Scintillation reduction using multi-beam propagating technique in atmospheric WOCDMA system

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We propose employing multi-beam propagating technology to mitigate the influence of atmospheric scintillation to the wireless optical code division multiple access (WOCDMA) system and then deduce the bit error rate (BER) formulas of systems in weak and strong scintillations, respectively. According to simulation experiment results, multi-beam propagation can improve the system performance very well compared with single-beam propagating technique. Moreover, the more beams we use, the better the performance we get. When the received optical power is –30 dBm, the BER of the system employing four beams is 5 and 1 dB lower than that of using single-beam propagating technique in weak and strong scintillations, respectively.

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Wireless optical code division multiple access (WOCDMA) combines code division multiple access (CDMA) with wireless-optic communications. It can not only reserve the advantage of CDMA technology in radio frequency (RF) communication, but also use huge bandwidth and have simple network protocol, random access, and other characteristics.

Researchers do much work in terms of spreading code word and coder/decoder[1−3], channel codes[4], multi-user detection, and analysis of system performance[5], among others. As an effort to weaken the influence of scintillation and improve system performance, Ohba *et al.*[6] proposed a symbol decision scheme, while Kozawa *et al.*[7] proposed a new system structure using modified pseudo orthogonal M-sequence sets. Moreover, using turbo as channel codes to improve system performance was reported[8]. Adaptive optics[9], large-aperture receiving[10], and multi-beam propagating[11] were proposed to mitigate the effects of scintillation and improve system performance in atmospheric laser communication.

This letter employs multi-beam propagating technique to the WOCDMA system and then deduces the bit error rate (BER) formulas of systems using multi-beam propagation in weak and strong scintillations, respectively. We simulate and compare the BER of the systems using one, two, four, and eight beams, and then analyze the improvement of using multi-beam propagation to the WOCDMA system.

WOCDMA system employs pulse position modulation (PPM), which does not need dynamic estimation of the receiver threshold and has higher energy information efficiency than on-off keying (OOK) modulation. This is because in atmospheric communication, systems are easily influenced by background light and scintillation. The system is composed of laser, PPM modulator, encoder, transmitting/receiving antenna, decoder, avalanche photo diode (APD) detector, and PPM demodulator. Figure 1 shows the model of the system.

At the transmitter, the user's data are passed to the PPM modulator and changed into PPM symbols. The laser is then modulated by the PPM symbols to emit the optical pulses placed in one of the M time slots of the PPM frame. The pulses are encoded into their desired code sequences and sent to the atmospheric channel. In the receiver, the received signal is decoded by the decoder and converted into electrical signal by the APD. The signal is then passed to the PPM demodulator, which can decode the PPM symbol into the user's data.

In the atmospheric channel, laser beam propagation is subject to the following effects: beam spread, scintillation, angular spread, absorption-induced attenuation, and depolarization. Scintillation is one of the main problems. It is generally divided into weak scintillation (logarithm variance of scintillation $\sigma_x^2 < 0.35$) and strong scintillation ($\sigma_x^2 > 0.35$ or longer than 1 km range)[12].

The multi-beam propagating technique is the effective way to reduce the effect of scintillation. It combines laser beams through different paths to smoothen the scintillation of the received signal. It can also be considered as a transmitting diversity technique. Hence, we employ the multi-beam propagating technique in the WOCDMA system.

Figure 2 shows the model of the multiple-beam propagating technique. In the transmitter, n beams are sent by different transmitting antennas and go to the receiver antenna through different paths simultaneously. They undergo signal processing (Fig. 1) in the receiver, and the desired data are obtained. We can employ geometry symmetrical structure so that only one receiving antenna

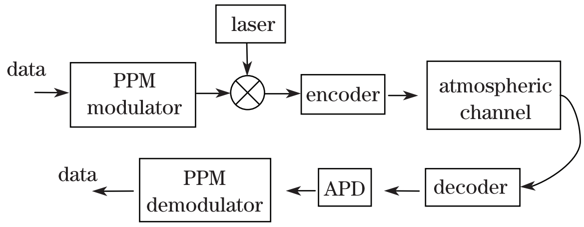

Fig. 1. System model.

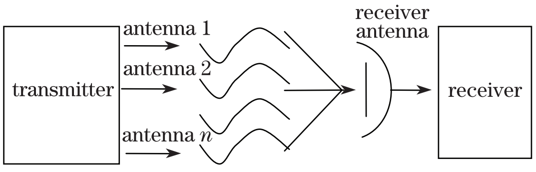

Fig. 2. Model of the multiple-beam propagating technique.

