Measurement of scintillation and link margin for laser beam propagation on 3.5-km urbanised path

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An experiment of laser propagation was carried out at the urban terrain range of 3.5 km during the period of March to May of 2006. The received intensity scintillations and atmosphere turbulence strength in complex urban atmosphere circumstance were simultaneously measured concentratively. The results show the statistical characteristics of irradiance scintillation and atmosphere turbulence strength and link fade margin for urban free-space optical links.

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In recent years free-space optical communication (FSO) has been grew interest in the telecommunication community. In the former case the FSO is mainly considered for last-mile links in urban areas where the deployment of fiber optics is more expensive and takes far more time for installation. Additional benefits, ranging from lack of spectrum license requirements and immunity to interference with respect to radio-frequency links make FSO particularly appealing[1,2]. However, the FSO performance can be seriously degraded by the cantonal atmospheric turbulence. The experimental and theorical studies on atmospheric scintillation have been conducted[3−8], with purposes of filling gaps in the atmospheric propagation theory. Thus a few measurements have implemented at densely urban terrain. The experiments were carried out on 3.5-km urban path during March — May of 2006 and concentrated on simultaneous measurements of the received intensity scintillations and angle of arrival (AOA).

The experimental setup is shown in Fig. 1. The path travels over a densely urban area and lies approximately 50 m above street level. The transmitter is a single mode (TEM_{00}) solid laser at 0.532 μm with output power of 8 mW. The beam passes through a beam expander (diameters of input and output apertures are 4 and 24 mm, respectively, and multiple of expending is 3) and is transmitted with 2-mm output diameter and 0.725-mrad beam divergence. The receiver antenna is a transmission telescope system, in which diameter of receiving aperture is 6 cm, multiple of magnifying is 20, and field of view (FOV) is 0.065°. The incoming light is firstly filtered by a filter at 0.532 μm with ±5-nm passband width. The received laser is split by a splitter with transmission and reflection ratio 50/50 at 0.532 μm. One beam is focused on avalanche photo diode (APD) after passing through a lens L1 ($f = 78.2$ mm) for measuring scintillation index σ_I^2. The output of APD is sampled at rate of 3000 Hz using analog/data (AD) converter system with dynamic range of 60 dB and is recorded by a computer. The other beam is focused on complementary metal-oxide semiconductor (CMOS) by a lens L2 ($f = 50$ mm). The image centroid coordinate is calculated at a 1000-Hz rate, and the AOA is determined. The refractive index structure parameter C_n^2 is obtained from the variance of AOA as[9]

$$C_n^2 = \frac{\sigma_\alpha^2}{2.914LD^{-1/3}}, \quad (1)$$

where σ_α^2 is the AOA, L is the path length, and D is the receiver diameter. According to maximal pixel grey level of CMOS and statistic mean output of APD, the attenuation ratios of neutral density filters (F1 and F2) and exposal time of CMOS and APD gain are adjusted respectively in order to prevent detector from saturation. A digital weather device is used to monitor the ambient temperature, and relative humidity in the experiment.

The typical scintillation data are shown in Fig. 2. These data are the normalized received signal power (each data normalized by means of data series) of 33 seconds at various scintillation indexes (or refractive index

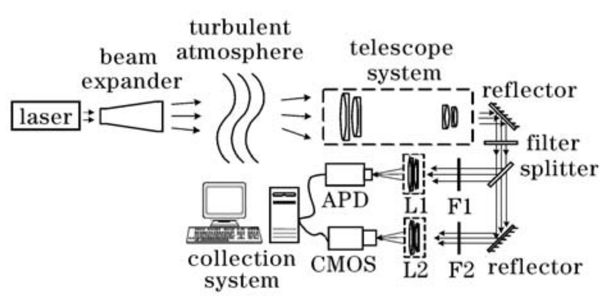

Fig. 1. Experimental setup of free space optical propagation.

