Research of diversity receiving in wireless laser communications*

KE Xi-zheng (柯熙政)** **and ZHANG Tong** (张彤)
The Faculty of Automation & Information Engineering, Xi'an University of Technology, Xi'an 710048, China

(Received 4 May 2014)

Based on aperture averaging effects on scintillation, a diversity reception system consisting of three apertures has been designed. The transmitted laser beam (λ=1.06 μm) propagates for 3 km, and is received through apertures with different sizes. Various numbers and configurations of apertures are studied to investigate the received laser beam's spatial profile and quality. Our results show that the diversity reception system with three apertures can suppress atmospheric scintillation with relatively simple configuration and low cost.
Document code: A **Article ID:** 1673-1905(2014)04-0285-5
DOI 10.1007/s11801-014-4072-0

Optical signals disturbed by turbulent effects in wireless laser communication can seriously influence the communication stability and reliability. The receiving spot images are always polluted by kinds of noises. In order to effectively achieve the real spot information, we need to remove the noises[1]. Ref.[2] employed the multi-resolution analysis to remove noises. Ref.[3] proposed image reducing noise of wavelet contraction threshold based on Bayesian estimation. This method can enhance peak signal-to-noise ratio (SNR) and reduce centroidal deviation. Ref.[4] proposed a wavelet transformation combined with math morphology. In order to reduce the fading effect on optical communication, we can exploit diversity that the least correlation signals with the same information are received at multiple receivers synchronously and then they are converged to output[5-9]. Ref.[10] proposed a space diversity reception structure based on single-input multi-output orthogonal frequency division multiplexing (OFDM) system, which lowered the system complexity and power consumption. There are also several other reports about diversity receiving[11-15].

Based on a series of laser spot data collecting experiments in far field, combined with laser transmission characteristics in turbulent atmosphere and smooth effect principle of alignment receiving aperture, a ternary diversity receiving algorithm consisting of 3 detectors is proposed in this paper. In addition, a test is made for collecting laser facula data within out-field 3 km, and then the relation between scintillation index and time is studied in diversity reception of different aperture dimensions, including 2 detectors, 3 detectors, 4 detectors and a single small detector.

In inclined transmission path, C_n^2, the structure constant of atmosphere refractive index of atmospheric turbulence intensity, is uneven and related with factors of wind speed, temperature and air pressure. The H-V atmosphere structure constant model is

$$C_n^2(h) = 8.148\times10^{-56} v_{\mathrm{RMS}}^2 h^{10} \mathrm{e}^{-h/1\,000} + 2.7\times10^{-16} \mathrm{e}^{-h/1\,500} + C_{n0}^2 \mathrm{e}^{-h/100} , \tag{1}$$

where h is altitude, C_{n0}^2 is atmosphere structure constant near the ground whose typical value is 1.7×10^{-14} $\mathrm{m}^{-2/3}$, $v_{\mathrm{RMS}} = \sqrt{v_{\mathrm{g}}^2 + 30.69 v_{\mathrm{g}} + 348.91}$ is root-mean-square wind speed in the vertical path, and v_g is wind speed near the ground and its approximation is 2.8 m/s.

Atmospheric turbulence movement results in uneven fluctuation of refractivity and optical intensity fluctuation within the channel. The main characteristic of strength index of optical intensity is the optical intensity flashing variance:

$$\sigma_{\ln I}^2 = <(\ln(I/I_0) - <\ln(I/I_0)>)^2> , \tag{2}$$

where $\ln I/I_0$ is logarithm value of the instant optical intensity and $<\ln I/I_0>$ is logarithm value of the average optical intensity. Kolmogorov spectrum is used to analyze transmission distance L of plain wave in the turbulent atmosphere, optical intensity flashing variance is derived in the wake fluctuation field under Rytov ap-

