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High-efficiency and high-fidelity optical signal transmission in free space through scattering media using 2D random amplitude-only patterns and look-up table

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A R T I C L E I N F O

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A B S T R A C T

A new approach using 2D random amplitude-only patterns and look-up table (LUT) is proposed to realize high-efficiency and high-fidelity optical signal transmission in free space through scattering media. Any digital signal only containing 0 and 1 can be optically transmitted with high fidelity in free space through scattering media using only 4 pre-generated 2D random amplitude-only patterns stored in a database. Any grayscale image with values ranging from 0 to 255 can also be transmitted with high fidelity in a direct mode using only 512 pre-generated 2D random amplitude-only patterns stored in a database. For analog signals, a LUT can also be constructed to facilitate optical signal transmission in free space through scattering media. Optical experiments are carried out to verify feasibility and effectiveness of the proposed method. The proposed method can provide a novel insight for high-efficiency and high-fidelity optical signal transmission in free space through scattering media.

1. Introduction

In the field of optical signal transmission, optical wave serves as an important means for transmitting the signals. Optical signal transmission in free space is regarded as one of the most attractive areas in recent years [1–4]. However, real conditions can result in wave scattering [5], which leads to performance degradation of optical signal transmission in free space that hampers the widespread use of free-space signal transmission techniques. A major challenge for optical signal transmission in free space is to address information loss caused by scattering media when light wave propagates in free space [6,7]. The disordered medium could make it impossible to accurately calculate wave propagation by using mathematical tools, and the inhomogeneity of scattering media scrambles the desired waveform into noise-like patterns, making it difficult to extract effective information at the receiving end [8–12]. How to directly transmit analog signal (rather than just binary signals) in free space through multi-layer scattering media is another serious concern. Until now, for optical signal transmission in free space, signal transmission mainly uses optical wave with large wavelengths to partially overcome the obstacles in free space. Hence, it is meaningful and significant to further realize high-fidelity and high-robustness optical analog-signal transmission in free space especially through scattering media.

In conventional methods, a signal is usually encoded into light intensity by 1D amplitude modulation with an expensive waveform generation device. It has been found that optical imaging could be realized using a single-pixel detector [13–20], and the signal can be encoded using a series of 2D matrices. The 2D matrices are embedded into a spatial light modulator (SLM) to realize amplitude modulation of light source. A single-pixel detector [13–20] is used to collect the light intensity, and the image or signal can be recovered from the collected light intensity. However, it has been well recognized that realizing high-efficiency and high-fidelity optical transmission in free space through scattering media is a significant challenge and time-consuming.

In this paper, a new approach using the properly-designed 2D random amplitude-only patterns and look-up table (LUT) is proposed to realize high-efficiency and high-fidelity optical signal transmission in free space through scattering media. Here, when the LUT is designed and applied, it is feasible to realize high-fidelity and high-efficiency optical transmission of any digital signal (i.e., 0 and 1) in free space through scattering media by using only four pre-generated 2D random amplitude-only patterns stored in a database. Any grayscale image with values ranging from 0 to 255 can also be transmitted with high-fidelity and high-efficiency in a direct mode using only 512 pre-generated 2D random amplitude-only patterns stored in a database. For analog signal, it is also proven to be feasible to realize high-fidelity and high-efficiency optical transmission in free space through scattering media by using the proposed method. Optical experiments are conducted to show validity of the proposed method, i.e., to realize high-fidelity and high-efficiency optical transmission of different types of signals in free space through

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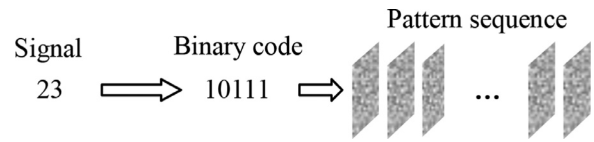


Fig. 1. A schematic for optical transmission of digital signal.

scattering media using properly-designed 2D random amplitude-only patterns and the LUT.

