

Free-space optical communication using patterned modulation and bucket detection

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In this Letter, free-space optical (FSO) communication using patterned modulation and bucket detection is introduced to improve the bit error rate (BER) performance in complex and noisy environments. The scattered light is averaged in this communication structure. Second-order correlation, wavelet normalization, and compressed sensing are combined in the reconstruction algorithm. A signal with N bits is reconstructed well from much less than N measurements. Numerical simulations and experiments are performed without the narrowband optical filters used in traditional FSO communication. It can also be employed in real networks where secure communication is required. This provides the great opportunity to pave the way for real applications of FSO communication.

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Free-space optical (FSO) communication, over the last years, has opened new avenues for remote sensing, last mile access, and military applications owing to its unique features, which include a large bandwidth, license-free spectrum, high data rate, easy and quick deployability, and less power and low mass requirements^[1–8]. The basic principle of FSO communication transmission is very similar to that of fiber optic communication except that unlike fiber transmission, in this case the modulated data is transmitted through an unguided channel instead of a guided optical fiber. In real applications, the FSO communication link is often infeasible in complex and noisy environments, for example, a turbulent atmosphere. Recently, various techniques have been proposed to solve this problem, e. g., aperture averaging, diversity, adaptive optics, modulation and coding, and orbital angular momentum^[9–16]. However, there exists a limitation of the sampling rate or they are expensive and computationally complex and thus difficult to use in practical applications.

In this Letter, we present an FSO communication approach using patterned modulation and bucket detection to improve the bit error rate (BER) performance in complex environments. By using compressed sensing (CS), the proposed method can break the limitation of the Nyquist–Shannon criterion in signal processing and transmit information to a remote party securely. It is also unnecessary to deploy any narrowband optical filters before photodetectors in this approach.

The experimental setup of our method is shown in Fig. 1. The speckle patterns, $S_k(x_i, y_i)$, generated by a spatial light modulator (SLM) as a transmitter (Tx), sequentially

sample the unknown signal, $R(x_i, y_i)$. A synchronous single-pixel detector, as the receiver (Rx), measures the total intensity of the modulated light with a collecting lens, which provides the signal

$$y_k = \sum_{x_i} \sum_{y_j} S_k(x_i, y_j) R(x_i, y_j), \quad (1)$$

where k denotes the number of speckle patterns.

In real applications, various unpredictable environmental factors such as rain, fog, and clouds seriously limit the performance of the optical signal in the atmospheric channel. The disturbance in the optical signal could be

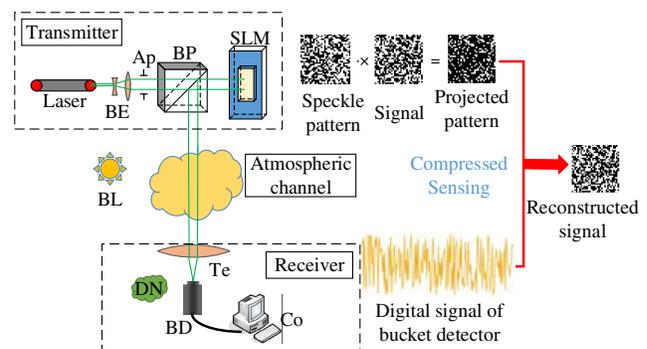


Fig. 1. Experimental setup of FSO communication using patterned modulation and bucket detection. BE: beam expander, Ap: aperture, BP: beam splitter, BL: background light, Te: telescope, DN: device noise, BD: bucket detector, Co: computer.

divided into two aspects: multiplicative noise and additive noise. In the real atmosphere, the scattered and absorbed light is termed as multiplicative noise. The scintillation, background light, and device noise are summarized as additive noise.

