applied optics

Optical analog-signal transmission and retrieval through turbid water

Zilan Pan, Yin Xiao, Yonggui Cao, Lina Zhou, and Wen Chen*

Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong, China
*Corresponding author: owen.chen@polyu.edu.hk

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In this paper, we propose a new, to the best of our knowledge, and robust method to optically transmit analog signals in free space through turbid water. In the proposed method, each pixel of original signal is sequentially encoded into random amplitude-only patterns as information carrier. A single-pixel detector is utilized to collect light intensity at the receiving end. To verify feasibility and effectiveness of the proposed method, a number of optical experiments are carried out in different kinds of water conditions, e.g., clean water, water mixed with milk, water with salt, and water with salt and milk. In addition, real seawater samples are also tested. Experimental results demonstrate that the proposed method shows high robustness against different propagation distances through turbid water and resists the effect of various turbulence factors. The proposed method is applicable to transmit information with high fidelity and high robustness against light wave diffusion in free space through complex environment. Furthermore, the proposed method is easy to operate and is cost-effective, which could open up a novel insight into optical signal transmission in free space through turbid water.

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1. INTRODUCTION

As an information carrier, optical waves have drawn much attention in recent years [1,2]. The high-bandwidth optical wave offers an opportunity for data transmission. Different from optical fiber communication, optical communication in free space has its own advantages and application background [3–5]. However, light waves propagating in free space usually encounters scattering media, e.g., turbid water or opaque materials in which scattering and absorption are unavoidable [6–10]. As a result, spatial information of the incident light is scrambled, and partially or completely ballistic photons are lost. In general, an optical system through scattering media yields speckle due to the interference inside the scrambled light beams [6–8], which makes it difficult to deliver accurate information of signal in the field of data transmission. Hence there is strong interest in the investigation of high-robustness and high-fidelity optical signal transmission in free space through scattering media [9,10]. Several approaches have been proposed in the literature to analyze the propagation of electromagnetic waves, e.g., wavefront shaping [9] and transmission matrix measurement [10]. However, wavefront shaping needs feedback control by iterative algorithms when dealing with the scattering modifications. In transmission matrix measurement, random scattering media are considered as a matrix to complete transformation on light waves. However, measurement of the scattering matrix in real applications could be complicated and time-consuming, since it requires a *priori* calibration process. Another potential approach to dealing with the effect of scattering is adaptive optics (AO), which relies on calibrated distortions of light beam [11]. Digital signal processing (DSP) is also feasible to tackle the scattering effect [12]. To obtain effective results, AO and DSP require high cost and rely on the complexity of system. Therefore, it is highly desirable to design new optical systems to easily transmit the signal in free space and simultaneously possess high fidelity and high robustness through scattering media.

As one kind of scattering media, turbid water is still a great obstacle for transmitting signal in free space, since the property of scattering in turbid water is complicated. In the environment with turbid water, various turbulence and attenuation factors in water environment affect the transmission efficiency and accuracy between the transmitter and the receiver. The approaches for transmitting information through turbid water using optical waves could be restricted by low robustness, low transmission quality, and complicated devices [13–18]. How to overcome the challenges that exist in optical signal transmission through turbid water remains an open question.

In this paper, we propose a new and robust method that takes advantage of a series of random amplitude-only patterns to build up a high-fidelity transmission channel in free space through turbid water and transmit analog signals by utilizing visible and coherent light source. In this proposed approach, analog signal is considered as independent pixel values, and each pixel value is encoded into a random amplitude-only pattern, which is a two-dimensional matrix. Then these patterns are sequentially embedded into spatial light modulator (SLM) and are illuminated to propagate through turbid water. At the receiving end, a single-pixel detector is utilized to detect the light intensity. By employing the proposed method, the receiver can obtain high-fidelity signal information. Different water conditions are studied, and experimental results in each case are quantitatively evaluated. The main contributions of this article are described as follows: (1) It realizes optical signal transmission in free space through turbid water utilizing a series of random amplitude-only patterns as information carrier. (2) The proposed approach is easy to operate and is robust against the high scattering and absorption effect in turbid water, which can realize high-fidelity transmission in free space through turbid water and can be applied to the field of underwater communication. Moreover, prior knowledge about turbid water is not needed for signal retrieval. (3) At the receiving end, light intensity is detected by a single-pixel (bucket) detector [19–23], which makes the proposed method advantageous for analog signal.