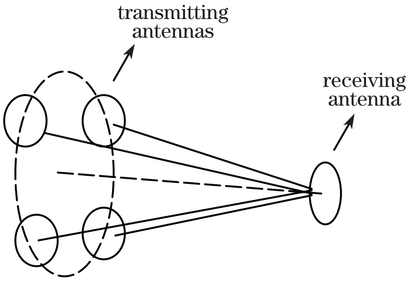

Fig. 3. Position structure of the transmitting/receiving antennas.

can simultaneously receive multiple signals coming from multiple transmitting antennas. As an example, the structure when four beams are used is shown in Fig. 3.

We then analyze the BER of the WOCDMA system using single-beam propagating technique in the weak and strong scintillations, and deduce the BER formulas of the system using multi-beam propagation.

In Ref. [5], the BER of the atmospheric PPM WOCDMA system is

$$P_{\rm b} \leqslant \frac{M}{2(M-1)} P_{\rm e}^{\rm U} \leqslant \frac{M}{2} \times \sum_{k_d \in L} (P_{\rm I})^{|k_d|} (1-P_I)^{N-1-|k_d|} P\{Y_d \geqslant Y_0|0, k_0=0, k_d\}, \tag{1}$$

$$\begin{aligned} & P\{Y_d \geqslant Y_0|0, k_0=0, k_d\} \\ & = \int_0^\infty P(X_0) \cdots \int_0^\infty P(X_{N-1}) \\ & \times P_{\rm e}(\vec{X}) {\rm d}X_0 {\rm d}X_1 \cdots {\rm d}X_{N-1}, \end{aligned} \tag{2}$$

$$\begin{aligned} P_{\rm e}(\vec{X}) = & \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma_d^2(\vec{X})}} {\rm e}^{-[x-\mu_d(\vec{X})]^2/2\sigma_d^2(\vec{X})} \\ & \cdot \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi\sigma_0^2(\vec{X})}} {\rm e}^{-[x-\mu_0(\vec{X})]^2/2\sigma_0^2(\vec{X})} {\rm d}y {\rm d}x, \end{aligned}$$

where $P_{\rm b}$ is the BER of WOCDMA system; M is the number of PPM modulation; $P_{\rm e}^{\rm U}$ is the union bound of the word error probability; $P_{\rm I}$ is the probability that a user causes interference to the desired slot of the desired user, and its value is decided by the address codes; k_i is the number of users causing interference to the ith slot of the desired user; Y_d and Y_0 are the output of the optical correlators in the dth and 0th slots; σ_d^2 and σ_0^2 are the variances of Y_d and Y_0; μ_d and μ_0 are the means of Y_d and Y_0; X_i is the scintillation of user i; N is the number of users. The mean and variance of Y_d and Y_0 are derived in Ref. [5].

$P(X)$ is the X probability density function. The difference between the multi-beam and single-beam propagating techniques is the distribution of $P(X)$. Thus, in the following analysis of BER, we only provide Eqs. (2) into (1) to obtain the BER of the systems.

For weak scintillation, atmospheric scintillation is a stationary random process. According to Rytov, the received logarithmic amplitude X can be expressed as the superposition of many individual contributors. On the basis of the central limit theorem, the received optical power of single-beam propagation is satisfied with logarithmic normal distribution.

$$P_1(X) = \frac{1}{X\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(\ln X + \sigma_s^2/2)^2}{2\sigma_s^2}\right], \tag{3}$$

where the average of scintillation X is normalized to unity and σ_s^2 is the logarithm variance of X.

We can then get the P of the system using single-beam propagating technique in weak scintillation, as shown

$$\begin{aligned} & P\{Y_d \geqslant Y_0|0, k_0=0, k_d\} \\ & = \int_0^\infty P_1(X_0) \cdots \int_0^\infty P_1(X_{N-1}) \times P_{\rm e}(\vec{X}) {\rm d}X_0 \cdots {\rm d}X_{N-1}. \end{aligned} \tag{4}$$

For strong scintillation and single-beam propagation, according to the Dashen path integral theory, the received optical power is satisfied with the negative exponential distribution[12].

$$P_2(X) = \frac{1}{< X >} \exp\left[-\frac{X}{< X >}\right]. \tag{5}$$

We can then get the P of the system using single-beam propagating technique in strong scintillation

$$\begin{aligned} & P\{Y_d \geqslant Y_0|0, k_0=0, k_d\} \\ & = \int_0^\infty P_2(X_0) \cdots \int_0^\infty P_2(X_{N-1}) \times P_{\rm e}(\vec{X}) {\rm d}X_0 \cdots {\rm d}X_{N-1}. \end{aligned} \tag{6}$$

In the following analysis, we analyze the system using multi-beam propagating technique and assume that n beams are incoherent with the others.

