Fast wave front correction method of reception diversity laser communication based on the analysis of distorted wave front of different receivers

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Abstract. Reception diversity laser communication can improve the channel capacity as well as weaken light intensity scintillation caused by atmospheric turbulence. However, it can’t reduce the wave front distortion. Wave front distortion is usually corrected by adaptive optics system, because that reception diversity laser communication has more than one receiver, it would take much more time as well as resources to correct the distortion of different receivers. Based on the analysis of wave front distortion of different receivers, we set the best correcting voltage of one receiver as the initial correcting voltage of the other receiver, it can be concluded from the simulation that using the method we propose need less iteration times than the traditional methods when achieving same correcting effect and it can also achieve higher correcting effect when setting same iteration times.

1. Introduction
Compared with traditional communication way, free space optical (FSO) communication has many advantages including wide bandwidth, high confidentiality, cost effectiveness, high data rates[1-3]. As the optical signal transmits in the atmospheric, the quality of the communication such as channel capacity and received signal-to-noise ratio(SNR) may be degraded because of intensity scintillation as well as phase distortion[4] caused by atmospheric turbulence.

Reception diversity is an important way to improve the quality of laser communication, it can not only improve the channel capacity without widening spectrum range or increasing transmitted power, but also weaken light intensity scintillation [5-6]. However, reception diversity can’t reduce the wave front phase distortion, and there is no research about the wave front phase distortion of reception diversity laser communication.

Wave front distortion can be corrected through wave front senseless adaptive optics (AO) system, but when it’s used to correct the distortion of reception diversity laser communication, correcting speed would be slow because it has more than one receiver, and it would also consume more resource. So the paper proposed a new method to correct the wave front distortion of reception diversity laser communication quickly based on the analysis of wave front characteristics.

The paper is organized as follows: In section 2, system model is shown. The characteristics of distorted wave front are analyzed in section 3. In section 4, a new method is proposed to correct the
wave front distortion according to the characteristic of the wave front. And the simulating results are shown in section 5. The conclusions are concluded in section 6.

2. System model
Reception diversity is an important way to improve the quality of FSO communication, the more the receivers are, the better the communication quality. But when the number of receivers is up to a certain value, with the increase of receivers’ number, the improvement of communication quality would be inconspicuous. At the same time, the more receivers would lead to higher cost. In this paper, reception diversity laser communication system with two receivers is taken as the example to analyze.

The schematic diagram of reception diversity laser communication system with two receivers is shown in the Fig.1, within the scope of the dashed line is the simulation area of the phase screen, d is the distance of the adjacent receiver, L_x, L_y is the simulation size of the phase screen, and we define the radius of the receiver is a.

Wave front distortion is corrected through deformable mirror (DM)[7], in this letter, we use 32-element to correct the phase distortion. The layout of 32-element DM actuators is shown in Fig.2.

The influence function of DM can be described as[7]:

\[ S_j(x, y) = \exp \left\{ \frac{1}{d} \ln \frac{1}{\sqrt{(x - x_j)^2 + (y - y_j)^2} + \omega} \right\} \]

where \((x_j, y_j)\) is the position coordinates of jth actuator, \(\omega\) is the coupling coefficient which defined as the ratio of the surrounding actuators center deformation value to the maximum deformation value of the working actuator. \(d\) is the interval of the actuators. The phase compensated by DM[7] is

\[ u(x, y) = \sum_{j=1}^{32} v_j S_j(x, y) \]

where \(v_j\) is the controlling voltage of the jth actuator.
3. The analysis of distorted wave front corresponding to different receivers

The atmospheric turbulence is formed of many vortexes of a certain scale[8], which we call outer scale. When the distance of two points is shorter than the outer scale, the atmospheric turbulence has correlation, so the wave front distortion caused by atmospheric turbulence of the two receiving areas also has certain relationship. In order to figure out the relationship of wave front distortion of different receivers, the phase screen used to simulate the phase distortion caused by atmospheric turbulence is generated through power spectrum inversion[9] and low frequency compensation[10]. We take modified von-Karman power spectrum[11] as atmospheric turbulence power spectrum, in this paper, we mainly consider the influence of atmospheric turbulence outer scale to the correlation of two receiving areas, so we set $l_0 = 0$.

Traditionally speaking, the distance between the receivers is shorter than outer scale, the atmospheric turbulence of different receivers has correlation with others, so the phase screens of different receivers shouldn’t be generated independently. We generate the the phase screen of the area surrounded by the receivers, then we choose part of the generated phase screen to analyze the characteristic of the phase screens of the receivers.