2. PRINCIPLES

A detailed description of our approach is given here, and a schematic optical experimental setup is shown in Fig. 1.

In the proposed method, a series of computer-generated random amplitude-only patterns are sequentially embedded into the SLM and then are illuminated to propagate in free space. The 2D patterns displayed by the SLM are fully covered by the laser beam. The propagating wave is scattered and absorbed through turbid water. At the receiving end, light intensity is collected by a single-pixel detector as shown in Fig. 1.

The procedure for encoding analog signals into random amplitude-only patterns is described as follows:

(1) Generate a random amplitude-only pattern R with real values by computer;
(2) apply fast Fourier Transform (FFT) to R and obtain its spectrum F;
(3) in the Fourier spectrum F, zero frequency is substituted by one pixel value of the analog signal and a new spectrum SF is generated;
(4) inverse fast Fourier transform (IFFT) is applied to SF to obtain an updated amplitude-only pattern P;
(5) repeat the above steps until each point of original analog signal is processed.

It is observed that when optical wave propagates through turbid water, the generated random amplitude-only pattern P, which is considered as information carrier has ultrahigh robustness against scattering and absorption [21–23]. Another

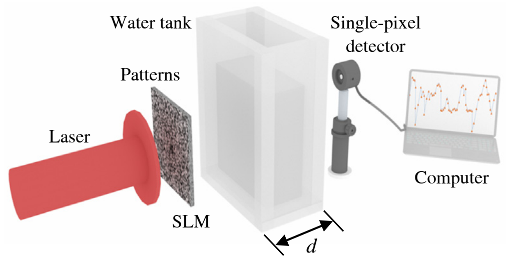

Fig. 1. Schematic experimental setup for the proposed method to optically transmit analog signal in free space through turbid water. SLM, amplitude-only spatial light modulator; d, axial distance in water tank.

feature is that we can flexibly adjust the pattern size according to practical conditions. In other words, each pixel of original signal can be projected onto one random amplitude-only pattern with any size, e.g., 512×512 pixels. However, size of the patterns may affect quality of the retrieved signal. In practice, compressed sensing can also be applied to reduce the number of 2D patterns to be generated.

A flow chart to illustrate the proposed method is shown in Fig. 2. In Fig. 2, a 2D image is used as original signal, and each pixel of this 2D image is converted into one amplitude-only pattern according to the proposed principle. In general, the generated random amplitude-only pattern contains negative values which are not suitable to be embedded into the SLM. To overcome this challenge, the generated random pattern P is further transformed into two independent patterns, i.e., $m + P$ and $m - P$, where m denotes a positive constant to eliminate negative values. In optical experiments, random amplitude-only patterns generated correspondingly to each pixel of original signal are sequentially embedded into the SLM.

When optical wave propagates through turbid water, the light intensity $I(z)$ decays due to the scattering and absorption effect. According to the Beer–Lambert law [24], the light intensity attenuates exponentially, which can be described by

$$I(z) = I_0 e^{-\tau R}, \tag{1}$$

where I_0 denotes the incident light intensity; τ is equal to $\sigma_{\mathrm{ext}} z_m$, which denotes optical depth; σ_{ext} denotes the attenuation coefficients including an attenuation coefficient and a scattering coefficient; z_m denotes the light path length; and R is equal to unity. In turbid water condition, the turbidity of water can affect light propagation and can lead to partial or complete attenuation of light intensity. In addition, salinity inhomogeneity also leads to irregular change in the refractive index of water and eventually influences data transmission. The different turbulence factors are tested and verified from the perspective of optical experiments in Section 3, which gives a detailed description of experimental process and experimental results.