For weak scintillation and multi-beam propagation, the received logarithmic amplitude can also be expressed as the superposition of more individual contributors. Hence, according to the central limit theorem, the optical power is also satisfied with the logarithmic normal distribution. Letting X denote the superposition power from n beams in the receive aperture, the power from each beam X_k (k= 1−n) follows the same logarithmic normal distribution and is mutually independent.

$$X = \sum_{k=1}^{n} X_k = nX_1,$$

where X_1 satisfies $D[\ln X_1] = \sigma_0^2$ and $< \ln X_1 >= -\sigma_0^2/2$.

Therefore, the logarithm mean and variance of X are

$$D[\ln X] = D[\ln nX_1] = D[\ln X_1] = \sigma_0^2,$$

$$\begin{aligned} & < \ln X >=< \ln nX_1 >=< \ln n + \ln X_1 > \\ & = \ln n + < \ln X_1 >= \ln n - \sigma_0^2/2. \end{aligned}$$

Its probability density function is derived as

$$P_3(X) = \frac{1}{X\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(\ln X + \sigma_s^2/2 - \ln n)^2}{2\sigma_s^2}\right]. \tag{7}$$

We can then get the P of the system using multi-beam propagation in weak scintillation, as shown

$$P\{Y_d \geqslant Y_0|0, k_0 = 0, k_d\} \\ = \int_0^\infty P_3(X_0)\cdots\int_0^\infty P_3(X_{N-1}) \times P_e(\vec{X})\mathrm{d}X_0\cdots\mathrm{d}X_{N-1}. \quad (8)$$

For strong scintillation, we let X denote the superposition power from n beams in the receive aperture. The power from each beam X_k (k= 1∼ n) follows the same negative exponential distribution and is mutually independent.

$$X = \sum_{k=1}^{n} X_k, < X_k >=< X > /n.$$

The X_k characteristic function is

$$M_{X_k}(\omega) = \frac{1}{1 - \mathrm{j}\omega < X_k >} = \frac{1}{1 - \mathrm{j}\omega < X > /n}.$$

The X characteristic function is

$$M_X(\omega) = [M_{X_k}(\omega)]^n = [\frac{1}{1 - \mathrm{j}\omega < X > /n}]^n.$$

After the inverse fast Fourier transform (IFFT), we get the probability density function:

$$P_4(X) = \left[\frac{n}{< X >}\right]^n \frac{X^{n-1}\exp(-nX/ < X >)}{\Gamma(n)}. \quad (9)$$

We can then derive the P of the system using multi-beam propagation in strong scintillation:

$$P\{Y_d \geqslant Y_0|0, k_0 = 0, k_d\} \\ = \int_0^\infty P_4(X_0)\cdots\int_0^\infty P_4(X_{N-1}) \times P_e(\vec{X})\mathrm{d}X_0\cdots\mathrm{d}X_{N-1}. \quad (10)$$

We put Eqs. (4), (6), (8), and (10) into (1) to obtain the BER formulas of the four systems in weak/strong scintillation and single-beam/multi-beam propagating technique. We then simulate and compare them.

The pattern of modulation we used is 4 PPM. For atmospheric WOCDMA, the use of two-dimensional (2D) codes has better performance than that of one-dimensional codes. Therefore, this letter employs the 2D Prime/OOC codes[13] (43 × 49, 7, 0, 1; OOC: optical orthogonal code). The system's encoder/decoder employs the combination of fiber Bragg gratings and optical fiber delay line. In addition, the P_I in Eq. (1) is calculated as

$$P_\mathrm{I} = \frac{K^2}{MF \times K^2} = \frac{7^2}{4 \times 43 \times 7^2}. \quad (11)$$

Table 1 shows the parameters chosen in this letter.

In the experiment, firstly we simulate the BER of atmospheric OCDMA systems versus the received power in different types of scintillation using single-beam propagating technique (the number of users is 2). We then analyze the effect of scintillation. Figure 4 shows the result, where the values 0.1, 0.05, and 0.01 indicate the intensity of atmospheric scintillation. From Fig. 4, it can be observed that the BER of the WOCDMA system increases along with the increase in scintillation (the logarithm variance of the scintillation σ_0^2). When $\sigma_0^2 > 0.1$, the system cannot communicate normally, indicating that atmospheric scintillation greatly affects the performance of the WOCDMA system.