2. Principle

For the proposed optical transmission of digital signal in free space through scattering media, binary values 0 and 1 are, respectively encoded into two different 2D random amplitude-only patterns *P* at first. The encoding procedure is described as follows: (1) generate an initial 2D random pattern *R* with real values; (2) apply Fourier transform to the initial 2D random pattern *R* and obtain its Fourier spectrum *FR*; (3) use the value 0 or 1 to replace zero-frequency component of the Fourier spectrum *FR* and get a new Fourier spectrum *FR'*; (4) apply inverse Fourier transform to *FR'* and finally generate a desired 2D random amplitude-only pattern *P*. After the encoding process, i.e., Steps (1)-(4), the binary value 0 or 1 is fully encoded into a 2D random amplitude-only pattern, and the generated 2D random amplitude-only pattern can be embedded in the optical path to conduct amplitude modulation of light source to realize signal transmission in free space through scattering media. The finally generated 2D amplitude-only pattern $P(x, y)$ can be described by

$$B = k \iint P(x, y) e^{-2\pi j(x\xi + y\eta)} dx dy \Big|_{\xi=0,\eta=0} = k \iint P(x, y) dx dy, \tag{1}$$

where $j = \sqrt{-1}$, k denotes scaling factor, (x, y) denotes the coordinate in spatial domain, (ξ, η) denotes the coordinate in frequency domain, and B denotes zero-frequency component which is equivalent to the encoded binary value (i.e., 0 or 1). To facilitate practical implementation in optical experiments, each pattern *P* corresponding to 0 or 1 is further divided into *a*+*P* and *a*-*P* where *a* denotes a constant which can avoid negative values and suppress various noise during optical transmission by using differential detection.

In this study, a LUT is further constructed, as shown in TABLE 1. For instance, the value of 23 in Fig. 1 can be transformed into its binary code, and then the 2D random amplitude-only patterns corresponding to binary code can be easily accessed and retrieved based on the LUT in TABLE 1 which can dramatically enhance efficiency of optical transmission in free space through scattering media, i.e., to facilitate data encoding process and save data storage memory. In other words, it is not needed to repeat to generate 2D random amplitude-only patterns for optical transmission of each signal, when the designed LUT is used.

The signal decoding or retrieval process is as follows: (1) For each pixel value *z* to be transmitted, its corresponding patterns *a*+*P* and *a*-*P* are sequentially embedded into the SLM and are illuminated to propagate through scattering media in free space; (2) Intensity values *B*1 and *B*2 corresponding to the two patterns (i.e., *a*+*P* and *a*-*P*) are recorded by using a single-pixel bucket detector at the receiving end; (3) Value *z'*, i.e., *B*1-*B*2, serves as a retrieved pixel value; (4) Step (1) to Step (3) are iteratively applied, and then all pixel values can be retrieved; (5) All the retrieved pixel values are further divided by the maximum value in order to obtain a normalized signal, i.e., the finally retrieved signal.

When the patterns *a*+*P* and *a*-*P* are sequentially used, single-pixel optical detection process can be respectively described by

$$B1 = k \iint (a + P) e^{-2\pi j(x\xi + y\eta)} dx dy \Big|_{\xi=0,\eta=0} + noise, \tag{2}$$

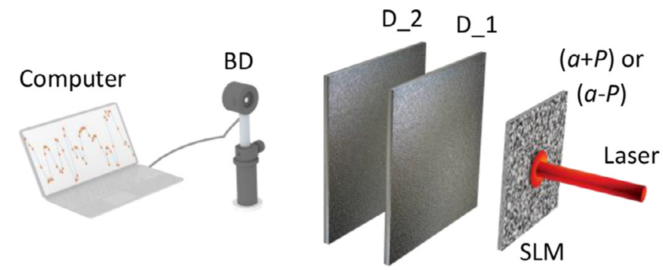


Fig. 2. A schematic optical setup. (*a*+*P*) or (*a*-*P*): amplitude-only pattern sequentially embedded into the SLM; D: diffuser; BD: single-pixel (bucket) detector.