After wave propagation through turbid water, a single-pixel detector is used to collect the light intensity. The recording and retrieval process is described by [21–23]

$$\mathrm{B}' = \gamma \iint [m + P(x, y)]\, e^{-2\pi j(x\xi + y\eta)} \mathrm{d}x\mathrm{d}y \,\Big|_{\xi=0,\eta=0}, \tag{2}$$

$$\mathrm{B}'' = \gamma \iint [m - P(x, y)]\, e^{-2\pi j(x\xi + y\eta)} \mathrm{d}x\mathrm{d}y \,\Big|_{\xi=0,\eta=0}, \tag{3}$$

$$\mathrm{B} = \mathrm{B}' - \mathrm{B}'', \tag{4}$$

where $j = \sqrt{-1}$, (x, y) denotes the coordinate in spatial domain, (ξ, η) denotes the coordinate in frequency domain, $m + P(x, y)$ and $m - P(x, y)$ denote 2D random patterns with 512×512 pixels, m denotes a matrix with a positive constant, B' and B'' denote the recorded intensity values, B denotes the retrieved value, and γ denotes a scaling factor. The detailed process is shown in Fig. 2. When the first pixel of original signal is transmitted, the first and second measurements by using a single-pixel detector are respectively denoted by B_{11} and B_{12},

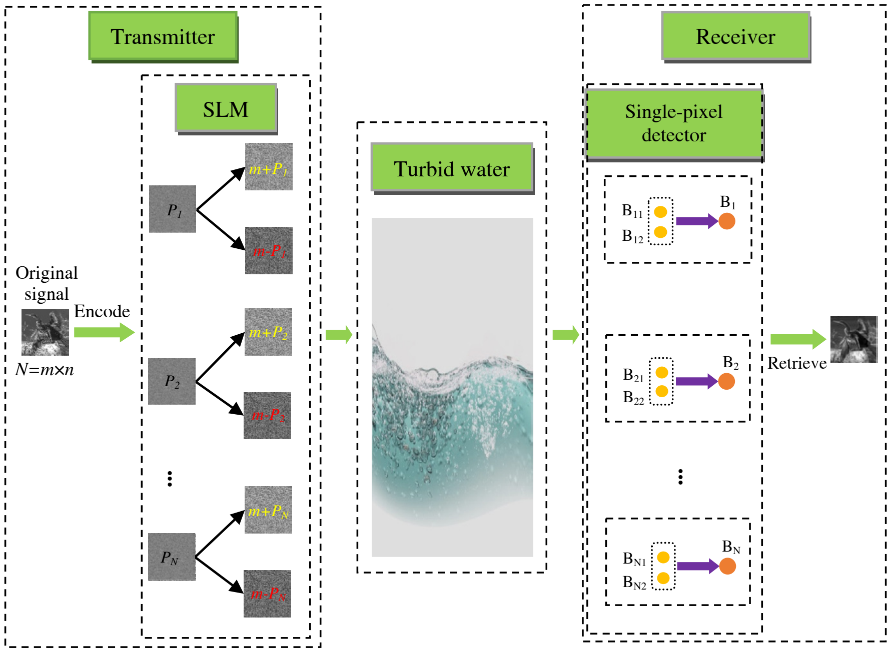

Fig. 2. Schematic procedure for the proposed optical transmission in free space through turbid water: a 2D image is used as a typical signal here, and a single-pixel (bucket) detector collects light intensity in the detection stage.

where B_{11} denotes the intensity obtained from the pattern $m + P_1$, and B_{12} denotes the intensity obtained from the pattern $m - P_1$. Then the value B_1 is equal to $B_{11} - B_{12}$ and is proportional to the first pixel value of original signal. Therefore, after all pixel values of the signal are transmitted, intensity values collected by single-pixel detector can be directly used for signal retrieval.

According to the flow chart in Fig. 2, high-fidelity signal transmission through complex environment can be realized. This realizes high-fidelity optical transmission in free space through turbid water by taking random amplitude-only patterns as information carrier. In addition, the designed experimental setup has the advantage of being cost-effective and is easy to implement.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A number of optical experiments are conducted to evaluate performance of the proposed method. The proposed method is verified in different water conditions, i.e., clean water, water mixed with milk, water with salt (salinity inhomogeneity), and water with milk and salt. In addition, real seawater samples are also tested in our optical experiments. In Fig. 1, a laser beam (He–Ne laser, 17.0 mW) with wavelength of 633.0 nm is utilized, and the laser is collimated to be a plane wave. It is worth noting that the proposed approach can be applied by using other wavelengths in practice. The collimated light illuminates the SLM (Holoeye, LC-R720) with pixel size of 20.0 μm. In this study, a modulation rate of 1.25 Hz is used to conduct a proof-of-principle experiment and verify the proposed method. Different kinds of analog signals, including 1D signals and 2D images, are tested. Temperature in the laboratory for the whole optical experiments is set as 24°C.

