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Effects of frequency-domain deconvolution on suppression of multiplicative noise in an atmospheric laser communication system

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Abstract: Multiplicative noise brought about by atmospheric turbulence can cause performance deterioration of atmospheric laser communication links, leading to increased error rates. In this study, a method of frequency-domain deconvolution was proposed to filter out multiplicative noise in atmospheric laser communication systems. In the Gamma-Gamma channel model, the multiplicative noise in a 4PSK atmospheric laser communication system was filtered out using this method. The simulation computations were conducted over the constellation diagrams and bit error rates of the modulation signals before and after deconvolution. The results show that frequency-domain deconvolution can smoothly filter out multiplicative noise. The measured and simulated results for near-surface sighting distance under different weather conditions were basically consistent, showing that the proposed method can effectively suppress atmospheric turbulence and reduce the bit error rate of atmospheric laser communication systems.

Key words: atmospheric laser communication;　atmospheric turbulence;　multiplicative noise;　frequency-domain deconvolution

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大气激光通信系统中频域解卷积抑制乘性噪声的研究

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摘　要： 大气湍流引起的乘性噪声会导致大气激光通信链路性能的恶化，引起误码率增加。在 Gamma-Gamma 湍流信道模型下，采用频域解卷积滤除 4PSK 调制大气激光通信系统中的乘性噪声。通过计算机仿真对 4PSK 大气激光通信系统的星座图和误码率进行分析，结果表明在不同天气条件下采用频域解卷积可以滤除系统的乘性噪声，有效地抑制了大气湍流对大气激光通信系统的影响，减小了大气激光通信系统的误码率。

关键词： 大气激光通信；　大气湍流；　乘性噪声；　频域解卷积

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0 Introduction

The influence of atmospheric random channels on laser communication is manifested as light intensity attenuation, pulse broadening, light intensity fluctuation, light intensity scintillation, beam dithering, beam expansion, phase fluctuation, and other effects. The channel noise can be divided into additive noise and multiplicative noise according to its influencing mechanism. Multiplicative noise changes are complex and pose difficulties for the application of atmospheric laser communication equipment.

The main methods for suppressing atmospheric turbulence in atmospheric laser communication systems include large-aperture receiving, diversity, partially coherent optical transmission, adaptive optics, and other methods. Channel encoding (RS code and LDPC coding) and homomorphic filtering can further reduce the bit error rate[1-6]. In 2005, Yuksel[7] studied the receiver-aperture averaging effect. This method can significantly reduce the optical power fluctuations caused by atmospheric turbulence. The larger the aperture, the more obvious the effect is. When the size of the receiver is increased to a certain level, the optical power fluctuations will not be significantly reduced with increasing aperture size. Chen and Yang[8] studied the relationship between the receiver aperture under different atmospheric turbulence conditions and the output signal-to-noise ratio of the detector with turbulence effects to provide a basis for selection of aperture size. Ke and Song[9] reduced the bit error rate of a system using three aperture receiving schemes designed into the Gamma-Gamma channel model. With increasing number of receiving apertures, the aperture smoothing factor and the bit error rate of the system will further decrease. Wang and Tao[10] examined the light intensity fluctuation characteristics of multi-beam atmospheric transmissions. This technology averages the non-coherent light beams emitted from several overlapping emission sources at the receiving aperture and reduces fluctuations in light intensity. However, control of coaxial and servo transmission is more difficult. The literature[11] has shown that the smaller the initial coherence length of the light beams in a partially coherent optical transmission, the stronger the inhibitory effect will be on the scintillation of light intensity, but that light-beam expansion caused by free-space diffraction will be aggravated. In practical application, the optimal beam coherence length should be determined based on actual needs. Adaptive optics technology uses anti-wavefront distortion techniques to offset the wavefront distortion caused by atmospheric turbulence through wavefront sensing and reconstruction. Yang[12] et al proposed an adaptive optics technology with wavefront tilt compensation and presented a computational formula for bit error rate. The computed results showed that wavefront tilt compensation could significantly improve the performance of a communication system, but that under conditions of strong scintillation, the discontinuous points appearing in the beam wavefront could pose difficulties for wavefront sensing and reconstruction[13]. Other researchers [14] have proposed an adaptive optics technology without a wavefront sensor. In this type of adaptive optics system, which uses the light energy received and other performance indices as objective functions for the optimization algorithm, an ideal corrective effect can be achieved. Yuan[15] introduced an adaptive optics technology without a wavefront sensor for correcting wavefront distortion and weakening signal scintillation from the optical link, which showed clear effectiveness in improving optical transmission under atmospheric turbulence of less than moderate intensity.