$$B2 = k \iint (a - P) e^{-2\pi j(x\xi + y\eta)} dx dy \Big|_{\xi=0,\eta=0} + noise, \tag{3}$$

where *B*1 denotes single-pixel value corresponding to pattern *a*+*P*, and *B*2 denotes single-pixel value corresponding to pattern *a*-*P*. There is environmental and shot noise during data recording.

After the detection, we have

$$\begin{aligned} B1 - B2 &= k \iint (a + P - a + P) e^{-2\pi j(x\xi + y\eta)} dx dy \Big|_{\xi=0,\eta=0} \\ &= 2k \iint P e^{-2\pi j(x\xi + y\eta)} dx dy \Big|_{\xi=0,\eta=0} \\ &= 2kz. \end{aligned} \tag{4}$$

In Eq. (4), the retrieved value is proportional to original pixel value *z*, and scaling factor in Eq. (4) can be omitted by a normalization operation. The proposed method can effectively suppress noise. Therefore, the retrieved signal is of high fidelity by using the proposed method.

3. Experimental results and discussion

Optical experiments are conducted to show validity of the proposed method, and a schematic optical experimental setup is shown in Fig. 2. In optical experiments, a He-Ne laser with wavelength of 633.0 nm is used as light source to be expanded and collimated, and 2D random amplitude-only patterns (i.e., acting as information carrier) retrieved from the LUT are successively embedded into a SLM. Here, the SLM (Holoeye, LC-R720) conducts amplitude-only modulation, and has pixel size of 20.0 μm. The pattern size is of 512×512 pixels. Scattering environment in optical experiment is constructed by using two cascaded diffusers (Thorlabs, DG10-1500) as shown in Fig. 2. The random amplitude-only patterns are illuminated to propagate through two cascaded diffusers in free space. At the receiving end, a single-pixel bucket detector (Newport, 918D-UV-OD3R) is used to collect light intensity. The axial distance between two diffusers is 1.0 cm. The single-pixel bucket detector is placed 3.5 cm away from the second diffuser, and is placed 12.5 cm away from the SLM.

For the proposed optical transmission of digital signal, when the value 0 needs to be transmitted, two patterns directly retrieved from the LUT, i.e., *a*+*P* and *a*-*P* in Table 1, are sequentially embedded into the SLM and are illuminated to propagate through the cascaded diffusers and then two intensity points (B1 and B2) are correspondingly collected by single-pixel detector. In this case, the two intensity values are subtracted to be considered as equivalently to 0, as typically shown in Fig. 3(a). When the value 1 is transmitted, two patterns directly retrieved from the LUT, i.e., *a*+*P* and *a*-*P* in Table 1, are used in the optical setup and two intensity points (B1 and B2) collected by the single-pixel detector are subtracted to obtain the result which corresponds to binary code 1, as typically shown in Fig. 3(b). Many digital signals have been tested based on the optical setup in Fig. 2 by using the proposed method, and typical experimental results are shown in Fig. 3(c). As seen in Fig. 3(c), binary signals transmitted in free space through scattering media are accurately retrieved.