A. Clean Water

The proposed method is first used to transmit analog signals through clean water, and different wave propagation distances in the water tank, i.e., d in Fig. 1, are studied. With the increase of wave propagation distances through clean water, the intensity of the optical wave attenuates gradually. In this case, three typical propagation distances (i.e., 110, 160, and 310 mm) through clean water are tested to verify the proposed approach. For each propagation distance d, three irregular analog signals are utilized and tested for optical transmission in free space.

Three different signals are respectively encoded into a series of random amplitude-only patterns according to the principle introduced in Section 2, and the patterns carrying signal information are first illuminated to propagate through clean water with axial distance d of 110 mm. After the light intensity behind the water tank is collected by single-pixel detector, the results retrieved at the receiving end are shown in Figs. 3(a)–3(c). As can be seen in Figs. 3(a)–3(c), three signals experimentally retrieved at the receiving end almost overlap with original signals, indicating that high-fidelity optical signal transmission through clean water is realized.

When the propagation distance d in water tank increases to 160 mm, the generated amplitude-only patterns corresponding to the three different analog signals are still used and tested. In this case, the signals retrieved at the receiving end are shown in Figs. 4(a)–4(c). As can be seen in Figs. 4(a)–4(c), high-fidelity signal transmission is still realized when the longer propagation distance d is used. Although the longer distance decays the light intensity to be collected by single-pixel detector, the results shown in Figs. 4(a)–4(c) demonstrate that the proposed method is robust against propagation distance d in Fig. 1, which is meaningful and significant in practical applications.

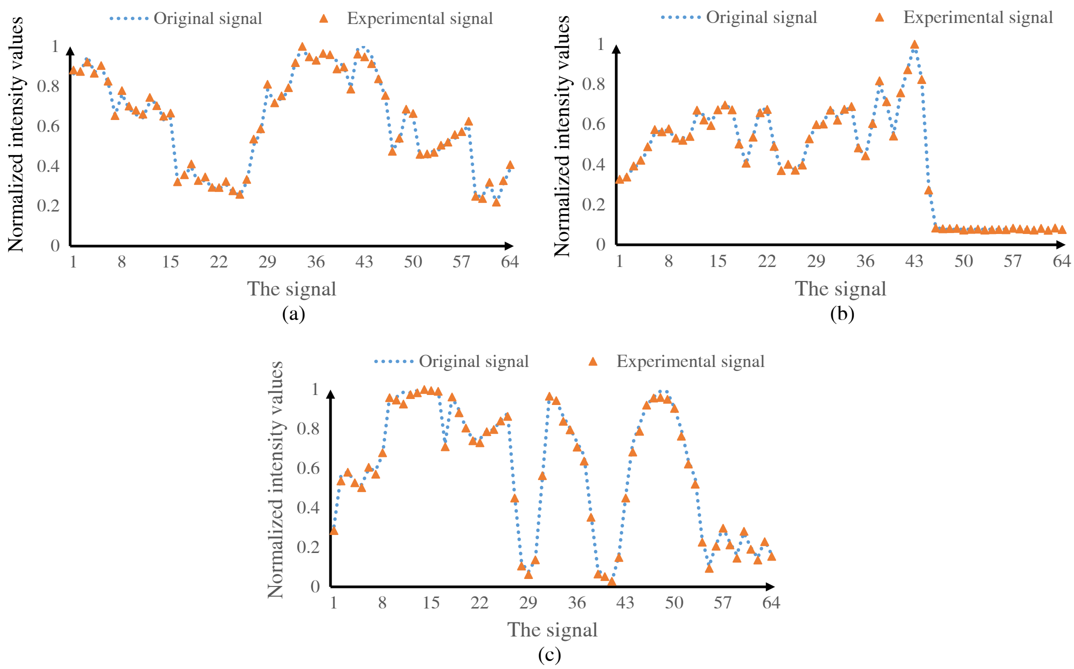

Fig. 3. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when the propagation distance d in Fig. 1 is 110 mm.

