Influence of space between atmospheric channels and beams' number on scintillation

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On the basis of Kolmogorov's theorem, the physical meanings of beams' correlation function on received plane are extended. Approximate formula of channels' across correlation coefficient is deduced from multiple beams through atmosphere. And the scintillation variance of multiple beams is also induced. The result shows along with the channels close to one another, the correlation coefficient increases, and so does the scintillation variance. When the channels completely combine, the scintillation variance of multiple channels is with no difference from that of one channel.

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In recent years, near-ground atmospheric laser communication is becoming a popular subject of research for another time. Research on "last-mile access" is being commercialized and put into primary utilization. Compared to other methods of communication, atmospheric communication has some advantages: low cost for installation, good secrecy, good flexibility, and high data rates, etc. But it is more subject to influence of atmosphere than other communication methods. In addition to decrease of channel caused by atmospheric aerosol, atmospheric turbulence also exerts some influence on the channel, which can be seen in terms of atmospheric scintillation, beam wandering, beam spreading and the angle of arrival fluctuation, etc. To reduce the influence of atmospheric turbulence, some optical communication products adopt multiple aperture launching, that is, multiple beam is adopted to reduce the attenuation of atmospheric turbulence so as to improve the quality of communication. The American company AstroTerra has ever done experiments on near-ground atmospheric communication for aperture of 1, 2, 4, 8 and 16 and in this way the normalized scintillation variance is reduced to $3 - 8$ dB[1]. But this experiment can only be made under the condition of multiple beams outside of all halo, that is, it can only be made under the supposition that there is no correlation between light beams. It has been proved by theory and experiment[2−4] that for the correlation of the atmospheric turbulence, the amplitude fluctuations of all the beams also have correlation on the receiving surface, and at the same time, because there are always some overlap parts for the channels in practical communication, the influence of atmospheric turbulence on all light beams cannot be seen as independent completely. Because there are few reports in the present literatures on the theoretical research of multi-beam atmospheric communication, it is necessary to make some analysis on the correlation between channels.

To a communicative system, divergent angle of launched beams cannot be too small so as to ensure that the receivers will be in the range of launched beams. When beams reach the receiving plane, the size of speckle is usually much larger than that of receiving aperture. So it is feasible to utilize approximate plane-wave. To a beam, through weak turbulence according to Kolmogorov, it is only necessary to take consideration of

$\sqrt{\lambda L} \gg l_0$ (which is always true in practice). After the beam goes through a distance of L, normalized correlation function of logarithm amplitude fluctuation on receiving surface will be[2]

$$B(r, L) = \frac{\int_0^\infty J_0\left(\frac{1}{r}\sqrt{\frac{xk}{L}}\right)(1 - \sin x/x)x^{-4/3}\mathrm{d}x}{\int_0^\infty (1 - \sin x/x)x^{-4/3}\mathrm{d}x}, \quad (1)$$

where r refers to the space between two points on receiving plane, k is the amount of wave, and $J_0\left(\frac{1}{r}\sqrt{\frac{xk}{L}}\right)$ is the zero order Bessel function. In the system of communication, beams transmitted by all apertures are parallel. If the space between beams is r and the space between the corresponding speckles is also r (see Fig. 1), the space of r between two points reflects the correlation of the fluctuation of the respective speckle. So in Eq. (1), r can be seen as the space of transmitter apertures. Taking $r/\sqrt{\lambda L}$ as X-coordinate and drawing the correlation function $B(r, L)$, we can get Fig. 2.

Figure 2 shows the variation of correlation function with the changing of r and L. When $r/\sqrt{\lambda L} = 0.54$, $B(r, L) = 0$. If r_0 is defined as correlate distance, it bears the scale of $\sqrt{\lambda L}$. When $\lambda = 780$ nm, $B(r, L) = 0$, r_0 is about 6 cm. The existence of negative value area shows that for any two points which hold a space of Fresnel, in sense of mean value, when one of the two points is in the area which is brighter than the mean value, the other one
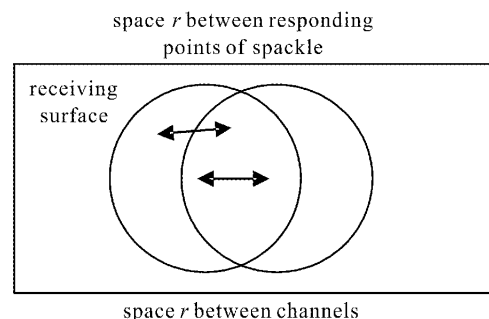

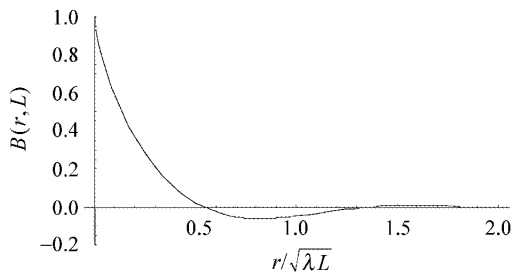Fig. 1. Space of channel and the relationship of the responding points.

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Fig. 2. Relationship of relevant function $B(r, L)$ and $r/\sqrt{\lambda L}$.

will be in the area less bright, *vice versa*[2]. When the space between two atmospheric channels $r < r_0$, logarithm amplitude bears some correlation; when $r > r_0$, the variation of logarithm amplitude is not similar and even there is nearly no correlation.