Assuming that there exists a beam in the middle of the two beams, and its’ tilt angle is $\varphi_0$ , We firstly generate a phase screen corresponding to reception diversity laser communication system, and the phase screens of the receiving areas are the two corners of the system’s phase screen. Considering the the tilt angle of the optical signals arriving at different receivers are different from each other, the phase screens need to be modified. From the equations of generating phase screen[8-9], we can draw a conclusion that the phase distortion has positive correlation with the square root of $\sec(\frac{\pi}{2} - \varphi)$, so the phase screen can be modified through multiplying $\sqrt{\sec(\frac{\pi}{2} - \varphi_0) / \sec(\frac{\pi}{2} - \varphi)}$.

We define the correlation coefficient between two phase vectors $x_1$ and $x_2$—the mth columns of two phase screens as follows:

$$ r_{nm} = \left\langle \frac{\sum_{i=1}^{n} (x_{1i} - \bar{x}_1)(x_{2i} - \bar{x}_2)}{\sqrt{\sum_{i=1}^{n} (x_{1i} - \bar{x}_1)^2} \sqrt{\sum_{i=1}^{n} (x_{2i} - \bar{x}_2)^2}} \right\rangle \tag{3} $$

Where, $\langle \rangle$ means ensemble average, n is the row number, and then we define the correlation coefficient of two phase screens is the average of correlation coefficient between phase vectors in corresponding position : $r = \frac{\sum r_{nm}}{n}$

In this paper, we generate a phase screen of reception diversity laser communication system with 512x64 sample points, and we set d/a=14, which means that the size of the phase screen of the receiver is 64x64. Fig.3 shows the correlation coefficient of the phase screens of different receivers, and we can find that the correlation coefficient gets larger with the increase of the outer scale of atmospheric turbulence.
Fig. 3. The correlation coefficient of the phase screens of different receivers in the average of 1000 times calculation.

We also compare the correlation coefficient of the phase screens of different receivers in different atmospheric turbulence coherence length $r_0$. From the Figure 4, we can get the conclusion that the coherence length of atmospheric turbulence has little influence on the correlation coefficient.

Fig. 4. The correlation coefficient of the phase screens of different receivers in different atmospheric coherence length.

We simulate the correlation coefficient of the phase screens in different distances of the receivers, the result is shown in Fig. 5, it can be find that the correlation coefficient increases with the distance of the receivers shortening.

Fig. 5. The correlation coefficient of the phase screens of different receivers in different receivers’ distance.
From Fig.3-Fig.5, we can draw a conclusion that the phase distortion in different receivers have correlation, so if the phase distortion in one receiver is corrected, the phase distortion of other receivers can be corrected quickly.

4. Wave front Correction

For reception diversity system has more than one receiver, correct wave front directly would influence correcting speed, and it’s also a waste of resources. From the analysis above, we know that the phase distortion of different receivers has correlation, so we can correct phase distortion of other receivers more quickly if the phase distortion of one receiver has been corrected.

Particle swarm optimization (PSO) algorithm, proposed by Kennedy and Eberhart, has already been used in many fields[12]. PSO algorithm can meet the requirements of AO system because of its advantages such as simple, quick convergence.

The principle of PSO algorithm can be described as follows[13]:

In moment t, \( X_i = (x_{i1}, x_{i2}, \ldots, x_{in}) \) is the position of the i-th particle, \( n \) is the dimension of the particle, \( V_i = (v_{i1}, v_{i2}, \ldots, v_{in}) \) is the speed, \( P_i = (p_{i1}, p_{i2}, \ldots, p_{in}) \) is the best position, we set the number of the particle is \( M \), \( P_p(t) \) is the best position of all particle.

The evolutionary process of basic PSO algorithm is:

\[
\begin{align*}
V_{ij}(t+1) &= V_{ij}(t) + c_1 r_{ij}(t) [P_{ij}(t) - x_{ij}(t)] + c_2 r_{2j}(t) [P_{gj}(t) - x_{ij}(t)] \\
x_{ij}(t+1) &= x_{ij}(t) + v_{ij}(t+1)
\end{align*}
\]

(4) (5)

\( c_1, c_2 \) are the accelerated factors, \( r_{ij}, r_{2j} \) are uniformly distributed random number in interval \((0,1)\), \( r_i \in U(0,1), r_j \in U(0,1) \).