To test robustness of the proposed method through clean water, a propagation distance d of 310 mm is also tested in optical experiment. In this case, original signals to be tested are the same as those used in Figs. 3 and 4, which can be useful for a comparison about performance of the proposed method when different wave propagation distances are used. After random amplitude-only patterns embedded into the SLM are illuminated to propagate through clean water, the experimentally retrieved signals are shown in Figs. 5(a)–5(c).

As can be seen in Figs. 5(a)–5(c), the signals experimentally obtained at the receiving end are highly close to original signals, indicating that the proposed method can realize high-fidelity and high-robustness optical signal transmission when different propagation distances through water medium are used. It is worth noting that other wave propagation distances can also be tested in our experiments, and for the sake of brevity the results are not presented here. It is found that the propagation distance d in our experiments does not affect performance of the

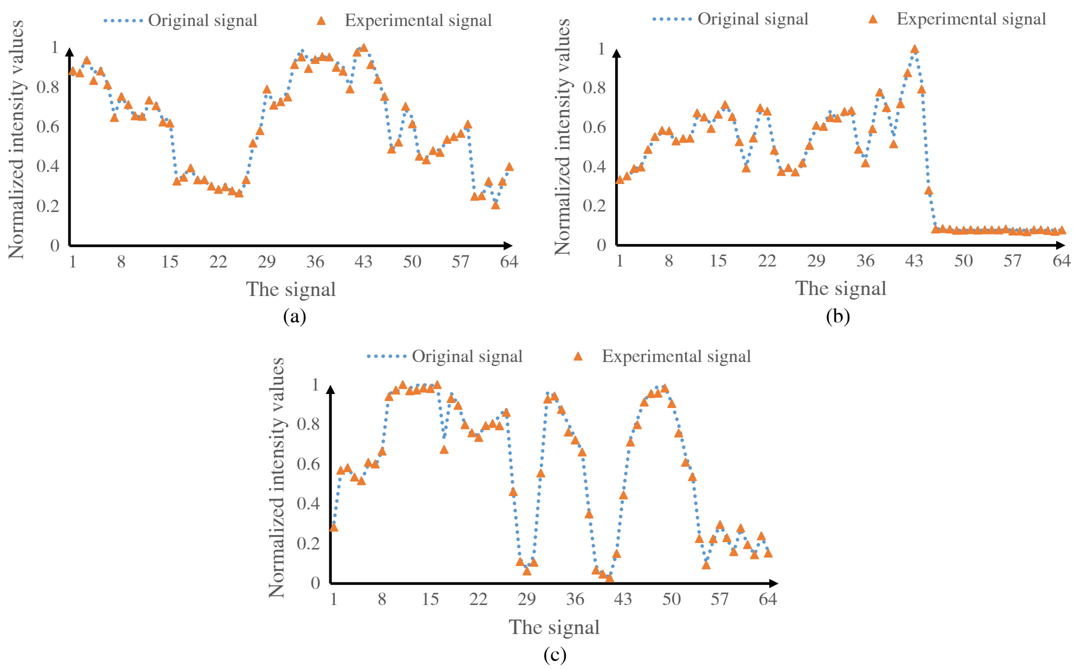

Fig. 4. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when the propagation distance d in Fig. 1 is 160 mm.