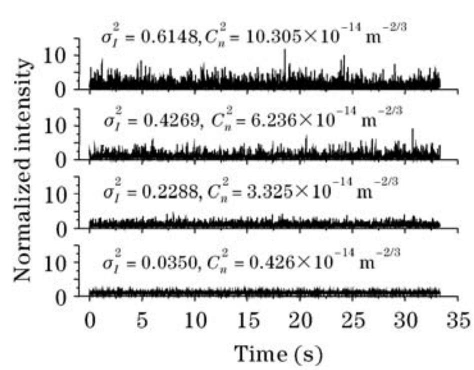

Fig. 2. Time series of normalized received signal power for different scintillation variances.

structure parameters). From it, we can see that the irradiance fluctuations increase with scintillation index and atmosphere turbulence strength. It is noted that scintillation not only can cause data loss due to deep downward fades, but can also increase the received signal strength over the mean value. Over the range of results obtained, deep fades up to 32 dB are recorded with surge values having a maximum value of 10 dB. In the measurement, F1 was adjusted to prevent signal amplitude from overstepping dynamic range of detecting system. However, there are occasionally saturations due to urbanised turbulence complexity.

The probability density functions (PDFs) for different scintillation indexes (and refractive-index structure parameter) are shown in Fig. 3. From it, we can see that, the wider and lower the PDF of intensity is, the greater the signal fluctuations (and atmosphere turbulence strength) is due to scintillation. With scintillation index decreasing, the normalized intensity corresponding to the greatest probability approaches gradually to 1 of mean. Meanwhile the greatest probability decreases and then increases, and the minimum scintillation index equals 0.2288. The intensity fluctuations are nearly log-normal in strong turbulence regime due to aperture averaging.

To better show the scintillation fades, the typical probabilities of fade for different scintillation indexes are presented in Fig. 4. The curves show that the fade probability decreases with threshold increasing, and fade speed of minimum scintillation index is rapider than that of maximum scintillation index. The method to determine

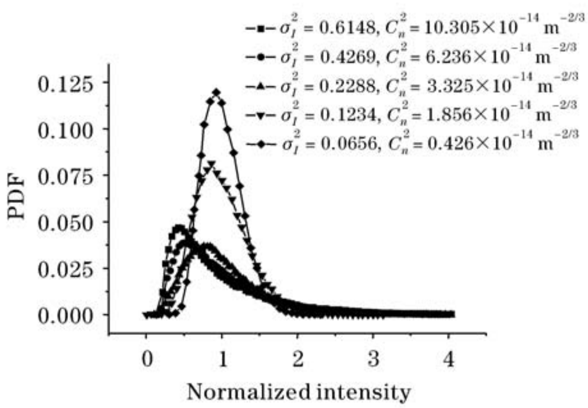

Fig. 3. Probability density function (PDF) of the time series for different scintillation variances.

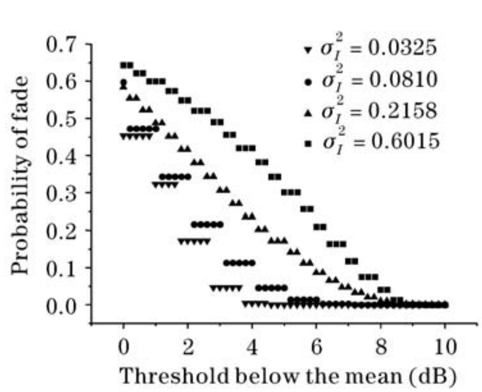

Fig. 4. Probability of fade for different scintillation variances.

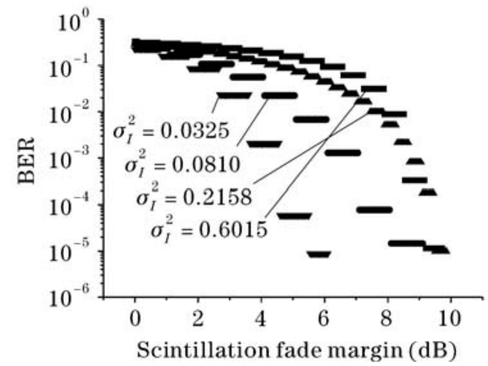

Fig. 5. Scintillation fade margin for different scintillation variances.

