Improved free space optical communications performance by using time diversity

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A laser beam propagating through turbulence experiences random amplitude and phase fluctuations, which can severely degrade the performance of free space optical communication systems. In this letter, time diversity is demonstrated as a technique which can decrease turbulence influence. Statistically, laser propagation along an atmospheric path is uncorrelated with an earlier-time path for a time interval greater than the atmospheric turbulence correlation time. To estimate time diversity system performance, a 2.2-km optical link is set up for comparing the fade probability of a system using time diversity with a system not using time diversity. The experimental results obtained under different turbulence conditions are shown which are in good agreement with the theory.

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When a free space optical communication (FSOC) system is operated in the atmosphere, turbulence induced scintillation results in power losses at the receiver, which can cause the received signal to fade below a prescribed threshold level. The probability of fade serves as an estimate of how likely the detector output is to drop below the threshold. Since the irradiance of an optical field propagating though the atmosphere is a random, fluctuating quantity, the incoming signal in a FSOC system will fade randomly. Hence, the probability density function (PDF) of the irradiance fluctuation is needed in order to predict the probability of fade for a FSOC system. To improve the reliability of fading channel, spatial diversity schemes are discussed widely[1−4]. Based on the Taylor frozen turbulence hypothesis, spatial statistics can be converted to temporal statistics by given knowledge of the average wind speed transverse to the direction of propagation. So time diversity can improve performance of FSOC system in theory[5].

In the time diversity scheme, identical messages are transmitted in different time slots separated by time periods on the order of the coherence time. The receiver receives M independently faded copies of the signal, applies appropriate delay to each copy, combines them, and demodulates the messages. When the slot is longer than the correlation time of the atmosphere, the bit errors reduce. The reason is if one bit is detected in error for channel fluctuations, then there is an independent probability of correctly re-detecting the same bit, because the diversity delay is longer than the memory time of the channel. Communication performance is improved because the joint probability of error is less than the probability of error from individual channels[6].

Based on the Taylor frozen turbulence hypothesis, spatial statistics can be converted to temporal statistics by the knowledge of the average wind speed transverse to the direction of propagation. If we assume that the wave incident on the collecting lens is an unbounded plane wave, this action leads to the temporal covariance function[7]

$$B_I(\tau, D) = 8\pi^2 k^2 L \int_0^1 \int_0^\infty \kappa \Phi_n(\kappa) J_0(\kappa V \tau) \times \exp\left(-\frac{D^2\kappa^2}{16}\right)\left(1-\cos\frac{L\kappa^2\xi}{k}\right) \mathrm{d}\kappa \mathrm{d}\xi, \quad (1)$$

where V is the average transverse wind speed, D is the receiver diameter, Φ_n is the spatial power spectrum of refractive index, J_0 is the Bessel function of the first kind. L is the propagation length, $k = 2\pi/\lambda$ is the optical wave number, τ is the time lag, κ is the spatial wave number, and ξ is the transformation variable.

The temporal covariance function is useful in determining the correlation time t_c, which is defined as the e^{-1} point of the normalized covariance function $b_I(\tau)$ given by

$$b_I(\tau, D) = \frac{B_I(\tau, D)}{B_I(0, D)}. \quad (2)$$

The probability of fade serves as an estimate of how likely the detector output is to drop below a prescribed threshold. When the signal-to-noise ratio (SNR) at the output of the detector is sufficiently high, the noise contribution to the fading issues can be neglected. In this case, the probability of fade is given by

$$P(I < I_t) = \int_0^{I_t} p(I) \mathrm{d}I, \quad (3)$$

where I_t is the threshold irradiance. Rather than expressing the probability of fade as a function of I_t, the fade threshold parameter, F_T, is introduced[7]. F_T is defined as the number of decibels below the mean. For the on-axis portion of a Gaussian beam wave, F_T becomes

$$F_T = 10 \lg\left(\frac{\langle I \rangle}{I_t}\right). \quad (4)$$

A lognormal distributed normalized irradiance ($\langle I \rangle = 1$) is described by