In this study, a method of frequency-domain deconvolution is proposed from the perspective of engineering applications to suppress the influence of atmospheric turbulence on laser communication systems. Channels are estimated according to experimental data for near-surface sighting distance under different weather conditions. For the received modulation signals, frequency-domain deconvolution is used to filter out multiplicative noise; the constellation diagrams of the demodulated signals before and after deconvolution in the theoretical channel model and the empirical channel model are compared to analyze the bit error rate (BER) of the system before and after filtering.

1 Principle

The block diagram for filtering out multiplicative noise by frequency-domain deconvolution in an atmospheric laser communication system is shown in Fig.1. 4PSK modulation is conducted for the information source. The multiplicative noise of the atmospheric channels is measured experimentally under heavy rain, drizzle, moderate rain, foggy weather, and cloudy weather; next, the channel parameter $h(n)$ is estimated; then the multiplicative noise is filtered using frequency-domain deconvolution; and finally, the signals are subjected to 4PSK demodulation.

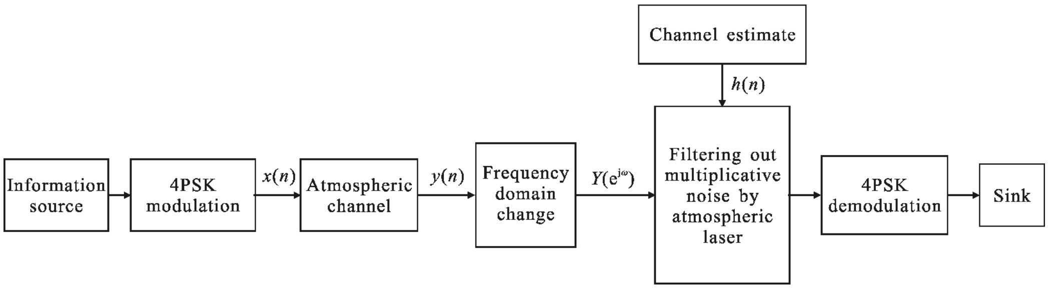


Fig.1 Block diagram for filtering out multiplicative noise by frequency-domain deconvolution in an atmospheric laser communication system

1.1 Channel estimation

Figure 2 shows the estimation process for the distribution of the measured channel data. The window length for channel estimation is N, the sliding interval of the window is 1, the estimated data in the first group range from 1 to N, those in the second group range from 2 to N+1, and so forth. The sampling points of group (M-N+1) range from M-N+1 to M. The least-squares method is used for estimation.

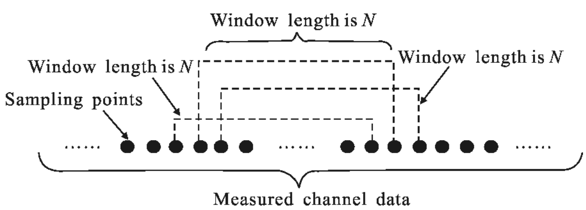


Fig.2 Channel estimation

Without considering the background noise generated by the electronic device, let $x(n)$ represent the known transmitted data and $z(n)$ the measured channel data. Under the impact of multiplicative noise, the output signal $y(n)$ passing through the atmospheric channel is given by:

$$y(n)=x(n)\cdot z(n) \tag{1}$$

It is assumed that the estimated value of the channel parameter is $h(n)$ and the transmitted data is $x(n)$. The output signal $y(n)$ passing through this channel is given by:

$$y(n)=x(n)\cdot h(n) \tag{2}$$

From Eq.(1) and (2):

$$x(n)\cdot z(n)=x(n)\cdot h(n) \tag{3}$$

A discrete Fourier transform is applied to both sides of Eq.(3) to yield:

$$X(\omega)*Z(\omega)=X(\omega)*H(\omega) \tag{4}$$

where $X(\omega)$, $Z(\omega)$, and $H(\omega)$ are the discrete Fourier transforms of $x(n)$, $z(n)$, and $h(n)$ respectively, and the operator * represents convolution.

