High-fidelity ghost diffraction through complex media using a single-photon detector

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ABSTRACT

Free-space optical (FSO) transmission in complex scenarios remains a challenge, especially at low-light levels. Here, we report a ghost diffraction system with a single-photon detector to enable effective and robust transmission through dynamic scattering media under photon-limited conditions. At the transmitter, each pixel of a signal is encoded into a 2D random pattern via a single-layer convolutional neural network (SCNN). By using an all-ones matrix as an input and the random pattern as a convolution filter, SCNN can be designed to model the physical process of ghost diffraction, and can scale the sum of each random pattern to be proportional to a corresponding pixel of the signal in an untrained manner. The generated 2D random patterns, serving as information carriers, are sequentially displayed in a FSO channel to modulate a laser beam. At the receiver, weak and scattered light intensities are detected by using a single-photon counting module (SPCM). To verify the proposed ghost diffraction system, a series of optical experiments are conducted using varying water turbidities and different rotation speeds. Experimental results demonstrate that the proposed method can achieve high-fidelity and high-robustness FSO transmission in femtowatt-level low-light environments with random disturbances from dynamic and turbid water. The proposed ghost diffraction system with a single-photon detector offers a promising solution for high-fidelity FSO transmission in complex scenarios at low-light levels.

Free-space optical (FSO) transmission, as one of the prominent wireless communication techniques, has attracted significant attention over the past decades.[1] Utilizing infrared, visible or ultraviolet light as a medium to convey information,[2–4] FSO transmission offers a broad unlicensed spectrum,[5] high data rates, low cost and superior energy efficiency.[6] With these advantages, FSO transmission has shown great potential in various applications, e.g., celestial[7] and underwater exploration.[8] However, its performance can be compromised by absorption and scattering in the optical channel, leading to degraded transmission quality and restricting a widespread deployment.[5,9] To address the challenges, research efforts were made, such as aperture averaging,[10] adaptive optics[11] and channel coding schemes.[12]

Ghost diffraction has emerged as a promising solution for FSO transmission in complex environments.[13–15] Ghost diffraction was initially developed in the quantum domain[16] and later was demonstrated with classical light sources.[17,18] In a typical ghost diffraction system, the incident light is modulated by a series of illumination patterns, and the total light intensities are recorded by a single-pixel detector.[19,20] The sum of all pixel values in an illumination pattern is proportional to the corresponding recorded light intensity, allowing illumination patterns to be used as information carriers for data transmission.[21,22] Although the proportional relationship withstands interference from static scattering media, it can be disrupted in dynamic environments.[23–25] Moreover, rapid and severe attenuation in FSO channels may cause the recorded light intensity to fall below the sensitivity of single-pixel detectors (e.g., PIN photodiodes).[26,27] Therefore, it is meaningful to develop an advanced optical system to realize FSO transmission through dynamic scattering media under ultra-low-light conditions.

In this Letter, we report a ghost diffraction system with a single-photon counting module (SPCM) for high-fidelity FSO transmission through dynamic scattering media in low-light environments. A single-layer convolutional neural network (SCNN) is designed to represent the physical process of ghost diffraction and encode each pixel of a signal into a 2D random amplitude-only illumination pattern in an untrained manner. To mitigate the influence of dynamic environments, the random pattern generated by SCNN is divided into two patterns via a differential protocol, and a fixed reference pattern is placed before each generated random pattern as a temporal carrier. A series of random patterns carrying the information are uploaded into a spatial light modulator (SLM) to modulate the laser beam. In the FSO channel, the modulated laser beam is severely affected by the disturbances from dynamic and turbid water. At the receiving end, a series of photon-level light intensities are captured by SPCM to be used to decode the signal. Optical experiments for 1D analog-data transmission are conducted at different water turbidity levels and different rotation speeds. It is experimentally verified that the proposed ghost diffraction system can achieve high-fidelity FSO transmission through complex media in femtowatt-level low-light environments.