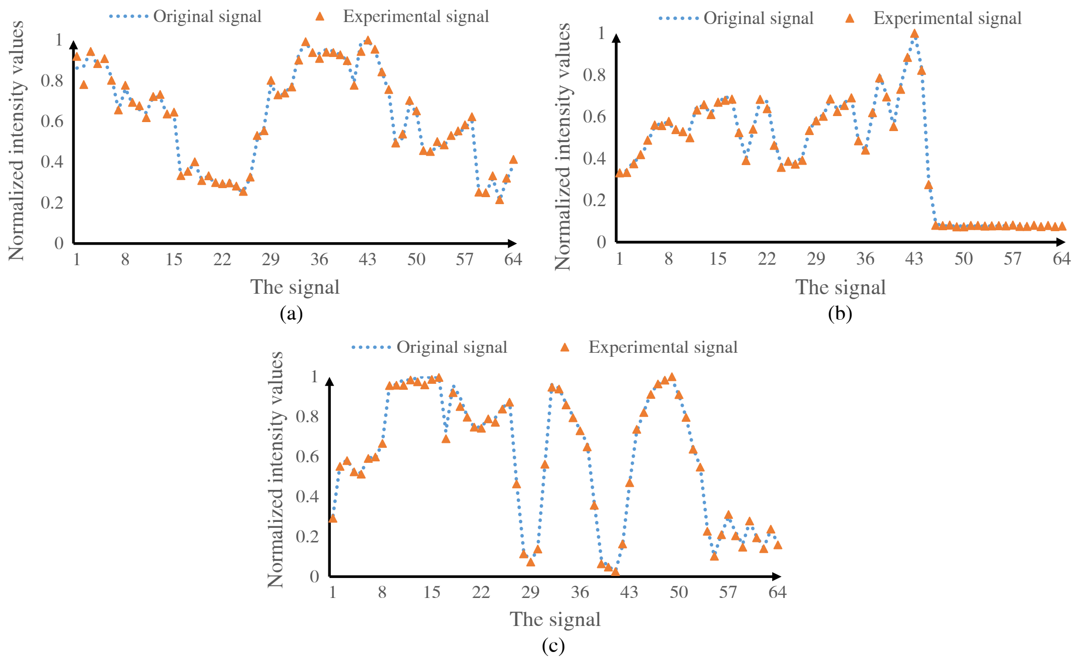

Fig. 5. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when the propagation distance d in Fig. 1 is 310 mm.

proposed approach. Although the long propagation distance can attenuate light intensity dramatically, the data collected by single-pixel detector can still be used for high-fidelity signal retrieval as long as the light intensity can be effectively detected and the laser power is properly controlled. However, light intensity is attenuated when a long transmission distance is used, which is also explained in Eq. (1). It was found that attenuation coefficient through clean water is close to 0.071 m^{-1} [25]. For instance, in this study, the transmitted power before turbid water is 3.5 mW, and the lower limit of received power is 600.0 nW. According to the attenuation coefficient and Beer–Lambert law in Eq. (1), the estimated propagation distance through turbid water could be less than 122.0 m in practice.

To quantitatively evaluate performance of the proposed method, signal-to-noise ratio (SNR) and mean squared error (MSE) are respectively calculated by

$$\mathrm{SNR} = 10 \times \log_{10}\left[\frac{\sum S_{\mathrm{ori}}^2}{\sum (S_{\mathrm{ori}} - S_{\mathrm{re}})^2}\right], \tag{5}$$

$$\mathrm{MSE} = \frac{1}{N}\sum (S_{\mathrm{ori}} - S_{\mathrm{re}})^2, \tag{6}$$

where S_{ori} denotes original signal, S_{re} denotes the retrieved signal, and N denotes the total number of pixels in original signal. The calculated MSE and SNR values in different cases are shown in Table 1. In Table 1, signal a denotes the signals in Figs. 3(a), 4(a) and 5(a); signal b denotes the signals in Figs. 3(b), 4(b) and 5(b); signal c denotes the signals in Figs. 3(c), 4(c) and 5(c). The low MSE values and high SNR values further illustrate that the proposed method can realize high-fidelity optical signal transmission in free space through clean water when different

Table 1. Quantitative Comparisons Using Clean Water with Different Wave Propagation Distances

Signal	Distance d	MSE	SNR (dB)
Signal a	110 mm	2.94×10^{-4}	31.82
	160 mm	2.31×10^{-4}	32.87
	310 mm	3.49×10^{-4}	31.07
Signal b	110 mm	8.60×10^{-5}	34.59
	160 mm	1.68×10^{-4}	31.71
	310 mm	1.24×10^{-4}	33.01
Signal c	110 mm	3.17×10^{-4}	31.65
	160 mm	3.35×10^{-4}	31.42
	310 mm	1.95×10^{-4}	33.77

propagation distances are used. In addition, as can be seen in Table 1, with different propagation distances, the MSE and SNR values always keep steady, which means the proposed method is robust against wave propagation distance through clean water.

From the experimental results in Figs. 3–5 and Table 1, it can be summarized that the propagation distance through water medium does not affect the quality of signal transmission in free space, since amplitude-only patterns are generated as the information carrier and a single-pixel detector is used to record light intensity. This kind of information carrier is a powerful tool, and the single-pixel detector has the feature of stability and sensitivity to light intensity.