* This work has been supported by the National Natural Science Foundation of China (Nos.61377080 and 60977054), Shaanxi Province "13115" Science and Technology Planning Support (No.2011KTCQ01-31), Education Department of Shaanxi Province Industrialization Development Fund (No.2010JC17), Xi'an Science and Technology Achievement Transformation Fund (No.CX12165), Project Supported by Natural Science Basic Research Plan in Shaanxi Province of China (No.2013JQ8011), Scientific Research Program Funded by Shaanxi Provincial Education Department (No.2013JK1104), and Technology Projects of Industrial Research of Shaanxi Province (No.2013K06-08).
** E-mail:xzke@263.net

proximation and C_n^2 is constant:

$$\sigma_{\ln I}^2 = 8\pi^2 k^2 \int_0^L \int_0^\infty K\phi_n(K)[1-\cos(\frac{K^2 z}{k})\mathrm{d}K\mathrm{d}z =$$

$$1.06\sigma_1^2 \int_0^1 \int_0^\infty \eta^{-11/6}(1-\cos\eta\varepsilon)\mathrm{d}\varepsilon\mathrm{d}\eta , \quad (3)$$

where k is wave number, $K = 2\pi / l$, l is the scale of turbulent cell, $\phi_n(K)$ is power spectrum density, $\phi_n(K) = 0.033C_n^2 K^{-11/3} G(K, l_0)$, $G(K, l_0)$ is function combination of low-pass and high-pass filtering, l_0 is turbulence endo-scale, $\varepsilon = z / L$ and $\eta = LK^2 / k$ are dimensionless measures, and σ_1^2 is Rytov variance, $\sigma_1^2 << 1$.

Under spherical wave transmission and Rytov approximation, when spherical wave transmission distance is equal to L within wake and strong fluctuation media, the optical intensity flashing variance is:

$$\sigma_{\ln I}^2 = 8\pi^2 k^2 \int_0^L \int_0^\infty K\phi_n(K)\{1-\cos[\frac{K^2 z}{k}(1-\frac{z}{L})]\}\mathrm{d}K\mathrm{d}z =$$

$$1.06\sigma_1^2 \int_0^1 \int_0^\infty \eta^{-11/6}\{1-\cos[\eta\varepsilon(1-\varepsilon)]\}\mathrm{d}\eta\mathrm{d}\varepsilon . \quad (4)$$

Based on Markov approximation, theoretical model of receiving optical intensity fluctuation is obtained as laser transmits in atmosphere[16] . Within the approximation of infinitesimal aperture, when Gaussian laser transmits in atmosphere under the consideration of atmospheric turbulence endo-scale and external scale, the optical intensity flashing variance will be

$$\sigma_{\ln I}^2 = 2.24k^{7/6}\sec^{11/6}(\theta)\int_0^L C_n^2(L)L^{5/6}\mathrm{d}L , \quad (5)$$

where θ is the zenith angle.

We employ random process analysis to get the relationship between system BER and optical intensity fluctuation[17]:

$$BER = \frac{1}{2}[\mathrm{erfc}(\frac{4}{\sqrt{2\sigma_{\ln I}^2}})] = \frac{1}{2}[\frac{4}{\sqrt{2}\times 1.24C_n^2 k^{7/6} L^{11/6}}] . \quad (6)$$

When exposure length is equal to τ , the optical intensity of spot signal can be denoted as[18]:

$$I = \int_{-\infty}^{+\infty} g(t,\tau) I_0(t)\mathrm{d}t , \quad (7)$$

where $I_0(t)$ is the optical intensity of signal when exposure length is $t \to 0$, $g(t,\tau) = \begin{cases} 1/\tau, & |t| \le \tau/2 \\ 0, & |t| > \tau/2 \end{cases}$.

The optical flashing aperture smooth factor G is defined as

$$G = \frac{16}{\pi D^2}\int_0^D \frac{C_I(\rho)}{C_I(0)}\left[\arccos\left(\frac{\rho}{D}\right) - \frac{\rho}{D}\left(1-\frac{\rho^2}{D^2}\right)^{1/2}\right]\rho\mathrm{d}\rho , \quad (8)$$

where $C_I(\rho)$ is covariance function of optical intensity, $C_I(0)$ is optical intensity variance, and ρ is atmosphere coherent length. For small endo-scale, the aperture smooth factor can be approximately written as:

$$G = \left[1 + 1.07\left(\frac{kD^2}{4L}\right)^{7/6}\right]^{-1} . \quad (9)$$

While on big endo-scale, the aperture smooth factor can be approximately written as[19]:

$$G = \left[1 + 2.21\left(\frac{D}{l_0}\right)^{7/3}\right]^{-1} . \quad (10)$$

The aperture smooth factor of spheric wave can be obtained combining power spectrum density function $\phi_n(K)$ and interpolation relation of aperture smooth factor as

$$G = 1 + [1 + (2.043\sigma_s^2(0)^{3/7})(kD_0^2 / 4L)^{1/2}]^{-7/3} , \quad (11)$$

where $\sigma_s^2(0)$ is spheric wave intensity considering turbulence external scale influence.