$$P_I(I) = \frac{1}{I\sqrt{2\pi\sigma_{\ln I}^2}} \exp\left[-\frac{[\ln(I) + \frac{1}{2}\sigma_{\ln I}^2]^2}{2\sigma_{\ln I}^2}\right], \quad I > 0 \quad (5)$$

where $\sigma_{\ln I}^2$ is the log-irradiance variance, $\sigma_{\ln I}^2 \approx \sigma_I^2$ under weak turbulence condition. An analytical expression for the probability of fade for lognormal distributed (on-axis) irradiance is

$$P_f = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{\frac{1}{2}\sigma_{\ln I}^2 - 0.23F_{\mathrm{T}}}{\sqrt{2}\sigma_{\ln I}}\right)\right], \tag{6}$$

where $\operatorname{erf}(x)$ is the error function.

The transmitter sends the signal N times, separated by fixed time periods that are much larger than typical deep fade duration. The receiver receives independently faded copies of the signal, combines them using some combining scheme, and determines whether a 0 or 1 is sent. A typical time diversity system is shown in Fig. 1. Consider data that is transmitted N times and separated by a delay period, the transmitted laser intensities can be defined as $I_1 = I(t)$, $I_2 = I(t-\tau), \cdots, I_n = I(t-n\tau+\tau)$. At the receiver, the received fading signal in each path R_i is defined as RP_i, where R is a const about receiver and P_i is received optical power for the ith interval. Thus, the fading signal can be considered as having similar statistical behavior to the intensity fluctuations.

The joint distribution describes the fading at different delay time at a single receiver, which can evaluate the performance of time diversity reception. We assume that the log-amplitude at receiver is described by a joint Gaussian distribution[8]. The auto-covariance matrix of the log-amplitude at different time is given by

$$B = \sigma_I^2 \begin{bmatrix} 1 & b(\tau) & \cdots & b(n\tau-\tau) \\ b(\tau) & 1 & \cdots & b(n\tau-2\tau) \\ \cdots & \cdots & \cdots & \cdots \\ b(n\tau-\tau) & b(n\tau-2\tau) & \cdots & 1 \end{bmatrix}. \tag{7}$$

The joint probability density function of I is

$$f_{I_1,I_2,\cdots,I_N}(i_1,i_2,\cdots,i_N) = \frac{1}{(2\pi)^{N/2}\,|B|^{1/2}\prod_{k=1}^{N} i_k} \times \exp\left[-\frac{1}{2}(\mathbf{A}-a)\mathrm{B}^{-1}(a-\mathbf{A})^{\mathrm{T}}\right], \tag{8}$$

where $\mathbf{A} = [\ln i_1, \ln i_2, \cdots, \ln i_N]$ and $a = (\ln\langle I\rangle - \sigma_I^2/2)I_{1\times N}$.

The probability of fade is then obtained by integrating Eq. (3) over the joint density function in Eq. (8). This leads to the expression

$$P = \int_0^{I_{\mathrm{t}}} \cdots \int_0^{I_{\mathrm{t}}} f_{I_1,I_2,\cdots,I_N}(i_1,i_2,\cdots,i_N)\mathrm{d}i_1\mathrm{d}i_2\cdots\mathrm{d}i_N. \tag{9}$$

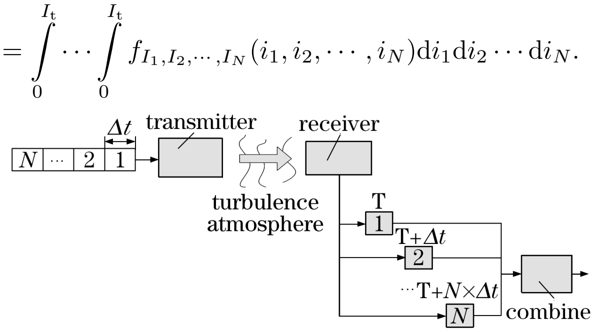

Fig. 1. Free space communication with time diversity.

In order to study time diversity properties, a 2.2-km laser link is set up. The experiment operating at 1550 μm is conducted at a 2.2-km test range facility located in Wuhan University in June, 2007. Rytov variance of the link is about 0.28, which can be considered as weak turbulence. The 1550-nm optical wave is transmitted through a telescope and received by a telescope of 203-mm diameter. The optical signal is coupled into multimode fiber, which is detected by positive intrinsic negative (PIN) detector and the amplified electric signal is sampled at 10 kHz by NI data acquisition (DAQ) hardware and data are saved in computer.