B. Water Mixed with Milk

Since clean water shows relatively low capability in absorption and scattering when the light wave propagates, the effect of turbid water on transmission efficiency and accuracy is further studied. In the experiments, clean water of 850 ml is mixed with different volumes of milk (i.e., 80, 90, and 100 ml). To quantify the turbidity level, milk in water is used in our optical experiments. Attenuation coefficient based on the Beer–Lambert law can also be calculated [24,26–28]. Then a complex environment with different turbidities is constructed. It is well recognized that the milk can effectively increase the turbidity of water, and makes wave propagation in murky water difficult. Owing to this reason, milk is considered a suitable candidate for altering the turbidity of water. In this case, a light wave propagating through turbid water encounters strong scattering and absorption, which usually destroys the information carrier drastically. In conventional methods, it is impossible or difficult to effectively transmit the desired signal to the receiver in free space through such a complicated environment. In our method, the information carrier, i.e., the generated random amplitude-only patterns, can still serve as a robust tool to transmit information. Although the murky water makes it impossible to accurately control amplitude-only patterns through complicated environment, the data collected by single-pixel detector are still effective for retrieving the signal with high fidelity. The performance of the proposed method is also verified from the perspective of optical experiments.

In Fig. 1, the propagation distance d through murky water is fixed as 160 mm in order to make a comparison due to different turbidities in the water tank. The single-pixel detector is placed 30 mm away from the water tank and 240 mm away from the SLM. The only variable in this case is the turbidity, which is controlled by different volumes of milk, i.e., 80, 90, and 100 ml. Here, another three different irregular analog signals are employed for optical transmission, and in each case these signals are tested independently. Optical experimental results obtained at the receiving end are shown in Figs. 6–8.

As shown in Figs. 6(a)–6(c), these signals can be experimentally retrieved with high fidelity, when turbid water is constructed by using clean water of 850 ml and milk of 80 ml. The experimental results shown in Figs. 6(a)–6(c) illustrate that our approach has the feature of high robustness against scattering. In addition, there is a dramatic attenuation in light intensity when milk is added into water owing to the absorption effect in murky water. It has been mentioned in Section 3.A that as long as a single-pixel detector can detect the light intensity effectively and the laser power is properly controlled, the data recorded can be employed to retrieve the signals with high fidelity. The experimental results in Figs. 6(a)–6(c) further verify this finding, since the light intensity detected after murky water is an order of magnitude lower than that detected when clean water is used. The dramatic reduction in light intensity through murky water does not affect high-fidelity signal transmission, which makes the proposed method be of value in practical applications.

To further investigate performance of the proposed method, clean water of 850 ml mixed with more milk, i.e., 90 ml and 100 ml, is also studied. Obviously, these two cases increase the turbidity of murky water. When the optical wave propagates through turbid medium, by taking advantage of the characteristic of single-pixel detector, which is able to detect weak light intensity, signal retrieval with high fidelity is still realized. The experimental results corresponding to these two cases are respectively shown in Figs. 7 and 8. The proposed method still performs well in these two complicated environments, which further illustrates that the proposed scheme is a powerful tool in the field of optical transmission in free space.

The performance of the proposed method is quantitatively evaluated by SNR and MSE, and the calculated SNR and MSE values are shown in Table 2. In Table 2, signal a denotes the signals in Figs. 6(a), 7(a), and 8(a); signal b denotes the signals in Figs. 6(b), 7(b), and 8(b); and signal c denotes the signals in Figs. 6(c), 7(c), and 8(c). As can be seen in Table 2, in more complex environments compared to clean water, the SNR and