A schematic experimental setup for the proposed ghost diffraction system through complex media is shown in Fig. 1. A green laser (MGI-III-532-200mW) is used as light source to irradiate an amplitude-only SLM (Holoeye, HED 6001). A series of random illumination patterns P serving as information carriers are sequentially displayed by SLM to modulate the laser beam. The modulated beam is subsequently attenuated using neutral density filters to establish a low-light environment before propagating through dynamic scattering media in the FSO channel. To design a dynamic scattering environment, 3-mL skimmed milk mixed with 100-mL clean water is continuously dropped into a tank initially containing 1000-mL clean water with dimensions of 5 cm (length) × 10 cm (width) × 30 cm (height). A rotator operating at 500 rpm is employed to agitate the milk emulsion inside water tank. At the receiving end, a fiber coupling mechanism is positioned adjacent to the water tank to collect all diverging light and focus it onto the active area of SPCM (Thorlabs, SPCM50A/M). The fiber coupling mechanism comprises a fiber collimator package (LBTEK, FC520-6.1-PC), a step index multimode fiber (LBTEK, MMC50L-0.22-PC-1), a lens tube with an internal adapter to hold an aspheric lens with a focal length of 5 cm, an X-Y translation mount, and SPCM. SPCM features an active detector diameter of 50 μm and a photon detection efficiency of 30.5% at wavelength of 532 nm. In experiments, the bin length of SPCM is set as 20 ms, and laboratory temperature is maintained at 24.5°C. The optical power behind SLM is measured to be 0.97 mW using a power meter (Newport, 1936-R) and is attenuated to 29 nW after passing through neutral density filters. The axial distance between SLM and the front face of water tank is 46 cm.

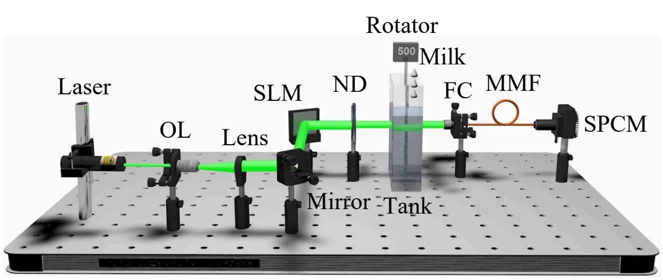

FIG. 1. A schematic experimental setup for the proposed method in complex and low-light environments. OL: objective lens with a magnification of 40x; SLM: an amplitude-only spatial light modulator; ND: neutral density filters; FC: fiber collimator; MMF: step-index multimode fiber.

Figure 2 shows a flow chart of the proposed ghost diffraction system designed for FSO transmission through complex media. In the proposed system, 1D normalized analog data S with 64 pixels are transmitted as typical examples, and each pixel S_i (i=1,2,3,…,64) is converted into a 2D random illumination pattern P_i via SCNN in the encoding procedure. SCNN consists of a single convolutional layer with an all-ones matrix Λ as input. The filter in the convolutional layer is designed to match the dimension of the input matrix, resulting in the network output related to the sum of pixel values of the filter. When the convolution filter is considered as a random illumination pattern, the forward process of SCNN can show a physical model of ghost diffraction, including optical modulation, wave diffraction and single-photon detection. The random illumination pattern extracted from SCNN carries signal information, once the network output approximates original pixel S_i. Therefore, an objective function for SCNN-based data encoding can be described by

$$\min_{P_i} \left\| \frac{\Lambda \otimes P_i}{\eta} - S_i \right\|^2 , \tag{1}$$

where ⊗ denotes a convolution operation in neural network leading to an output with a sum of the filter, and η denotes a weighting factor to achieve a fast convergence which is set as 30000 in this study. Adam optimizer[28] with a learning rate of 0.01 is used to update the parameters of the convolution filter, i.e., a random illumination pattern.

