Link loss of the free space optical communications of real-time transmission with 1 Gbps

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Abstract: The biggest challenge for free space optical (FSO) communication systems is the attenuation/fluctuation of light intensity caused by influence of atmospheric turbulence in long distance communication, resulting in communication link interruption. A method to calculate the link loss due to atmospheric turbulence, based on lognormal statistics of the received power, was presented. It can be used to evaluate the system parameters in FSO communication system. The effects of different intensity turbulence were simulated, and the relationship between optical communication link loss and transmission distance at 850 nm and 1 550 nm wavelengths at receiving terminals of 2 cm and 20 cm was obtained. Then the simulated analysis results were used to design a FSO communication system with a receiving aperture of 20 cm, which could transmit HD image and video at a distance of about 2 km under strong turbulence conditions. The transmission rate of the FSO communication system was 1 Gpbs which could meet the sharpness and real-time performance of large amount of uncompressed data transmission compared with the 4 G networks.

Key words: free space optical communication; flicker loss; receiving intensity distribution; optical link loss; high speed transmission rate

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1 Gbps 实时传输的自由空间光通信链路损耗

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摘 要: 远距离自由空间光学(FSO)通信系统面临的最大挑战是在大气湍流影响下信号传输会造成光强度衰减/波动,导致通信链路中断。文中提出了一种基于通信系统接收功率的对数正态统计来计算由湍流引起的通信链路损耗的方法,可评估指导 FSO 通信系统中的系统参数。文中模拟了不同强度湍流影响, 接收终端口径为 2 cm、20 cm 条件下,850 nm、1 550 nm 波长的光通信链路损耗与传输距离的关系。然后利用模拟分析结果设计了一个接收口径为 20 cm 的 FSO 通信系统, 在强湍流条件下完成~2 km 距离传输高清图像和视频。 FSO 通信系统的传输速率为 1 Gpbs,与 4 G 网络相比,可以满足大量无压缩数据流传输的清晰度和实时性。

关键词: 自由空间光通信; 闪烁损耗; 接收强度分布; 光链路损耗; 高传输速率

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0 Introduction

Free space optical (FSO) communication has the advantages of large capacity, high speed, small size, light weight, low power consumption, high reliability, good confidentiality and security[1-3]. When an optical beam which has at least several wavelengths with a longitudinal coherence length propagates through atmospheric optical index of refraction turbulence (IRT), the distortions caused by refraction imposed on the wave-front can generate random interference patterns in the far field, lateral intensity coherence length ρ_I, known as the intensity speckle patterns, which will lead to the reduction of received noise ratio and increased bit error rate in FSO communication[4-5].

When the diameter of the receiving aperture D_{RX} is greater than ρ_I, ρ_I represents the average aperture of the receiving intensity distribution. The effect reduces the intensity of received power fluctuations, thereby improving system performance of the FSO communication. A lot of research on optical receiving antennas for laser communications are reported [6-9]. Sun proposed an off-axis antenna system for FSO communication system [6]. Suryakant Gautam designed an off-axis two-way system [7]. Hu put forward the optimization design of Cassegrain antenna in FSO communication [8]. Guan introduced the free-form surface design to improve the performance of FSO[9]. The normalized variance of the intensity-commonly referred to as the intensity scintillation index σ_I^2-and the power scintillation index σ_p^2 is used for the received power ripple.

Based on σ_p^2 and the probability p_{thr} when the receiving power is below the limit P_{min}(p_{thr} is the fraction of the downtime of link), a direct method for calculating the corresponding scintillation loss a_{sci} is proposed. The idea of this method was proposed by McKinley and Yura [10], which is suitable for performance evaluations of systems with on-off keying (OOK). The derivation of σ_p^2 from σ_I^2, ρ_I, and D_{RX} is based on established approximation methods in reference [11].