In Ref. [1], the relationship between scintillation variance σ_x^2 and transmission distance L is shown as

$$\sigma_x^2 = 4 \times 0.124 C_n^2 L^{11/6} k^{7/6}. \tag{2}$$

If the space of atmospheric channel $r \gg r_0$, considering laser consisting of n beams which have the same parameters irradiates on an extended objective, average intensity fluctuation of every beam is $\tilde{I}$. The average intensity fluctuation of n beams on the screen is

$$\tilde{I}_{cn} = \frac{1}{n} \sum_{i=1}^{n} \tilde{I}_i, \tag{3}$$

where $\tilde{I}_{cn}$ is the average intensity fluctuation of n beams, $\tilde{I}_i$ is the average intensity fluctuation of every beam. If n beams are uncorrelated, the logarithm amplitude fluctuation of n beams on receiving surface is uncorrelated, and scintillation variance after overlap is[5]

$$\sigma_{xn}^2 = \frac{1}{n} \sigma_x^2, \tag{4}$$

where σ_x^2 is scintillation variance of one beam, σ_{xn}^2 is scintillation variance of n beams. If the flexibility of equipment and the real size of detector are taken into consideration, the probability of irrelevancy of beams is very little and the influence of correlation between beams on scintillation fluctuation must be taken into consideration. We suppose that the space between the beams is equal and distributed symmetrically for simplified analysis, the scintillation variance after overlap is

$$\sigma_{xn}^2 = \frac{1}{n}(1 - \gamma)\sigma_x^2 + \gamma\sigma_x^2. \tag{5}$$

The first part of the right of Eq. (4) represents the scintillation fluctuation caused by uncorrected proportions. In Eq. (5), γ is actually $B(r, L)$, the latter part represents the parts caused by the correlation between beams. From Eq. (5), it can be seen that scintillation variance will decrease with the increase of n. However, when beams are completely correlated, that is, $\gamma = 1$, the scintillation variance of beams is the same to that of single beam light.

Figure 3 shows the variation of scintillation variance

on receiving surface with the changing of transmission distance L and channels space r after the four beams go through their respective channels. It shows that with the accretion of transmission distance, scintillation variance will be larger; when channels space is larger, the possibility for all beams to go through the same atmospheric turbulence will be lower and the correlation of channels will decrease, which will improve the probability of inter-compensation among beams, and at the same time, scintillation fluctuation on receiving surface will be smaller.

Figure 4 shows the variation of scintillation variance on receiving surface with the change of launched beams amount and transmission distance when the value of channel space is defined as 5 cm. It can be seen that when atmosphere is static and space of aperture is certain, adoption of multi-aperture launching will reduce the scintillation fluctuation. The more apertures, the more significantly the scintillation will decrease, which is the same to the conclusion drawn in the experiment of Ref. [1]. In practical utilization, the flexibility and miniaturization of equipment should be taken into consideration and the amount of apertures can not increase infinitively.

Figure 5 shows the variation of scintillation variance with the change of channel space r and amount of aperture r when the value of transmission distance is 5000 m. It can be seen in the figure that for the influence of the
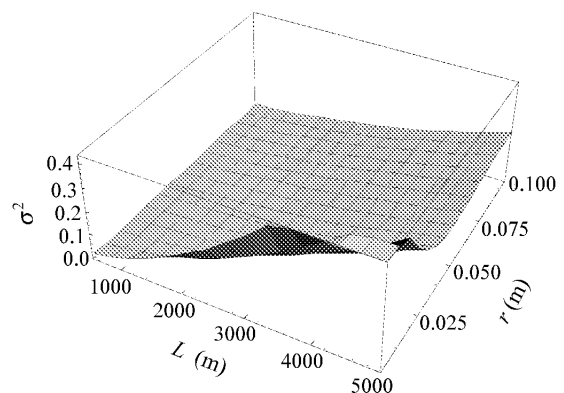

Fig. 3. Curve of scintillation variance and transmission distance L and channel space r with four channels.
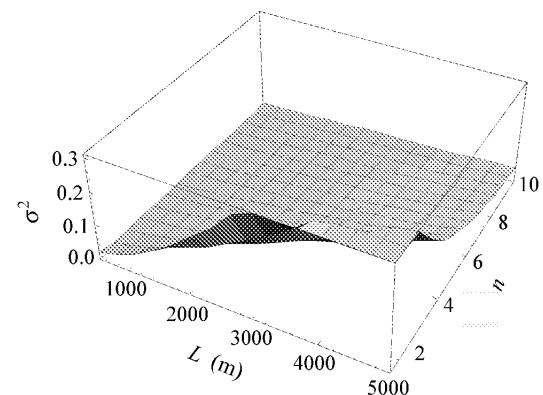

Fig. 4. Curve of scintillation variance with the changing of the amount of aperture n and transmission distance L when channel space $r = 0.05$.
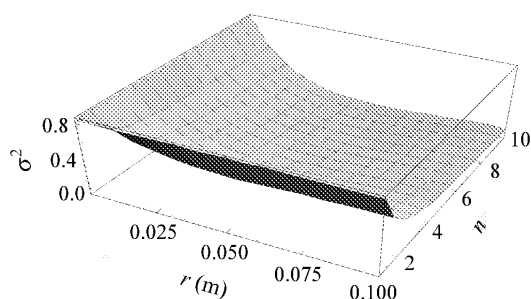
Fig. 5. Variation of scintillation variance with the changing of the amount of launching apertures and channel space.

amount of apertures and channels space on scintillation on receiving surface, with the consideration of capability of equipment, to optimize the received information, it is better for the amount of aperture to be 4 − 6 and the channel space 5 − 8 m.

In this paper, we deduce the approximate correlation coefficient of channels for multi-beam in atmospheric communication under the supposition of average statis-

tics. A primary analysis and calculation on the scintillation variance on receiving plane is made, and the result drawn in our experiment is similar to that of Kim's[1]. In later research, analysis and study will be done on beam wave which is expected to provide reference for the application of multi-aperture free space optical communication.

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