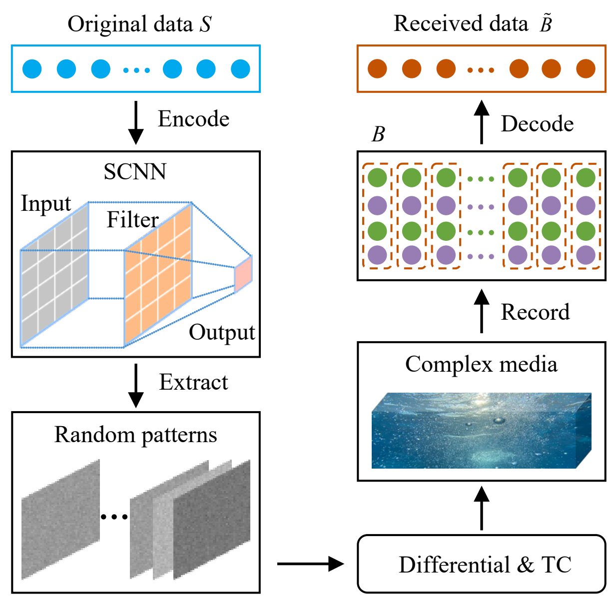

FIG. 2. A flow chart of the developed ghost diffraction system with single-photon detection in complex environments. TC: a temporal carrier (i.e., a fixed reference pattern).

The dimensions of the input matrix and the illumination pattern are 256×256 pixels. After optimization, the scaled sum of all pixel values in a generated random pattern is close to original pixel S_i, thereby encoding original pixel into a random pattern. A differential protocol is further adopted to suppress noise in experiments. A positive pattern $1+P$ and a negative pattern $1-P$ can be obtained. It is worth noting that the negative pattern could be too dark to be distinguished by SPCM in experiments when the encoded pixel is >0.5. To address this issue, for any pixel of the signal S with a value exceeding 0.5, 0.5 is subtracted before data encoding and then is added to the retrieved data at the receiving end. The encoding procedure is performed on a NVIDIA GeForce

RTX 4090 GPU and is repeated until all pixels in original signal S are converted into random illumination patterns. No any datasets or labels are needed in the proposed SCNN-based encoding method.

With a series of generated random patterns as information carriers, the light intensities recorded by SPCM at the receiving end can be described by[29]

$$B_{i1} \approx k_{i1} \iint \left[1 + P_i(x, y) \right] dxdy, \tag{2}$$

$$B_{i2} \approx k_{i2} \iint \left[1 - P_i(x, y) \right] dxdy, \tag{3}$$

where B_{i1} and B_{i2} denote the recordings (i.e., the collected photon counts respectively corresponding to patterns $1+P_i$ and $1-P_i$), k_{i1} and k_{i2} denote scaling factors, and (x, y) denotes a spatial corrdinate. With a dynamic and turbid water environment in the FSO channel, time-varying scaling factors could destroy the linearly proportional relationship between the sum of pixel values in random patterns and the collected photon counts, impeding a direct retrieval of high-fidelity data. To eliminate the influence of dynamic scaling factors, a fixed random pattern P^t with a uniform distribution is introduced as a temporal carrier and applied before each random illumination pattern generated by SCNN.[23] The total photon counts B^t collected by SPCM corresponding to the temporal carrier P^t can be described by

$$B^t \approx k^t \iint P^t(x, y) dxdy, \tag{4}$$

where k^t denotes a scaling factor corresponding to the temporal carrier P^t. The scaling factor k^t can be assumed to be the same as that scaling factor of its adjacent illumination pattern due to a short time interval. The dynamic scaling factors are corrected by simply applying a division operation, and the retrieved data $\tilde{B}_i$ can be described by

$$\tilde{B}_i = \frac{B_{i1}}{B_{i1}^t} - \frac{B_{i2}}{B_{i2}^t}, \tag{5}$$

where B_{i1}^t and B_{i2}^t denote the total photon counts collected corresponding to the fixed temporal carriers placed before the patterns $1+P_i$ and $1-P_i$, respectively.

A series of optical experiments are conducted to validate the effectiveness of the proposed ghost diffraction system for FSO transmission through complex media under low-light conditions. Peak signal-to-noise (PSNR)[30] is calculated to quantitatively evaluate transmission accuracy. Four different analog signals are individually encoded into random patterns via SCNN which are illuminated to propagate through dynamic and turbid water in Fig. 1. As shown in Figs. 3(a)–3(d), the retrieved data at the receiver overlap with the original data with PSNR values higher than 35 dB, overcoming the challenge posed by dynamic and complex scattering environments at low-light levels. The received optical power, calculated from the photon counts detected by SPCM,[31] decreases to ~66 fW after optical data transmission process is completed. It is illustrated that analog data can be transmitted with high fidelity in femtowatt-level low-light environments, showing potential of the proposed system for the long-distance FSO communication in complex environments with heavy attenuations.