In the recent research on light transmission in turbid media, the strongly scattering process is characterized as the transmission matrix K with complex coefficients k_{ij} and the transmitted field is a linear combination of the fields coming from n different segments of the modulator^[17–20]. By doing straightforward calculations, one obtains the light intensity received by the bucket detector as follows:

$$\begin{aligned} I^{\text{out}} &= \sum_{i=1}^s I_i^{\text{out}} = \sum_{i=1}^s \left| \sum_{j=1}^n k_{ij} E_j \right|^2 \\ &= \sum_{i=1}^s \sum_{j=1}^n |k_{ij}|^2 |E_j|^2 + \sum_{i=1}^s \sum_{j=1}^n \sum_{\substack{j'=1 \\ j' \neq j}}^n k_{ij} k_{ij'}^* E_j E_{j'}^*, \end{aligned} \quad (2)$$

where E is the light field from the segments of the modulator and s is the number of output modes. Note that I^{out} is the light intensity in one measurement that cannot recover the signal R . It is seen that the optical paths from the j th input mode to the i th output mode are independent because the light is scattered randomly, so the second terms (or cross terms) in Eq. (2) are averaged on the photosensitive surface of the bucket detector. More precisely, the coefficient of the second term is negligible compared with that of the first term in Eq. (2). Instead, the contributions of all s paths for each light field nearly become equally weighted in the static scattering media. However, the properties of the atmospheric channel as a propagating medium are random functions of space and time. Consequently, the k th measurement of the light intensity received by the bucket detector can be written as

$$I_k^{\text{out}} = \alpha_k \sum_{j=1}^n |E_j|^2, \quad (3)$$

where α_k is the average transmittance of the atmospheric channel in the k th measurement. As mentioned above, the received light intensity is also related to the additive noise, and thus, Eq. (3) can be rewritten in matrix notation as

$$y = \alpha \cdot (SR) + n, \quad (4)$$

where $y \in R^{M \times 1}$ is the captured intensity data, $\alpha \in R^{M \times 1}$ is the vectored average transmittance of the atmospheric channel, $S \in R^{M \times N}$ is the vectored patterned modulation, $R \in R^{N \times 1}$ is the vectored signal, $n \in R^{M \times 1}$ is the vectored additive noise, M is the number of measurements, and N is the number of pixels of the SLM.

When $M < N$, the inversion of Eq. (4) becomes an ill-conditioned problem that can be solved by using CS algorithms. However, prior to the non-linear reconstruction, Eq. (4) is denoised and normalized in two steps. First, the magnitude of the additive noise is reduced by applying

the second-order correlation that was proposed in Ref. [21]. Second, a frequency time-domain transformation (Haar wavelets)^[22] is applied to normalize the significant fluctuations of the acquired data. By doing straightforward calculations, an estimate of noise-free data sets can be mathematically obtained using

$$\Phi = \Delta R, \quad (5)$$

where $\Phi \in R^{N \times 1}$ is the result of the second-order correlation and $\Delta \in R^{N \times N}$ is the orthogonal covariance matrix of the matrix S ^[19]. It is important to emphasize that Eq. (5) is also ill-posed because the denoised and normalized operation will not change the number of maximal independent systems of the covariance matrix. To solve the inversion problem, we use a CS reconstruction algorithm called TV minimization by augmented lagrangian and alternating direction algorithms (TVAL3)^[23]. The TV-based regularization reconstructs the original signal R as \hat{R} by solving the following optimization problem:

$$\hat{R} = \min_x \sum_i \|D_i R\|_{\ell_1} + \frac{\mu}{2} \|\Phi - \Delta R\|_{\ell_2}^2, \quad (6)$$

where D is the gradient operator, $\|\cdot\|_{\ell_1}$ is the ℓ_1 norm, $\|\cdot\|_{\ell_2}$ is the ℓ_2 norm, and μ is a constant scalar used to balance these two terms.

To evaluate the effectiveness of FSO communication using patterned modulation and bucket detection, we started with numerical simulations. In our numerical simulations, an unknown signal with 640000 bits was divided into 100 groups, and each group contained 6400 bits. The speckle patterns, with 80×80 pixels, were generated to satisfy a binary uniform distribution. Each group of the unknown signal was arranged in a two-dimensional matrix notation and sampled by the speckle patterns. Considering the speed and accuracy of the reconstruction, the measurements of each group were 1600, which is 25% of all the pixels. The reconstructed signal was enhanced using threshold value 0.5. The commercial SLM in recent years could reach up to 40 kHz in the binary mode. In our simulations, the pattern projection rates are up to 20 kHz. The speed of FSO communication is defined as

$$v = \frac{M \times N \times f}{M \times N \times \eta} = \frac{f}{\eta}, \quad (7)$$

where f is the frequency of the SLM, and η is the sampling rate in the patterned modulation (that is, the rate of FSO communication using patterned modulation and bucket detection is 80 kb/s). It is noted that the impact of the noise causes relative fluctuations due to the second-order correlation operation, more precisely, the variance of noise σ^2 . Thus, the signal-to-noise ratio (SNR) was defined as $1/\sigma^2$ quantitatively^[24]. White Gaussian noise (WGN) and Poisson noise (PN) were considered to simulate the classical detection and semi-classical detection, respectively. Our simulations were conducted on the platform