According to Eq.(4), the estimated value of the channel parameter $H(\omega)$ can be obtained; the time-domain estimate $h(n)$ of the atmospheric channel parameters is found by applying an inverse discrete Fourier transform to $H(\omega)$.

1.2 Frequency-domain deconvolution

According to the estimated channel parameter **h**(**n**) described in Section 1.1, if the 4PSK signal is **x**(**n**), then the output signal **y**(**n**) passing through the atmospheric channel is given by Eq.(2); **Y**(ω) is determined by applying a discrete Fourier transform to **y**(**n**).

The signal will be contaminated with multiplicative noise **z**(**n**) after passing through the atmospheric channel, after which the signal is given by:

$$\mathbf{y}(\mathbf{n})=\mathbf{x}(\mathbf{n})\cdot\mathbf{z}(\mathbf{n}) \qquad (5)$$

A discrete Fourier transform is then applied to the right-hand side of Eq.(5). Then, according to the frequency-domain convolution theorem:

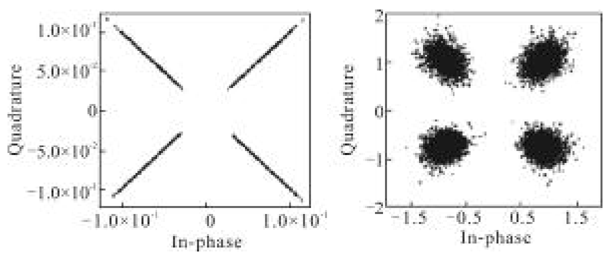
$$\mathbf{Y}(\omega)=\mathbf{X}(\omega)*\mathbf{Z}(\omega) \qquad (6)$$

where **Z**(ω) is the discrete Fourier transform of the multiplicative noise **z**(**n**). **X**(ω) can be obtained through frequency-domain deconvolution over **Y**(ω) and **Z**(ω), and the modulated signal **x**(**n**) after filtering out the multiplicative noise can be obtained by carrying out an inverse discrete Fourier transform.

2 Experiments and analysis

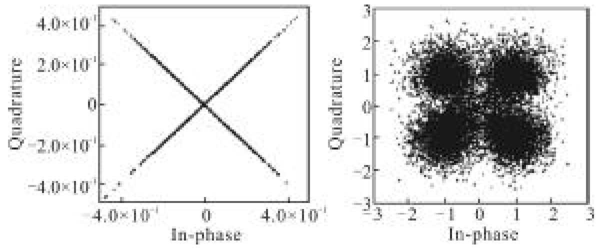
2.1 Digital simulation

Based on the atmospheric turbulence channel model of Gamma-Gamma light intensity scintillation[16], constellation diagrams before and after signal frequency-domain deconvolution were compared using 4PSK modulation, and the BER of the system was calculated under conditions of mild, moderate, and strong turbulence, as showe in Fig.3-Fig.5.



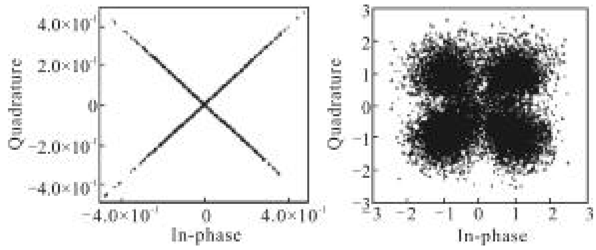
(a) Constellation diagram of modulated signal before deconvolution (b) Constellation diagram of modulated signal after deconvolution

Fig.3 Constellation diagrams before and after frequency-domain deconvolution under mild turbulence conditions



(a) Constellation diagram of modulated signal before deconvolution (b) Constellation diagram of modulated signal after deconvolution

Fig.4 Constellation diagrams before and after frequency-domain deconvolution under moderate turbulence conditions