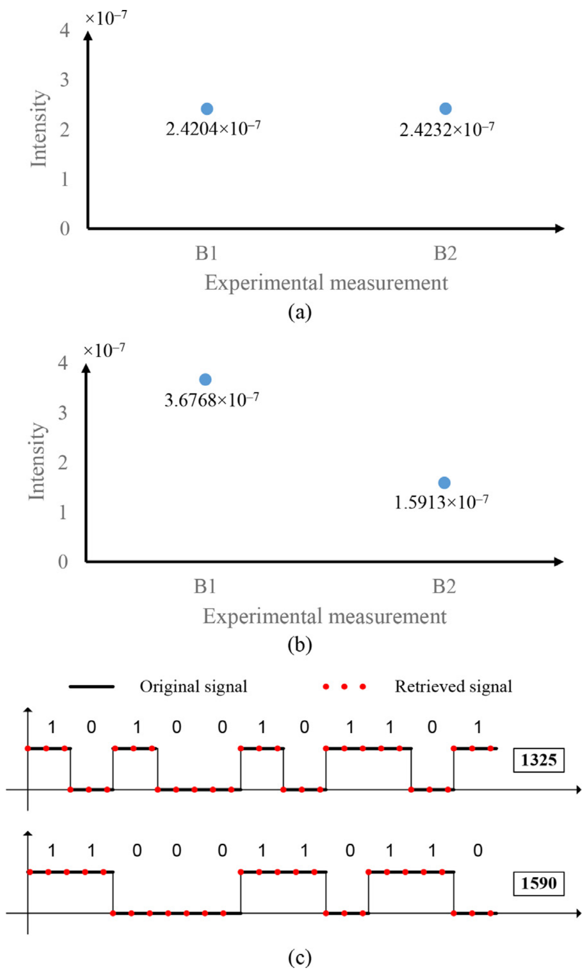


Fig. 3. Optical experimental results: the recorded intensity values to obtain (a) binary code 0 and (b) binary code 1, and (c) typical experimental results for optical transmission of digital signals using the proposed method. The optical setup in Fig. 2 is used.

The proposed method can be used for directly transmitting various types of signals with high fidelity through scattering media and also enhancing the efficiency of data encoding process, e.g., a grayscale image with values ranging from 0 to 255. Instead of converting each pixel value to binary codes, we can directly pre-generate 2D random amplitude-only patterns, respectively corresponding to each value from 0 to 255 by using the developed principle in order to establish a LUT. Therefore, the number of 2D random amplitude-only patterns to be sequentially embedded into the SLM, i.e., compared to that using binary codes in Fig. 1, can be dramatically reduced for optically transmitting the grayscale image, and efficiency of the encoding process can be dramatically enhanced. A LUT is constructed in Table 2, and all grayscale images with values ranging from 0 to 255 can be transmitted by using this designed LUT. It is straightforward to design a LUT for transmitting any image with the higher bit depth.

In Ref. [21], orbital angular momentum serves as information carrier to transmit the data through scattering media, and each pixel value of grayscale image (e.g., a value of 234) is transformed into binary (e.g., 11101010). In the proposed method, each grayscale pixel value can be directly transmitted. The data transmission rate can be efficiently enhanced under the same experimental conditions.

To demonstrate effectiveness of the proposed method, two grayscale images, i.e., Fig. 4(a) and (c), are individually tested based on the optical setup in Fig. 2, and experimental results obtained at the receiving end are shown in Fig. 4(b) and (d), respectively. To quantitatively evaluate quality of the images obtained at the receiving end, peak signal-to-noise ratio (PSNR) and mean squared error (MSE) are calculated, as given in Fig. 4. The high PSNR values and low MSE values demonstrate that high-fidelity data retrieval is realized by using the proposed method. A typical comparison between the values along the 32nd row of that in Fig. 4(b) and original values in Fig. 4(a) is shown in Fig. 4(e).

