 2, no. 3, pp. 437–441, 2008.

[38] Y. X. Zhang and Z. Y. Chi, *Transmission and Imaging of Light Waves in the Atmosphere*, 1st ed. Beijing, China: National Defense Industrial Press, 1997, pp. 45–55.

[39] T. Schneider, A. Wiatrek, S. Preußler, M. Grigat, and R.-P. Braun, "Link budget analysis for terahertz fixed wireless links," *IEEE Trans. THz Sci. Technol.*, vol. 2, no. 2, pp. 250–256, Mar. 2012.

[40] I. Y. Lesnov and V. F. Vdovin, "Corrected link budget analysis for terahertz wireless links," *Communications*, vol. 3, no. 6, pp. 158–161, 2015.

LEI CANG received the bachelor's degree in communication engineering from the Nanjing University of Posts and Telecommunications, in 2011. She is currently pursuing the Ph.D. degree with the School of Communication and Information Engineering, Shanghai University, China. Her current research interests include high frequency electromagnetic waves propagation in atmospheric turbulence and turbulence models.

HENG-KAI ZHAO received the bachelor's degree in electronic instruments and measurement technology from the Shanghai University of Science and Technology, in 1990, and the Ph.D. degree in communication and information systems from Shanghai University, in 2006, where he is currently an Associate Professor with the School of Communication and Information Engineering. His research interests include rail transit wireless communications, radio wave propagation in atmospheric turbulence, and signal detection.

GUO-XIN ZHENG received the bachelor's and master's degrees in electronic engineering from the Taiyuan University of Technology, in 1982 and 1987, respectively. He is currently a Full Professor with the School of Communication and Information Engineering, Shanghai University, China. Some of his professional positions include a Senior Fellow of the Institution of Engineering and Technology and the Vice Committee Chair of the Microwave Society of Shanghai Institute of Electronics. His research interests include confined space radio communications and wireless communications in metro systems.

* * *