Generally speaking, we need to consider speckle size of receiving plain and aperture smooth effect of optic receiving antenna. The differences between the speckle and the aperture size will result in different smooth or integral effects. When the reception aperture size is much smaller than the speckle coherence area, the receiver can keep the statistical properties of the original speckle. If the receiving aperture is big enough, and the aperture contains m incoherent scattering cells, the probability density function of integral optical intensity is[20]:

$$P(I_s) \approx \left[\frac{mn}{I_s}\right]^{mn} \frac{I_s^{(mn-1)}\exp(mnI_s / \langle I_s \rangle)}{\Gamma(mn)} , \ I_s \ge 0 , \quad (12)$$

where $\langle I_s \rangle$ is average optical intensity and I_s is integral optical intensity. For finite receiving aperture, the real optical power at receiver is statistic average of accumulated optical intensity within plain field of receiving aperture, so $I_s = \iint_R a_r(x,y)I(x,y)\mathrm{d}x\mathrm{d}y$, where $a_r(x,y)$ is weight function of receiving aperture, and $I(x,y)$ is instantly accumulated optical intensity of n-beam laser on the (x,y) within plain field of receiving aperture.

In order to achieve high speed data transmission and overcome flashing effect on communication, the multipath diversity receiving way is used. This system can reduce environmental optical noise and multi-path distortion due to little main signal delay light in each unit, which can receive signals with different directions and different strengths. Single pulse energy E_r received by detector can be denoted as:

$$E_r = E_p(A/S)\gamma L_a L_c L_{aw} L_w T f(\phi_r) , \quad (13)$$

where E_p is the single pulse energy from laser, A is the area of reception optic antenna, S is the spot area at receiving point, γ is the transmissivity of transmitter's optic system, L_a is transmissivity of atmosphere molecule scattering, L_c is cloud layer transmissivity, L_{aw} is interface transmissivity of energy, L_w is transmissivity of downward irradiance, T is the optic receiving system and light filter transmissivity, and ϕ_r is the field of view.

Known from space diversity theory, the number of detector array units is related to the improvement extent of composite signal. At the same time, we need to consider the distance between the structure of detector array unit and array unit in order to realize incoherent transmission. The distance between arbitrary two transmitting apertures should satisfy:

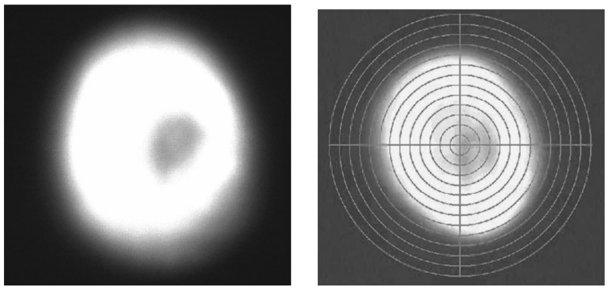
$$\sqrt{\lambda L} < r < \theta L , \qquad (14)$$

where θ is divergence angle, λ is wavelength, and L is transmission distance. When $\lambda = 1\,550$ nm and L=1 km, r=4 cm. It illustrates that the optical interference phenomenon can be avoided only if $r \geq 4$ cm .

The high-power 1.06 μm YAG crystal encoding laser is used in the experiment. Half power point and full duration of laser pulse is 10±2 ns. Pulse energy is not smaller than 400 mJ. Laser beam divergence is not bigger than 0.7 mrad and collimating beam diameter is not bigger than 9 mm. In external field within 3 km, the diversity receiving array consisting of detectors is placed at the point which has different distances away from laser and spot collecting assembly. Laser beam is formed as spot at receiver, the diameter of which is about 20 cm at 3 km away. The experiment takes kilomega high-speed interface CCD which can respond to 1.06 μm to collect spots.