1 System model of FSO communications

The quality of the received signal is determined by different noise sources and the received signal power P_{Rx} itself. A particular average of more than 1 and 0 bits of the minimum received power P_{min} can be defined, below P_{min} the receiver no longer meets a system-specific quality standard, which is usually given by a maximum bit error probability. When 1′s and 0′ s are equally distributed in an OOK data stream, P_{min} can be measured directly with a power meter, which satisfies $P_{min}=0.5P_{min\_1}$, where P_{min_1} represents the minimum Rx power allowed during a logical 1 reception. The exact value of P_{min} depends on several technical constraints, such as the background light and the performance of the receiver electronics, which should be determined in a measurement setup.

1.1 Statistics for intensity scintillations

Since the intensity field is a time and space traversal process, the intensity scintillation index σ_I^2 can be shown through the space or time intensity statistics at link distance L:

$$\sigma_I^2=\frac{\langle I^2(L,x,y,t)\rangle-\langle I(L,x,y,t)\rangle^2}{\langle I(L,x,y,t)\rangle^2}=\frac{\langle I^2(L,x,y,t)\rangle_{x,y}}{\langle I(L,x,y,t)\rangle_{x,y}^2}-1=\frac{\langle I^2(L,x,y,t)\rangle_t}{\langle I(L,x,y,t)\rangle_t^2}-1 \tag{1}$$

The flicker index σ_I^2 is usually evaluated in the form of the Rytov variance σ_R^2, which is an analytical method for the integrated amount of turbulence along the link, weighted with the wavelength λ:

$$\sigma_R^2=2.25k^{7/6}\int_0^L C_n^2(z)\cdot(L-z)^{5/6}\mathrm{d}z \tag{2}$$

When C_n^2 is const,

$$\sigma_R^2=1.23C_n^2k^{7/6}L^{11/6},\ k=\frac{2\pi}{\lambda} \tag{3}$$

For weak turbulence ($\sigma_R^2<0.5$), σ_I^2 is almost equal to σ_R^2, while for σ_R^2>0.5, σ_I^2 grows more slowly (intermediate turbulence), and after a maximum at typically $\sigma_R^2\approx 2.8$ (strong turbulence) drops and tends to uniform asymptotically (saturation regime)[11]. Thus, the most uncertain prediction area σ_I^2 is around its peak.

Based on the analytical calculations σ_I^2 of the position-dependent turbulence parameters along the link path, such as C_n^2(refractive index structure constant), l_0 (inner scales of turbulence), and L_0(extra dimensions of turbulence)-and in the transmission beam profile (plane, spherical, flat-top, Gaussian, etc.) is usually confined to certain states of turbulence intensity. Recently, a more general analysis of the description has been given[12], which allows the calculation of both σ_I^2 and σ_p^2 for some more general scenes, from weak to strong, to saturated turbulence. In particular, the plane and spherical waves are adequately treated to calculate the σ_p^2 for practical scenarios.

In moving internal air communication, we usually deal with spherical waves, because the divergence of the emission-beam has to be widened at a diffraction limited value to ensure that the partner terminal is illuminated from an unstable moving platform.

1.2 Rx-power scintillations

In the standard OOK receiver, the electrical signal amplitude S_{el} (t) is proportional to the received optical power $P_{Rx}(t)$ (ignoring some minor non-linear effects), which is the optical intensity I (x,y,t) over the receiving aperture area A_{Rx} again. For all further calculations, we can therefore use the received optical power P_{Rx} instead of the electrical amplitude after the receiver front:

$$P_{Rx}(t)=\iint_{A_{Rx}} I(x,y,t)\mathrm{d}x\mathrm{d}y \propto S_{el}(t) \tag{3}$$

We handle the remote communication link here, and the optical signal distribution on the Rx plane is at least several times larger than the Rx aperture. And according to the Rytov theory the intensity distribution follows logarithmic normal behavior only in weak intermediate turbulence, it also applies to a good approximation in strong and saturation turbulence from numerical and experimental verification[13-15].