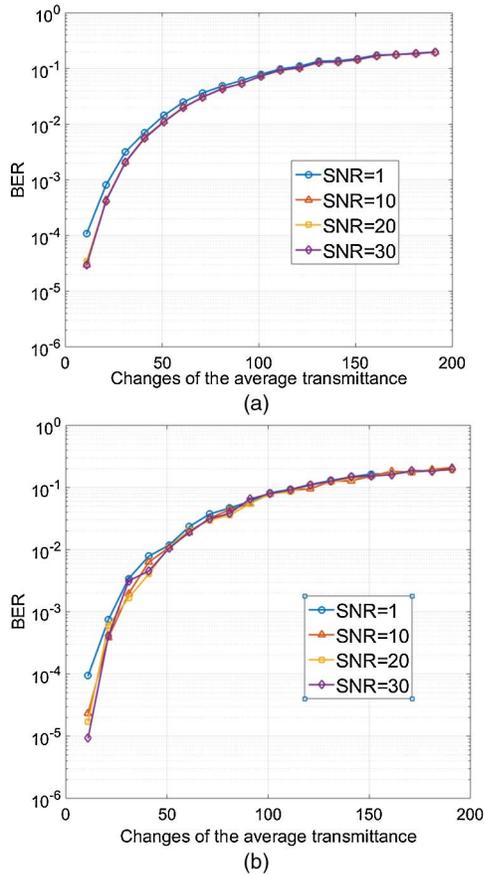


Fig. 2. (a) The results of the BER performance as a function of the changes in the average transmittance at different SNR levels (classical detection). (b) The results of BER performance as a function of the changes in the average transmittance at different SNR levels (semi-classical detection).

of Matlab 2015a. The transmission matrix of the scattering media was generated to satisfy a circular Gaussian distribution^[18,19], and the noise was generated by using a random toolbox. The results of the BER performance, as a function of the changes of the average transmittance at different SNR levels, are summarized in Figs. 2(a) and 2(b).

Both in classical detection and semi-classical detection, the BERs of our proposed method increase with the addition of changes in the average transmittance. It is seen that the influences of WGN and PN make little difference in the same complex environments. Different from traditional FSO communication, FSO communication using patterned modulation and bucket detection is much more robust in noisy environments.

To perform FSO communication using patterned modulation and bucket detection experimentally, the setup shown in Fig. 1 was established. The sampled patterns were projected by the use of a commercial digital projector (Texas Instruments DLP4100). Note that all the random speckle patterns were generated as 80×80 pixel images and satisfied a binary uniform distribution with elements “0” and “1.” The scattered light was collected using a single-pixel detector (DET100A/M, Thorlabs). The refresh

rate of DLP4100 in our experiments could reach up to 22.7 kHz in the binary mode. However, the illumination time of each pattern is set to 0.2 ms to ensure that enough photons are received. The sampling rate is also set at 25%. By doing straightforward calculations, the rate of FSO communication using patterned modulation and bucket detection is 20 kb/s. Commercial diffusers (DG $100 \times 100 - 1500$, Thorlabs) were used to simulate the scattering media, and an expanded halogen lamp (MI-150, Edmund) was used to simulate the background light. It is noted that the average transmittance of the moving diffuser is relatively stable, so the number of diffusers was changed randomly in our experiments. The signals of random binary elements “0” and “1” were arranged in two-dimensional matrix notation and then sampled by the speckle patterns. The reconstructed signal was enhanced using threshold value 0.5.

The experimental results of part of the signal are shown in Figs. 3(a)–3(c). It is seen that the signal was reconstructed well by FSO communication using patterned modulation and bucket detection. To analyze the performance of our proposed method in scattering media and noisy environments, eight random signals with lengths of 64000 bits were transmitted and reconstructed in different conditions. The BER performances of the experiments with moving diffusers are summarized in Table 1. The BER performances of the experiments with environmental illuminations generated by the expanded halogen lamp are summarized in Table 2. The BER performances of the experiments with moving diffusers and environmental illuminations generated by the expanded halogen lamp are summarized in Table 3.