The experiments based on single-aperture receiver system are carried out within 3 km in the far field at different moments during day and evening sections respectively. Every time, laser is used to irradiate receivers at different distances, and the spot image collected would be used for statistical calculation. It is found that the spot in the 3 km has the saturation phenomenon. With the increase of temperature and atmospheric turbulence, the effective scattering size of the turbulence decreases, which leads to the reduce of the effective scattering area, while the small scale of the scattering region increases, the coherence of the beam space deteriorates, the beam spreading increases, and the speckle duty cycle decreases.

Deriving from 990 frames of spots data with the proposed algorithm, we can get the optical intensity flashing variance tendency under different apertures within 0—200 mm (Fig.2). We can see that with the size of receiving aperture varying, the optical intensity has a uniform distribution. When the size is 40 mm, the optical intensity flashing variance is maximum of 7.360 3. With the increase of the aperture size, the variance begins to decrease. The flashing variance triggered by the flash of atmospheric turbulence is similar to an inverse square law, because of the nonlinear relationship between the receiving aperture and the flashing variance. We must optimize the receiving aperture to effectively overcome the influence of flashing on the spot receiving. Meanwhile, the research found that the optical intensity flashing variance with weak fluctuation is hardly influenced by external scale, while in strong turbulent field, the difference of optical intensity flashing variance is obvious, so we need to consider the influence on optical intensity variance by external scale.



(a) (b)

Fig.1 (a) Experimental spot received at 3 km; (b) Receiving process for the spot with different apertures

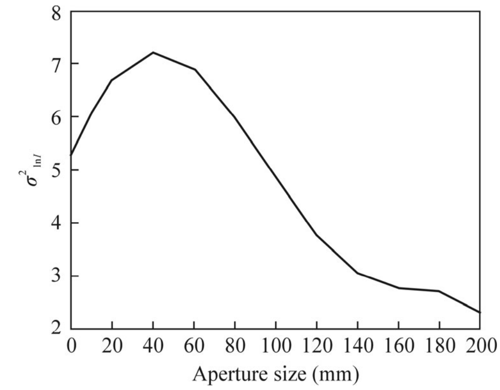
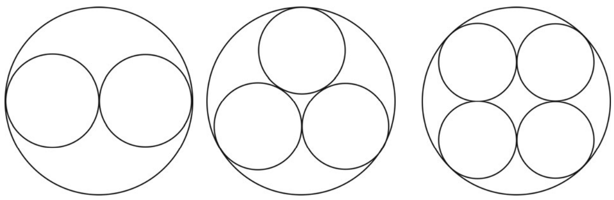


Fig.2 Optical flashing variance versus aperture size at a distance of 3 km

Based on diversity aperture laser receiving theory, we process the laser spot by changing the size of the receiving aperture. We select the key part from the whole spot, and then a standard circle exists. We divide it into 2-slice circle, 3-slice circle and 4-slice circle as shown in Fig.3, in order to design different aperture diversity receiving schemes.



(a) 2-slice circle (b) 3-slice circle (c) 4-slice circle

Fig.3 Diversity receiving schemes with different apertures

The experimental design of long-distance optical signal 3-aperture diversity reception system is shown in Fig.4.

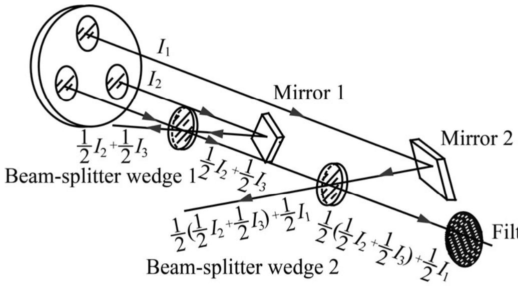


Fig.4 The experimental design of the long-distance optical signal 3-aperture diversity reception system

The focal length of the 3-aperture diversity reception system is 800 mm. Based on the above principle, the experimental setup of the long-distance optical signal 3-aperture diversity reception system is shown in Fig.5.

Fig.5 The experimental setup of the long-distance optical signal 3-aperture diversity reception system

We conduct experiments for small apertures with different aperture sizes ranging from 20 mm to 100 mm in each diversity scheme. In Fig.6, a, b and c represent 3 different small aperture units in the 3-aperture diversity receiving system, respectively.