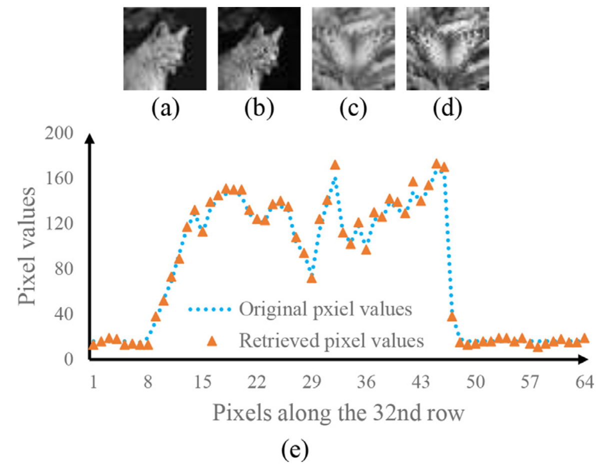


Fig. 4. (a) and (c) Original grayscale images (64×64 pixels), (b) and (d) the images (64×64 pixels) experimentally recovered at the receiving end by using the proposed method. PSNR values for (b) and (d) are 34.08 dB and 34.77 dB, respectively. MSE values for (b) and (d) are 3.91×10^{-4} and 3.33×10^{-4}, respectively. (e) A typical comparison between the values along the 32nd row of (b) and original values in (a). The optical experimental setup in Fig. 2 is used.

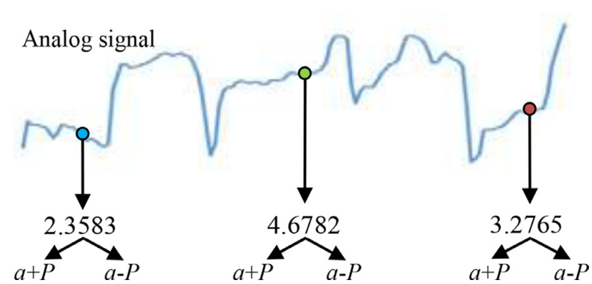


Fig. 5. A schematic for an analog signal.

It is recognized that it is a significant challenge to directly realize high-efficiency and high-fidelity optical transmission of analog signals in free space through scattering media. Here, analog signal is sampled to be a series of independent values as typically illustrated in Fig. 5. A LUT is also constructed by pre-generating and pre-storing 2D random amplitude-only patterns, respectively corresponding to each value of analog signal. The LUT is constructed to contain a series of 2D random amplitude-only patterns for all values of analog signal as shown in Table 3, and the analog signal is transmitted in free space through scattering media with high fidelity and high efficiency using the proposed method.

Here, three irregular analog signals are individually transmitted in free space through scattering media based on the optical setup in Fig. 2 using the proposed method in Table 3, and optical experimental results obtained at the receiving end are shown in Fig. 6(a)–(c). The high PSNR values and low MSE values are obtained as shown in Fig. 6. As can be seen in Fig. 6(a)–(c), the experimentally retrieved signals overlap with original signals, which means that high-fidelity and high-efficiency optical transmission is achieved by using the proposed method. It is straightforward to design a LUT for directly transmitting any analog signal through scattering media in the proposed method. It can be seen from the experimental results in Figs. 3, 4 and 6 that the proposed method not only accurately realizes digital signal transmis-