1.3 Normal distribution density function of Rx power

The Rx energy across the entire transverse range requires power-conservation, because IRT scintillation is a lossless process. Thus, the basic parameters of its normal distribution, σ and μ (the variance and mean of the original normal distribution), must follow the correlation:

$$\mu=-\frac{1}{2}\ln(\sigma_p^2+1)=-\frac{1}{2}\sigma^2 \tag{4}$$

Through Eq.(4) we can develop the Normal Rx power distribution $p_p(P_{Rx})$ for a long range link of the long-term average received power P_0:

$$p_p(P_{Rx})=\frac{1}{P_{Rx}[2\pi\ln(\sigma_p^2+1)]^{1/2}}\times \exp\left\{\frac{[\ln(P_{Rx}/P_0)+1/2\ln(\sigma_p^2+1)]^2}{2\ln(\sigma_p^2+1)}\right\} \tag{5}$$

2 Simulation results of the receiver performance and link-budget loss

When P_{Rx} is gradually disappearing in the case described by Eq.(5), an acceptable downtime section is defined, when $P_{Rx}<P_{min}$. The link-budget calculation is defined as the flicker loss a_{sci} of the FSO communication (in decibels):

$$a_{sci}=10\log_{10}\left(\frac{P_{min}}{P_0}\right),\ a_{sci}<0 \tag{6}$$

In this threshold method, it is assumed that no data reception is possible during times of P_{Rx} below P_{min}. This represents a good-bad-state channel modeling. The fraction of interrupt time is equal to the probability p_{thr} of the actual power below P_{min}. p_{thr} is calculated using the distribution function based on Eq.(5) by the analogy in reference [16], page 242[16]:

$$p_{thr}(P_{Rx}<P_{min})=\frac{1}{2}\left\{1+\mathrm{erf}\left\{\frac{\ln\left[\frac{P_{min}}{P_0}(\sigma_p^2+1)^{1/2}\right]}{[2\ln(\sigma_p^2+1)]^{1/2}}\right\}\right\} \tag{7}$$

This equation is shown in reference [1]. In order to calculate a_{sci}, Eq.(7) must be solved for P_{min}:

$$\frac{P_{min}(p_{thr})}{P_0}=\frac{\exp\{\mathrm{erf}^{-1}(2p_{thr}-1)\cdot[2\ln(\sigma_p^2+1)^{1/2}]\}}{(\sigma_p^2+1)^{1/2}} \quad (8)$$

$$a_{sci}=4.343\left\{\mathrm{erf}^{-1}(2p_{thr}-1)\cdot[2\ln(\sigma_p^2+1)^{1/2}]-\frac{1}{2}\ln(\sigma_p^2+1)\right\} \quad (9)$$

As can be seen from Fig.1, at the typical link requirements, a_{sci} can easily exceed 20 dB (e.g., BER< 10^{-6}). Otherwise, with saturation and aperture average, the value will hardly exceed 15 dB, because σ_p^2 will be less.

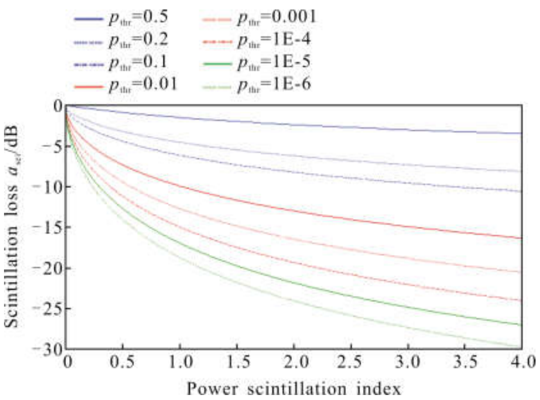

Fig.1 Scintillation loss a_{sci} versus power scintillation index σ_p^2 with the threshold p_{thr} as parameter

Equation (9) can be approximated by an error below 1.1 dB for σ_p^2<3 and $0.7>p_{thr}>2\times10^{-7}$ with the following curve fitting:

$$a_{sci}\approx[3.3-5.77(-\ln p_{thr})^{1/2}]\cdot(\sigma_p^2)^{0.4} \quad (10)$$