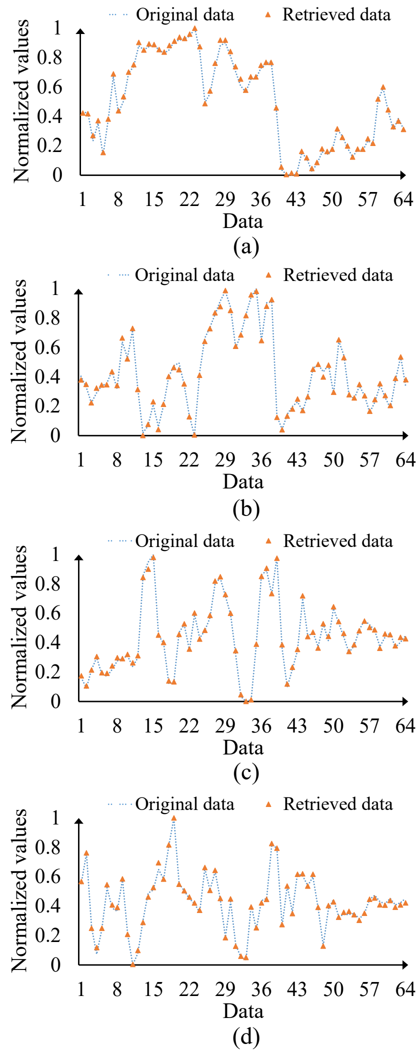

FIG. 3. (a)-(d) Comparisons between experimentally retrieved data and the original data for different analog signals. PSNR values are 35.27 dB, 35.52 dB, 36.25 dB and 36.40 dB, respectively.

To evaluate robustness of the proposed ghost diffraction system in complex environments, different water turbidity levels are investigated by dropping different volumes of skimmed milk into the water tank. The variations of PNSR and the received power are shown in Fig. 4(a) when 1-mL to 6-mL skimmed milk with an interval of 1 mL is individually used. With increasing turbidity, PSNR values decrease from 38.50 dB to 28.31 dB, and the received power drops from 90.87 fW to 29.60 fW. To be specific, in Fig. 4(b), the retrieved data well match with the original data when 1-mL skimmed milk is continuously dripped into water tank. Slight derivations from the original data can be observed with 5-mL skimmed milk, as shown in Fig. 4(c). The further increase in turbidity could result in pronounced transmission errors with PSNR values lower than 30 dB. Experimental results in Fig. 4 demonstrate that the proposed ghost diffraction system achieves high-fidelity FSO transmission when the volume of skimmed milk to be used is less than 5 mL.

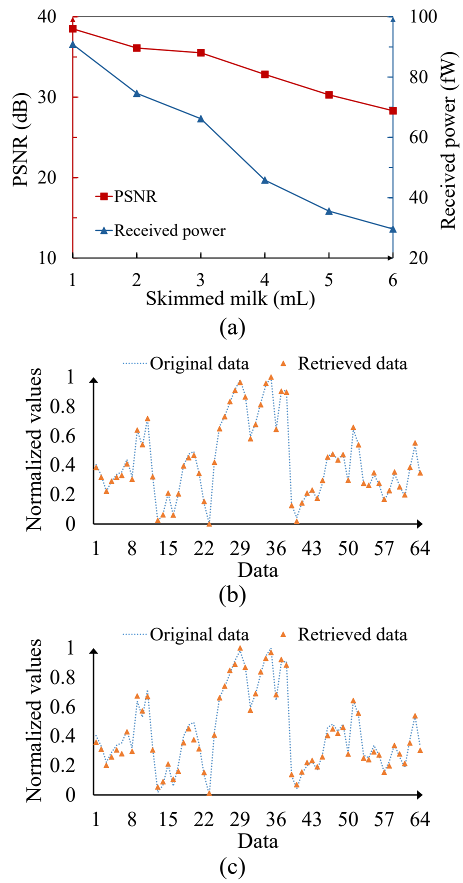

FIG. 4. (a) PSNR variations and the received power when different volumes of skimmed milk are used, and (b) and (c) comparisons between the experimentally retrieved data and original data respectively using 1-mL and 5-mL skimmed milk. PSNR values in (b) and (c) are 38.50 dB and 30.29 dB, respectively. Here, the rotation speed is fixed at 500 rpm in Fig. 1.