the scintillation fade margin is that, the total duration of the fades below that decibel value is calculated for each decibel level below the mean, the bit error ratio (BER) in the fade is assumed to be 0.5 (which is the worst possible case), and the total number of bit errors is then compared to the total number of bits for the complete time series to give a BER for that decibel level. In Fig. 5, it is obvious that more scintillation margin is needed with increasing signal fluctuations to compensate for the fades. The BER decreases to about 10^{-6} at fade margin of 3 dB for scintillation index of 0.035. The scintillation fade margin increases from 7.5 to 8 to 9 dB, as the scintillation index increases from 0.2288 to 0.4269 to 0.6148, for the BER of 10^{-6}. The discreteness of measurement point in the plots is due to limit of data acquisition system resolution.

The mean and variance of each series and C_n^2 as functions of the time are shown in Fig. 6. These data are taken from 2nd to 3th of May 2006. The average wind is 2 m/s, the air temperature is 15 °C, and the relative humidity is 65%. This result agrees with the theory that scintillation is directly related to the difference in air and ground temperatures. During the day from 9:00 to 15:00, the ground heats up and the differential between ground and air temperatures creates the turbulence in the air and thus the scintillation. At other time, the ground and air temperatures are approximately equal and thus reducing air turbulence and scintillation. Experimental results have also shown that the stronger turbulence and scintillation occur occasionally in the evening and the statistics of the scintillation intensity does not present

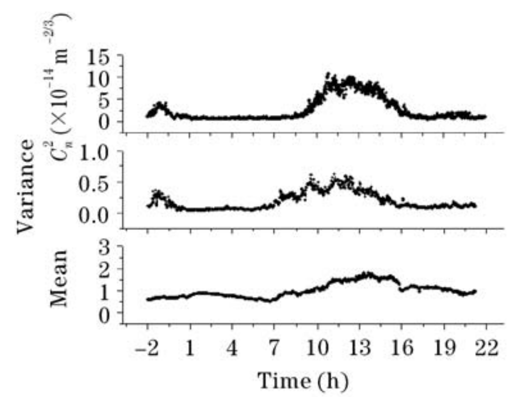

Fig. 6. Mean and variance of scintillation and C_n^2 over a day.

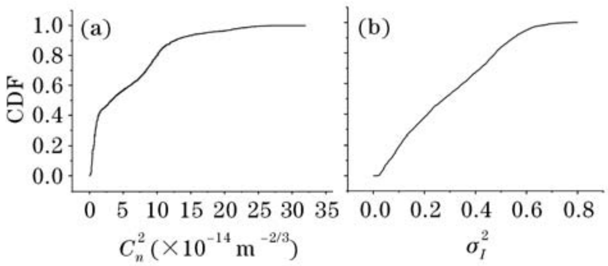

Fig. 7. (a) Refractive-index structure parameter distribution and (b) scintillation-index distribution over all measurements.

a strong diurnal cycle at some day. This is due to the wind burst movement and roughness elements effects on air turbulence. The flow increases the turbulence and scintillation at night.

The cumulative distribution function (CDF) of C_n^2 and σ_I^2 over all measurements (except for rain, fog, and snow) are shown in Fig. 7. The mean of C_n^2 observed is 5.4902×10^{-14} m$^{-2/3}$, the maximum is 3.1981×10^{-13} m$^{-2/3}$, and the minimum is 4.2641×10^{-16} m$^{-2/3}$. The C_n^2 above 10^{-14} m$^{-2/3}$ accounts for 67.2%, and so the atmosphere over urban areas is mostly strong turbulence. The mean of σ_I^2 observed is 0.2954, the maximum is 0.7791, and the minimum is 0.0155.

Extensive research on the laser atmospheric propagation over densely urbanised terrain has been conducted during March — May of 2006. Among the results obtained, the atmosphere in urban areas is usually the strong turbulence regime. The irradiance fluctuation is the strong function of the time of day and ambient wind. With aperture averaging, the scintillation index range from 0.0155 to 0.7791, and the PDF of received intensity is close to log-normal. The link margin of 10 dB is enough for 3.5-km urbanised link with a 6-cm receive aperture to maintain a BER of 10^{-6}.

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