Equation (77) of chapter 10 in reference [11] is used for calculating σ_p^2 of a spherical wave combining the Eqs.(9) and (2), then the flicker of the loss for different wavelengths λ, distances L, and D_{Rx} can be assessed as shown in Fig.2 and Fig.3:

$$\sigma_{p,sph}^2(D_{Rx})=\exp\left\{\frac{0.2\sigma_R^2}{[1+0.18d^2+0.2(\sigma_R^2)^{6/5}]^{7/6}}+\frac{0.21\sigma_R^2[1+0.24(\sigma_R^2)^{6/5}]^{-5/6}}{1+0.9d^2+0.21d^2(\sigma_R^2)^{6/5}}\right\}-1 \quad (11)$$

With $d=D_{Rx}(\pi/2\lambda L)^{1/2}$.

In Fig.2, it is possible to observe the advantageous behavior of the longer wavelengths in the strong-turbulence state, while for longer distances, the shorter wavelength are favorable because of the stronger aperture averaging (Because longer wavelengths are transmitted over long distances, the aperture size of the scattered light is larger than the shorter wavelength).

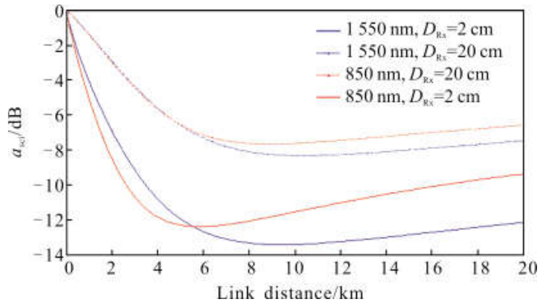

Fig.2 Flicker loss a_{sci} according to link distance L is assumed to be a spherical wave, with the Rx aperture D_{Rx} 2 or 20 cm, wavelength 850 and 1 550 nm as parameters. The IRT intensity is applied by a constant $C_n^2=10^{-14}\ \mathrm{m}^{-2/3}$ for strong near-ground IRT. The fraction of downtime is rather small with p_{thr} 0.001

In Fig.3, it can be seen that the aperture averaging effect is negligible in the case of low turbulence intensity and long-term propagation distance, therefore small and large apertures are similar. Since in this case the flicker saturation is not yet completely achieved, the flicker loss a_{sci} of the shorter wavelength behave advantageous over a long distance range (up to 400 km in this example).

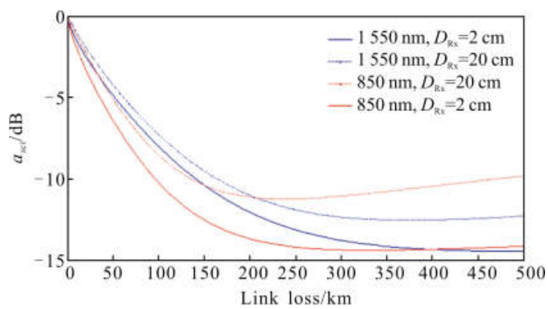

Fig.3 Same as Fig.2, but for a constant $C_n^2=10^{-17}\ \mathrm{m}^{-2/3}$, as can be observed at higher altitudes(more than 3 000 m above ground)

In FSO communication links, the scintillation index and communication distance (together with the aperture diameter of the receiver) are required in order to calculate the a_{sci}. When in the threshold approach, the a_{sci} can be calculated according to Eq.(9). Based on the assumption of lognormal power scintillation after aperture averaging, this formula is valid for general scenarios.

3 Experimental results and analysis

We use the simulated analysis results to design a FSO communication system. It can be seen that the flicker loss a_{sci} is greatly affected by the aperture averaging for strong near-ground IRT according to the simulated result. So the diameter of the receiver is chosen as 20 cm. The distance of FSO link is about 2 km on the surface ground. The physical diagram of the receiver (Newtonian reflector) is shown in Fig.4.