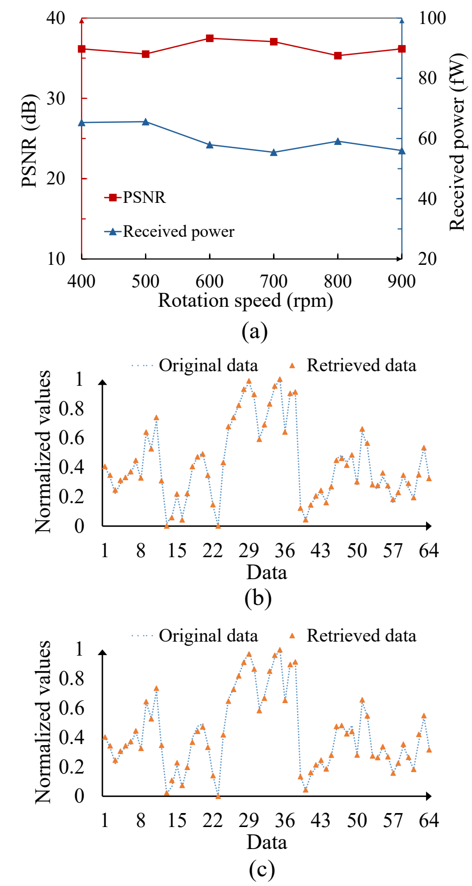

FIG. 5. (a) PSNR variations and the received power when different rotation speeds are used, and (b) and (c) comparisons between the experimentally retrieved data and original data respectively with rotation speeds of 600 rpm and 900 rpm. PSNR values in (b) and (c) are 37.49 dB and 36.17 dB, respectively. Here, the volume of skimmed milk is fixed at 3 mL in Fig. 1.

In addition to water turbidity, the performance of the proposed ghost diffraction system is also tested by using different rotation speeds. As shown in Fig. 5(a), when different rotation speeds are individually used from 400 rpm to 900 rpm with an interval of 100 rpm, PSNR values of the retrieved data are always high (i.e., >35 dB) and the received optical power is stable at the femtowatt level. The high overlapping between the original and retrieved data at rotation speeds of 600 rpm and 900 rpm in Figs. 5(b) and 5(c) also validates high fidelity and high robustness of the proposed method against water-flow-induced turbulences in low-light environments. In fact, high rotation speeds could promote a rapid mixture of milk and clean water for FSO transmission in dynamic and turbid water environments via avoiding abrupt intensity variations during the milk dripping.

In conclusion, we report a ghost diffraction system with single-photon detection to achieve high-fidelity FSO transmission through dynamic scattering media in low-light environments. SCNN is designed to model the physical process of ghost diffraction through a single-layer architecture, operating in an untrained manner. After optimization, pixels in the signal are encoded into a series of 2D random amplitude-only illumination patterns. The generated random patterns serve as information carriers to modulate the laser beam through dynamic and turbid water. At the receiving end, SPCM with fiber coupling mechanism is employed to record the photon counts. A series of optical experiments demonstrate that the proposed ghost diffraction system enables high-fidelity and high-robustness FSO transmission under different water turbidity levels and different rotation speeds in dynamic and complex scattering environments at the femtowatt level. It is believed that the proposed method can be used for other data (e.g., the longer signals and 2D images), and provides a direction for future research endeavors on FSO transmission in complex and low-light environments.

This work was supported by Hong Kong Research Grants Council General Research Fund (15224921, 15223522, 15237924), Hong Kong Research Grants Council Collaborative Research Fund (C5047-24G), Guangdong Basic and Applied Basic Research Foundation (2023A1515010831, 2025A1515011411), and The Hong Kong Polytechnic University (1-CDJA, 1-WZ4M).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Yang Peng: Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Writing – original draft (lead). **Yining Hao:** Formal analysis (lead); Investigation (lead). **Wen Chen:** Conceptualization (lead); Formal analysis (lead); Methodology (lead); Resources (lead); Funding acquisition (lead); Project administration (lead); Supervision (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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