(a) Constellation diagram of modulated signal before deconvolution (b) Constellation diagram of modulated signal after deconvolution

Fig.5 Constellation diagrams before and after frequency-domain deconvolution under strong turbulence conditions

Table 2 shows the BER of the system before and after frequency-domain deconvolution under the corresponding signal-to-noise ratio(SNR). It can be seen that the bit error rate under strong turbulence is the largest, followed by that under moderate turbulence, while that under mild turbulence is the smallest. The bit error rate under strong and moderate turbulence was reduced from 10^{-2} to 10^{-4} afterdecon-volution, and that under mild turbulence was also decreased by one order of magnitude, i.e., from 10^{-3} to 10^{-4}.

Tab.2 Comparison of BER before and after frequency-domain deconvolution in the Gamma-Gamma channel model

Turbulence condition	Before deconvolution (BER)	After deconvolution (BER)	SNR/dB
Strong	3.05×10^{-2}	4.0×10^{-4}	39.276 0
Moderate	1.83×10^{-2}	2.0×10^{-4}	43.644 0
Mild	3.50×10^{-3}	1.0×10^{-4}	50.840 2

2.2 Experiments

The block diagram of the atmospheric laser communication system is shown in Fig.6. The system consists mainly of the laser, the light-emitting antenna, the light-receiving antenna, and light-spot receiving and measurement units[17]. The receiving and measurement of light spots is achieved by monitoring light-spot intensity changes using a laser power meter; the magnitude of the power value serves to indicate the light intensity received by the detector. The measured data were used for channel estimation to establish the atmospheric random channel model, and then multiplicative noise was filtered out by frequency-domain deconvolution.

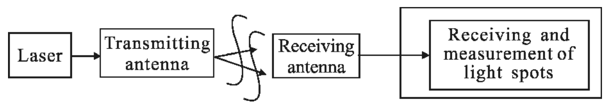
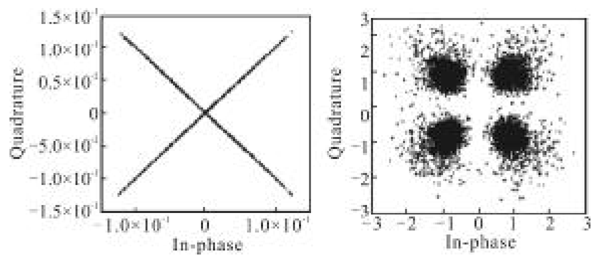


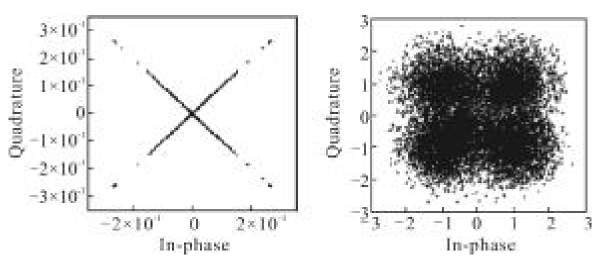
Fig.6 Block diagram of atmospheric laser communication system[18]

Figures 7-11 present the constellation diagrams



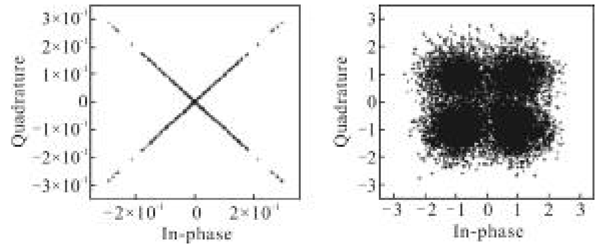
(a) Constellation diagram of modulated signals before deconvolution
(b) Constellation diagram of modulated signals after deconvolution.