The fitness value of i is calculated to measure whether the position of i-th particle at moment t is the best state. For wave front correction, we choose strehl ratio \( SR \) [14] as fitness function, \( SR \) is defined as \( SR = \frac{I(0,0)_{aberrated}}{I(0,0)_{unaberrated}} \), where I is the intensity of the laser beam.

The relationship between wave front correction parameters and PSO algorithm parameters is shown in Table.1

| Table.1 Corresponding relationship between wave front correction and PSO algorithm |
|-----------------------------------|-----------------------------------|
| PSO algorithm parameters          | Wave front correction parameters  |
| position                          | Controlling voltages of DM        |
| dimension                         | The number of DM actuator         |
| speed                             | The voltage increment             |
| Fitness function                  | SR                                |

After the wave front distortion of one receiver is corrected, we can set the best correcting voltage as the initial controlling voltage of the other receiver’s DM because that the wave front distortion of different receivers have correlation.

The best correcting voltage is set as the initial controlling voltage, which means DM only need to correct the difference of wave front distortion of the two receivers. The flow chart of PSO algorithm in wave front correction is shown as Fig.6.
Fig. 6 The flow chart of PSO algorithm in wave front correction of reception diversity laser communication.

5. Simulations
The phase screens of two receivers generated by power spectrum inversion within low-frequency compensation are shown in Fig.7, in order to correct the wave front distortion, we firstly use PSO algorithm to control DM voltages correcting Fig.7(a), the correcting result is shown in Fig.8(a). And the best correcting voltage is set as the initial voltage to correct Fig.7(b), the correcting comparison of random initial voltage and set initial voltage is shown in Fig.8(b).

Fig. 7 The phase screen of (a) receiver1, (b) receiver2 generated by power spectrum inversion within low-frequency compensation when the laser wavelength is 1550nm, \(L_0=100\)m, \(r_0=0.2\)m .

When comparing the correcting effect of random initial voltage and set initial voltage, in order to eliminate the influence of randomness voltage increment of PSO algorithm, we simulate 1000 times to get the mean value of SR. We can conclude from the Fig.8(b) that after 1000 iterations, SR of random initial voltage is approximately equal to 0.89, while SR of set initial voltage achieves 0.935. So when the initial voltage of receiver2 is set as the best correcting voltage of receiver1, it would have a considerable decrease of correcting time if we set a certain SR, and it would also have a considerable improvement of correcting effect if we set a certain iteration number.
We compare the correcting effect of set initial voltage and random initial voltage in different atmospheric coherence length, the results are shown in Fig. 9, it can be concluded that compared with large atmospheric coherence length, when atmospheric coherence length is small, the improvement of correcting effect is more obvious. Though the correlation coefficient is same in different atmospheric coherence length $r_0$, but when $r_0$ is small, the wave front distortion is more serious, random initial voltage is more difficult to correct the distortion, so the correcting effect of set initial voltage is more obvious than the condition in large $r_0$.

The correcting effects of set initial voltage and random initial voltage in different atmospheric turbulence outer scale are compared, the results are shown in Fig. 10, it can be concluded that compared with small atmospheric turbulence outer scale, when atmospheric turbulence outer scale is large, the improvement of correcting effect is more obvious. According to the conclusion: the correlation coefficient of different receivers’ wave front distortion gets larger with the increase of the outer scale of atmospheric turbulence, so the larger outer scale is, the more wave front distortion of receiver2 would be compensated when set the initial voltage as the best correcting voltage of receiver1, which leads to better improvement in larger atmospheric turbulence outer scale. From the Fig. 10, we can also find that when random initial voltage is used to correct wave front distortion, the larger outer scale is, the worse correcting effect is, which proves that the wave front distortion would be more serious in larger atmospheric turbulence outer scale.

![Figure 8](image1)

![Figure 9](image2)
Fig. 10 Comparison of correcting effect of set initial voltage and random initial voltage in different atmospheric turbulence outer scale, (a) $L_0=100$m, (b) $L_0=50$m.

It can be concluded from the simulations that set initial voltage of receiver2 as the best correcting voltage of receiver1 would have advantages in correcting speed as well as correcting effect. And it can be found that the improvement is more obvious in large atmospheric turbulence and small atmospheric coherence length.

6. Conclusion
In this paper, the correlation coefficient of the wave front distortion of different receivers is analyzed, and based on the analysis, we propose a method to quickly correct the wave front distortion of different receivers, which would help increasing the correcting efficiency as well as reducing the cost of resources.

Summary
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