Normalized covariance for different turbulence conditions are plotted in Fig. 2. The correlation time for these particular turbulence conditions is below 10 ms. This suggests that delays longer than few microsecond should be sufficient for time diversity systems to work efficiently. In our experiment, delayed time is set to $1-10$ ms.

In Fig. 3, probability of fade with time diversity is represented as F_{T}. In our experiment, probability density functions of optical signal fit lognormal distribution well. So we compute the probability of fade with lognormal distribution in theory and three different curves for $N = 1$, 2, 3 are plotted. The theory results predict that time diversity can give an F_{T} gain of about 1.5 and 2.7 dB respectively (both at 10^{-6} probability of fade). The experiment results show that time diversity can give an F_{T} gain of about 2.1 and 3.5 dB respectively (both at 10^{-6} probability of fade). In our experiment, the Rytov variance of the link is about 0.28. For comparing to theoretical probability of fade, we chose $\sigma_I^2 = 0.3$. Uncertainty of Rytov variance causes the difference between theoretical F_{T} gain and experimental F_{T} gain.

By increasing the delay period, we can improve performance but communication latency and the required buffer size are also increased. Therefore, the optimum delay period can be chosen to satisfy a given performance

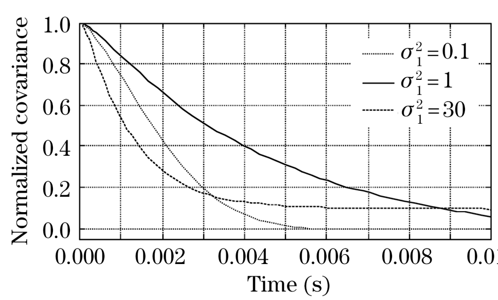

Fig. 2. Normalized temporal covariance for different turbulence variance.

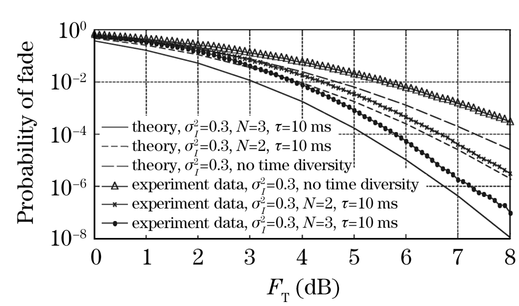

Fig. 3. 2.2-km link probability of fade versus F_{T}.

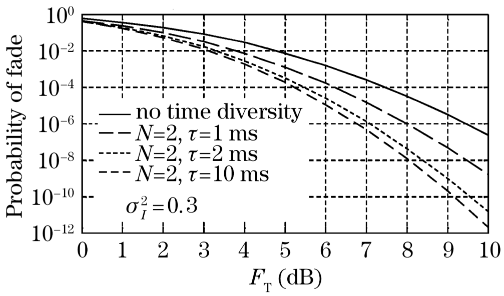

Fig. 4. Probability of fade versus $F_{\rm T}$ under different delay time.

requirement. Figure 4 show different delay time performance. The experimental results show that delay time $\tau = 1$, 2, 10 ms can give an $F_{\rm T}$ gain of about 1.5, 2.5, and 2.7 dB respectively (both at 10^{-6} probability of fade). So the optimum delay period is 2 ms in this experiment.

In conclusion, atmospheric turbulence causes significant transmission impairment for FOSC. Fades of magnitude is large as $5-15$ dB. The performance characterization of an FSOC system using time diversity scheme is presented. The results are used to determine the parameters required in developing an experimental time diversity system. For typical weak atmospheric turbulence conditions, the correlation time is found to be $1-10$ ms. We compute the average fade probability of FSOC in theory and test out the theory by experiment. Theory and experiment have proved the importance of diversity systems in reducing fading-induced fluctuations. The theoretical results indicate that time diversity with 3 can give a link gain up to 2.7 dB.

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