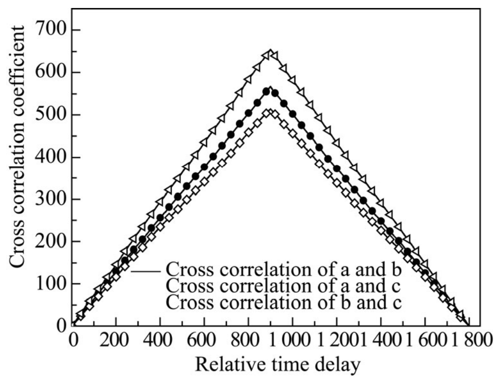


Fig.6 Correlation calculation results of aperture optical intensity distributions of spot time sequence 3-aperture diversity receiving

It is seen from Fig.6 that at the same delay, the cross-correlation function of different apertures has a maximum, and the whole curve presents symmetry about the maximum. In the experiment, when we adjust the distances between different apertures, the optical intensity distribution coherence of receiving spot of different apertures would reduce, thus meeting the incoherence addition. At the same time, the fluctuation variance of random noise in the signal would decrease with optical signal strengthening, which indicates that the spot data collected from 3-aperture diversity receiving system at different distances are hardly influenced by atmosphere environment.

Under different aperture receiving schemes, 5 small aperture optical intensity flashing variances with different aperture diversity receiving time sequences are calculated and shown in Fig.7.

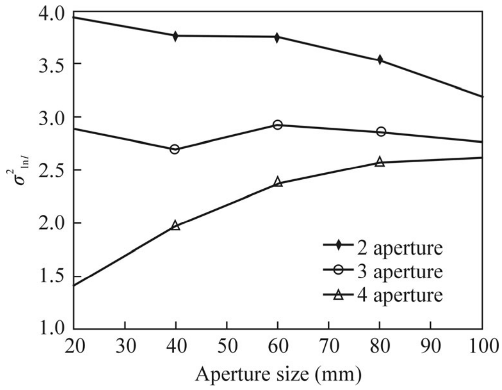


Fig.7 5 small aperture optical intensity flashing variances with different aperture diversity receiving time sequences

Generally speaking, the larger the receiver aperture size, the better the receiving result. However, when the receiver aperture size increases beyond a certain value, the optical power fluctuation will not continue to obviously reduce with aperture size increasing[21]. In addition, due to the limit of optic system price and structure, the receiver aperture size should not be too large. Fig.7 shows that the optical intensity flashing variance change of the 3-aperture diversity receiving scheme is steady with aperture size changing.

In the experiment, we use the 3-aperture diversity receiving system to collect 990 frames of optical spot data. The optical intensity distribution curves of unique small aperture with different aperture sizes ranging from 20 mm to 100 mm in the 3-aperture diversity receiving system are shown in Fig.8, from which we can see that the

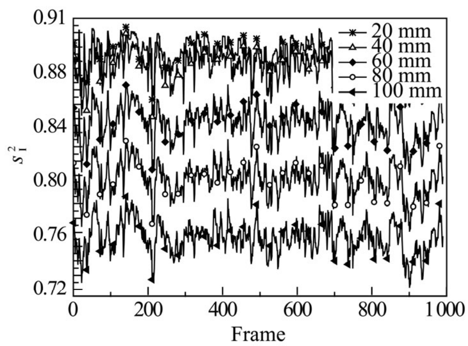


Fig.8 Optical intensity distribution curves of unique small aperture with different aperture sizes in the 3-aperture diversity receiving system

optical intensity distribution change of the 3-aperture diversity receiving scheme is steady, which denotes that the atmosphere turbulence flashing effect is suppressed obviously.

Based on finite aperture receiving optical intensity fluctuation variance model and diversity receiving techniques, this paper proposes the 3-aperture diversity receiving scheme in wireless optical communication. The experimental results show that in the 3-aperture diversity receiving system, 5 different small aperture optical intensity flashing variances have a normal distribution with time changing. The optical signal ternary diversity receiving system can effectively suppress flashing effect induced by atmosphere turbulence and reduce flashing optical intensity fluctuation variance. Compared with the traditional method of enlarging receiving antenna aperture, the ternary diversity receiving system can improve the quality of communication devices, reduce cost of receiving system as well as effectively overcome aperture smooth effect on optical communication.

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