Fig.4 (a) Beam of beacon light emitted from the collimation system, (b) the receiving terminal observes the beacon light of the transmitting terminal at a distance of 2 km, (c) receiver of the FSO communication system whose receiving aperture is 20 cm

The red beacon light was used for optical alignment, at the same time it could observe the surface turbulence. The flicker intensity distribution of the beacon light is shown in Fig.5. The strongest intensity position of the red light has been changed during a very short time because of the strong turbulence. Increasing the receiving aperture of the FSO communication system can effectively suppress the intensity flicker caused by strong turbulence. The results of transmitting HD image are shown in Fig.6.

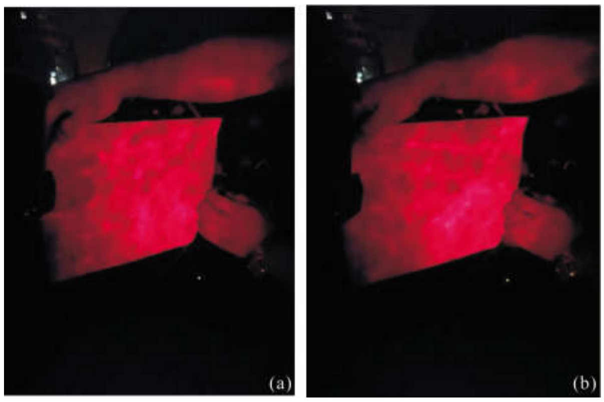

Fig.5 Flicker intensity distribution of the beacon light at different times

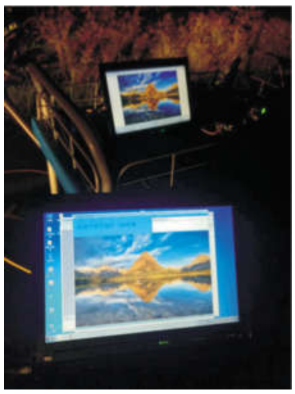

Fig.6 Results of transmitting HD image

In order to assess the quality of the transmitting image, the mean squared error (MSE) and the peak signal to noise rate (PSNR) are introduced. They are followed as:

$$\mathrm{MSE}=\frac{1}{M\times N}\sum_{0\le i\le N}\sum_{0\le j\le M}(f_{ij}-f_{ij}')^2 \tag{12}$$

$$\mathrm{PSNR}=10\times\log\frac{L\times L}{\mathrm{MSE}} \quad (13)$$

Where M and N are the length and width of the image, f_{ij} represents the pixel value of the original image, f_{ij}' represents the pixel value of the image after transmission by the communication system. L is the maximum gray value of the pixels in the image, whose value is generally 255. In the process of communication experiments, we used the computer to read the pixel values of the original image and the pixel values of the transmitted image, and calculate the MSE and PSNR. There are no obvious noises on the transmitting HD image whose PSNR is 38.2 dB (>30 dB).

From Fig.7 it can be seen that the high-definition video stream transmitted by the receiving terminal of the space optical communication system and the video of the 4 G network transmission. The video stream source is the real-time camera 2 km away. In the absence of test instruments such as BER testers, we use the mobile phone′s WeChat video call for image quality comparison. It can be seen from the image of the test results that the high-definition video stream transmitted by the spatial optical communication system has no obvious noise, and compared to the image of the 4 G network transmission (WeChat video), it is clear and has no delay. The space optical communication system has a communication rate of 1 Gbps and supports 1 080 p high-definition video streaming, which is not available in wireless 4 G networks(communication rate is about 100 MHz).

Fig.7 Quality comparison of 2 km, 1 Gbps rate transmission HD video stream transmitted by FSO communication and WeChat video transmitted by 4 G networks

4 Conclusion

In atmospheric FSO links, a direct method for calculating the corresponding scintillation loss a_{sci} is proposed. System model of FSO communications and simulation results of the receiver performance and link-budget loss are also shown in this paper. Then we use the simulated analysis results to design a FSO communication system at a distance of 2 km. It can transmit HD image with no obvious noises. Additionally, it can achieve real-time video transmission with 1 Gbps.

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