Table 1. Parameters

Parameter	Value
Laser Wavelength λ (nm)	1 550
APD Quantum Efficiency η	0.6
APD Gain G	100
APD Effective Ionization Ratio k_eff	0.02
APD Bulk Leakage Current I_b (nA)	0.1
APD Surface Leakage Current I_s (nA)	10
Modulation Extinction Ratio M_e	10
Receiver Noise Temperature T_r (K)	1 100
Receiver Load Resistor R_L (Ω)	1 030
Data Bit Rate R_b (Mb/s)	155
Background Light Photon Arrival Rate λ_b (counts/s)	10^9

Secondly, we simulate the BER of atmospheric WOCDMA systems employing different beams (n=1, 2, 4, and 8) versus the received power in weak/strong scintillation (the number of users is 2). We then analyze the effect of the number of beams to the system. Figure 5 shows the results. From Fig. 5, it can be observed that the BER decreases when there is higher number of beams in both the weak and the strong scintillations. In weak scintillation, if the system employs more than four beams, the BER is –9 dB and the system can communicate better. When the received optical power is –30 dBm, the BER of the system employing four beams is 5 and 1 dB lower those that of using single-beam propagation in weak scintillation ($\sigma^2 = 0.1$) and strong scintillation, respectively. This is because employing more beams can make the received power smoother and reduce the effect of atmospheric scintillation. Ultimately, the system's performance becomes better. Therefore, using multi-beam propagating technique can reduce the effect of scintillation well.

Thirdly, we simulate the BER of atmospheric WOCDMA systems employing different beams (n = 1 and 4) versus the received power with different numbers

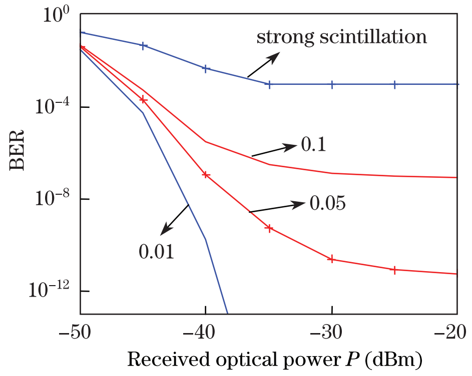

Fig. 4. BER versus the received power in different scintillations (single-beam propagation).

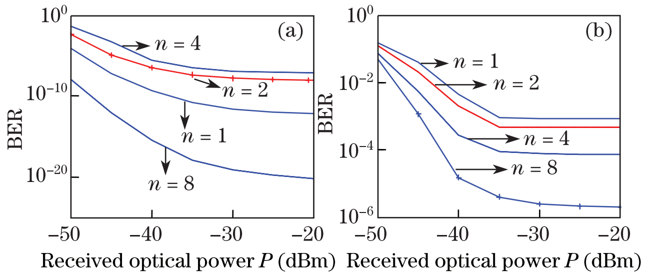

Fig. 5. BER versus the received power with different beams. (a) Weak scintillation ($\sigma^2 = 0.1$) and (b) strong scintillation.

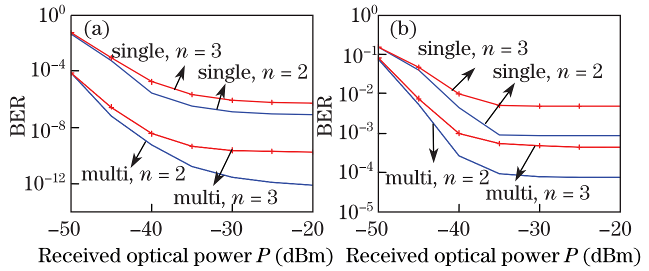

Fig. 6. BER versus the received power with different beams and different numbers of users. (a) Weak scintillation ($\sigma^2 = 0.1$) and (b) strong scintillation.

of users in weak/strong scintillation. We then analyze the effect of the number of users to the system. Figure 6 shows the results. From Fig. 6, we can see that the BER increases while the performance of the systems becomes worse when there is higher number of users in the WOCDMA systems, both using single-beam and multi-beam propagating techniques. This is due to the systems being affected not only by atmospheric scintillation, but also by multi-user interference. The performance of the systems using multi-beam propagation is low when there are more users. This means that the use of multi-beam propagating technique cannot suppress multi-user interference, thus it has to be combined with another technique to improve the performance of the system.

In conclusion, taking into account the influence of atmospheric scintillation, we propose the use of multi-beam propagating technique to improve the performance of the WOCDMA system. We deduce the formulas of the BER of the system using multi-beam propagation in weak and strong scintillations. By simulation experiments, we analyze and compare the respective BER of using single-beam and multi-beam techniques. We find that the BER decreases when there are more beams in both weak and strong scintillations. When the received optical power is −30 dBm, the BER of the system employing four beams is 5 and 1 dB lower than those of using single-beam propagation in weak (σ^2= 0.1) and strong scintillations, respectively. Therefore, using multi-beam propagating technique can reduce the influence of scintillation and improve the performance of the system, but it cannot restrain the multi-access interference.

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