Fig.7 Constellation diagrams before and after frequency-domain deconvolution in heavy rain



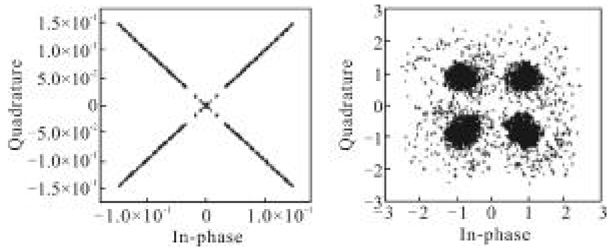
(a) Constellation diagram of modulated signals before deconvolution
(b) Constellation diagram of modulated signals after deconvolution

Fig.8 Constellation diagrams before and after frequency-domain deconvolution in moderate rain



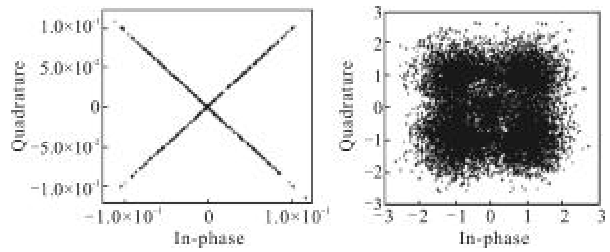
(a) Constellation diagram of modulated signals before deconvolution
(b) Constellation diagram of modulated signals after deconvolution

Fig.9 Constellation diagrams before and after frequency-domain deconvolution in light rain



(a) Constellation diagram of modulated signals before deconvolution
(b) Constellation diagram of modulated signals after deconvolution

Fig.10 Constellation diagrams before and after frequency-domain deconvolution on a cloudy day



(a) Constellation diagram of modulated signals before deconvolution
(b) Constellation diagram of modulated signals after deconvolution

Fig.11 Constellation diagrams before and after frequency-domain deconvolution on a foggy day

of signals modulated using 4PSK modulation before and after deconvolution in heavy, moderate, light rain and on a cloudy and a foggy day respectively. The convergence of the constellation diagrams after frequency-domain deconvolution in heavy rain and on a cloudy day is the best, followed by the diagrams for light or moderate rain; the results for the foggy day are the most scattered. According to the literature[18], the signal-to-noise ratios in heavy, moderate, and light rain and for foggy and cloudy days were calculated. Table 3 shows the corresponding BER before and after deconvolution under the various signal-to-noise ratios. The BER was the largest for moderate rain and on the foggy day, followed by light rain; the values for heavy rain and for the cloudy day were the smallest. The bit error rate after deconvolution in moderate and light rain was reduced from 10^{-2} to 10^{-4}, those in heavy rain and for the cloudy day were reduced from 10^{-3} to 10^{-4}, and that for the foggy day was also reduced by an order of magnitude.

Tab.3 Comparison of BER before and after frequency-domain deconvolution in the channel model

Weather condition	Before deconvolution (BER)	After deconvolution (BER)	SNR/dB
Heavy rain	3.60×10^{-3}	2.0×10^{-4}	33.375 6
Moderate rain	5.07×10^{-2}	5.0×10^{-4}	29.577 9
Light rain	3.18×10^{-2}	3.0×10^{-4}	15.686 1
Foggy day	4.56×10^{-2}	4.9×10^{-4}	12.332 4
Cloudy day	3.50×10^{-3}	1.0×10^{-4}	31.847 2

3 Conclusions

To suppress the multiplicative noise produced by atmospheric turbulence for laser transmissions in the atmospheric channel, this paper has presented a method of frequency-domain deconvolution. Using 4PSK modulation, the atmospheric turbulent channel was simulated using Gamma-Gamma light-intensity scintillation to compare and analyze the constellation diagrams and bit error rates of modulated signals before and after frequency-domain deconvolution under strong, moderate, and mild turbulence. Based on measured data, channel estimation was performed, and the atmospheric channel model was established. Constellation diagrams and bit error rates of modulated signals before and after frequency-domain deconvolution in heavy, moderate, and light rain and on foggy and cloudy days were compared and analyzed. Theoretical and experimental results showed that frequency-domain deconvolution could effectively suppress the multiplicative noise generated by atmospheric turbulence and significantly reduce the bit error rate of the system under a variety of weather conditions. In this paper, an approximately stationary process was used to treat the non-stationary channel, which might cause certain errors in channel estimation and affect the results of frequency-domain deconvolution. Subsequent studies will focus on how to estimate the non-stationary channel and how to reduce further the bit error rates of atmospheric laser communication systems.

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