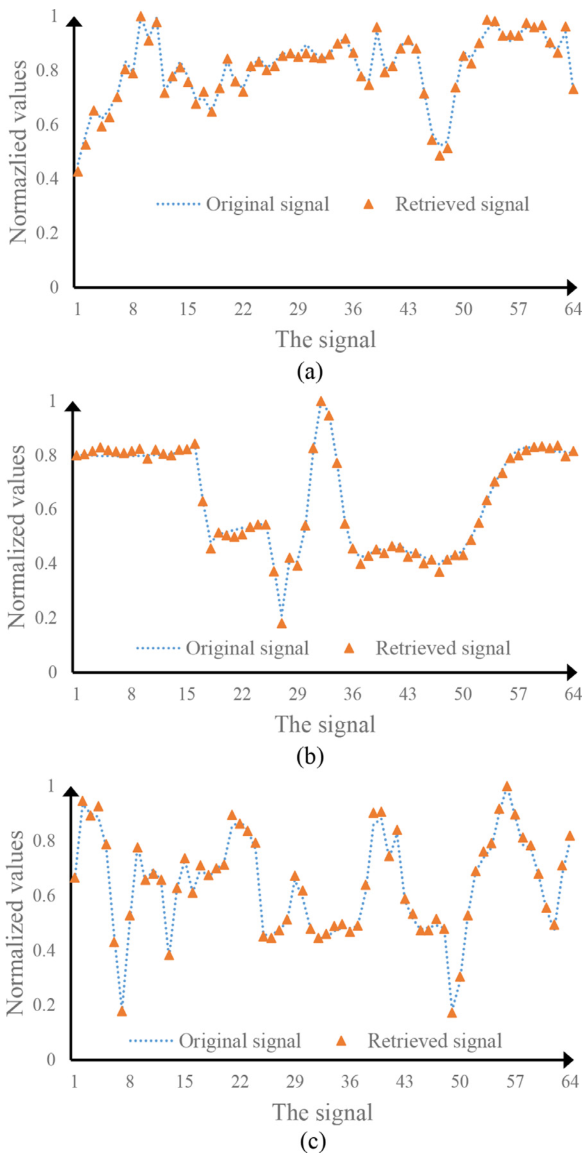


Fig. 6. Optical experimental results: (a)–(c) comparisons between analog signals experimentally obtained at the receiving end and original analog signals. The PSNR values for (a)–(c) are 35.50 dB, 36.88 dB and 35.54 dB, respectively. The MSE values for (a)–(c) are 2.82×10^{-4}, 2.05×10^{-4} and 2.79×10^{-4}, respectively. The optical experimental setup in Fig. 2 is used.

Binary	Pattern *P*	*a*+*P*	*a*-*P*
0			
1			

Table 1. The designed LUT for transmitting a binary signal.

Values	Pattern *P*	*a*+*P*	*a*-*P*
0			
⋮	⋮	⋮	⋮
188			
⋮	⋮	⋮	⋮
255			

Table 2. A designed LUT for transmitting grayscale image.

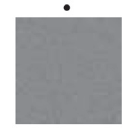
Analog signal	Pattern *P*	*a*+*P*	*a*-*P*
⋮	⋮	⋮	⋮
0.5342			
⋮	⋮	⋮	⋮
4.8563			
⋮	⋮	⋮	⋮
15.9634			
⋮	⋮	⋮	⋮

Table 3. A designed LUT for transmitting analog signal.

sion, but also is able to effectively and efficiently realize analog signal transmission in a direct mode through scattering media which can dramatically enhance channel capacity.

The proposed method is advantageous over conventional intensity modulation of light source, and can effectively enhance channel capacity since analog signal can be transmitted in a direct mode. In addition, without the arbitrary waveform generator used in conventional methods, the proposed method can realize high-precision analog-signal modulation and fully reduce the system cost. The proposed method is simple and easy to implement, and is also advantageous over conventional methods in algorithm complexity and the suppression of pointing errors. In terms of the refreshing rate of 2D random patterns [22–26], it can be further enhanced by using a digital micromirror device to display random patterns [27] or spatial multiplexing of temporally modulated light sources to generate 2D random patterns [28].

4. Conclusion

We have proposed a new approach using the properly-designed 2D random amplitude-only patterns and the LUT to realize high-fidelity and high-efficiency optical signal transmission in free space through scattering media. It has been experimentally demonstrated that the LUT can be flexibly designed for different types of signals, e.g., binary signals, grayscale images and analog signals etc. The LUT is pre-generated and pre-stored, and it is not needed to repeat to generate 2D random amplitude-only patterns for optical transmission of each signal. The designed LUT can facilitate data encoding process and save data storage memory. The proposed method can provide a novel insight for high-efficiency and high-fidelity optical signal (especially analog signals) transmission in free space through scattering media.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yin Xiao: Data curation, Methodology, Writing – original draft, Validation, Writing – review & editing. **Lina Zhou:** Writing – review & editing. **Wen Chen:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration.

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