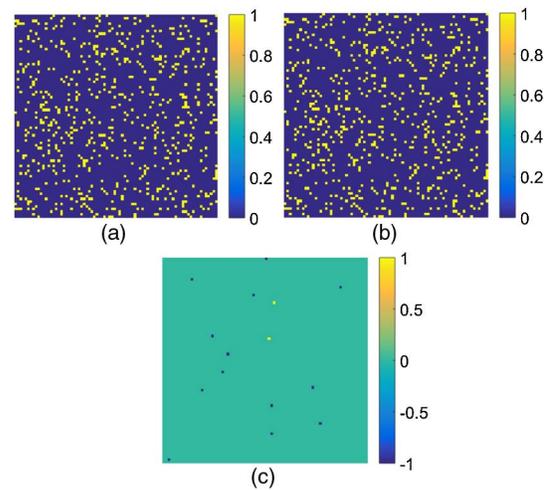


Fig. 3. Experimental results of FSO communication using patterned modulation and bucket detection. (a) is the original signal, (b) is the reconstructed signal, and (c) shows the corresponding bit errors of (a) and (b). The value “1” represents that the original signal is “1” and the reconstructed signal is “0.” The value “-1” represents that the original signal is “0” and the reconstructed signal is “1.” The value “0” represents the correct communication.

Table 1. Experimental Results of the Eight Random Signals (With Moving Diffusers)

	Signal 1	Signal 2	Signal 3	Signal 4
BER	0.28%	0.25%	0.42%	0.19%
	Signal 5	Signal 6	Signal 7	Signal 8
BER	0.14%	0.39%	0.33%	0.20%

Table 2. Experimental Results of the Eight Random Signals (With Environmental Illuminations)

	Signal 1	Signal 2	Signal 3	Signal 4
BER	0.17%	0.14%	0.31%	0.08%
	Signal 5	Signal 6	Signal 7	Signal 8
BER	0.03%	0.28%	0.22%	0.09%

The experimental results show that the proposed method can satisfy the requirements of FSO communication in complex and noisy environments. It is seen that the average BER performances of eight random signals in three conditions are 0.28%, 0.17%, and 0.32%. Compared with environmental illuminations (noise), moving diffusers (dynamic scattering media) have a greater impact on FSO communication using patterned modulation and bucket detection.

To consider the ability of our method for secure communication, the speckle patterns (in matrix notion) generated in the experiments were tested using the ENT program^[25]. The results of the test are summarized in Table 4. It is seen

Table 3. Experimental Results of the Eight Random Signals (With Moving Diffusers and Environmental Illuminations)

	Signal 1	Signal 2	Signal 3	Signal 4
BER	0.33%	0.30%	0.47%	0.23%
	Signal 5	Signal 6	Signal 7	Signal 8
BER	0.19%	0.44%	0.38%	0.25%

Table 4. Results of ENT Test

	Experimental results	Ideal results
Entropy	0.999990	1
Arithmetic mean value	0.5019	0.5
Monte Carlo value for π	3.1278320	3.1415926
Serial correlation coefficient	-0.002463	0

that the randomness of the speckle patterns is very good. The great randomness means that the distribution of the speckle patterns and orders must be guessed to recover the signals when the received data was intercepted. In our experiments, the size of the speckle patterns of each group (in matrix notion) is 1600×6400 , and thus the probability of them being deciphered through an exhaustive attack is $2^{-10240000}$. By doing a simple calculation, the enumeration method will take too many years even with the use of a supercomputer. Thus, FSO using patterned modulation and bucket detection can be considered secure.

In conclusion, we theoretically and experimentally demonstrate FSO communication using patterned modulation and bucket detection. Multiplicative and additive noise are dramatically limited to improve the BER performance of FSO communication in complex and noisy environments. In our experiments, the average BER of eight random signals is 0.32% with a 25% sampling rate. Though our method could hardly reach the standard of 10^{-9} - 10^{-6} in optical communication, it can satisfy the requirements of FSO communication in complex and noisy environments. The great randomness of speckle patterns ensures that the communication is secure. It is noticeable that the experimental setup is also simple and inexpensive and can be quickly employed. Combining FSO communication using patterned modulation and bucket detection with other proposed applications of FSO communication, especially in complex environments, will significantly improve the success rate and security of communication.

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