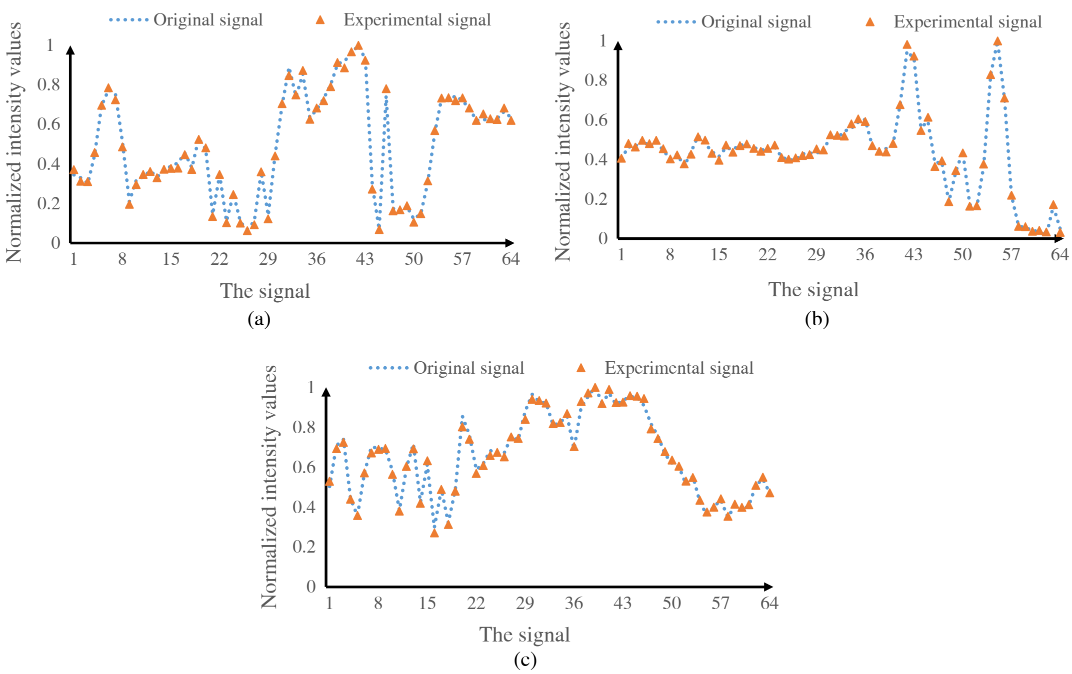

Fig. 6. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when milk of 80 ml and clean water of 850 ml are placed in the water tank.

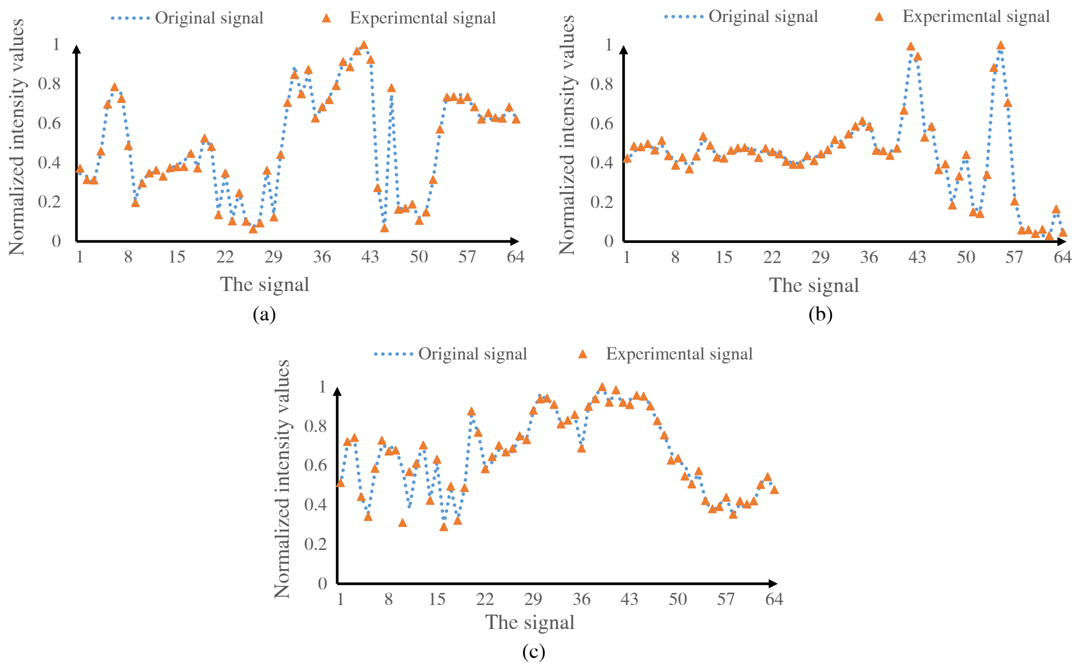

Fig. 7. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when milk of 90 ml and clean water of 850 ml are placed in the water tank.

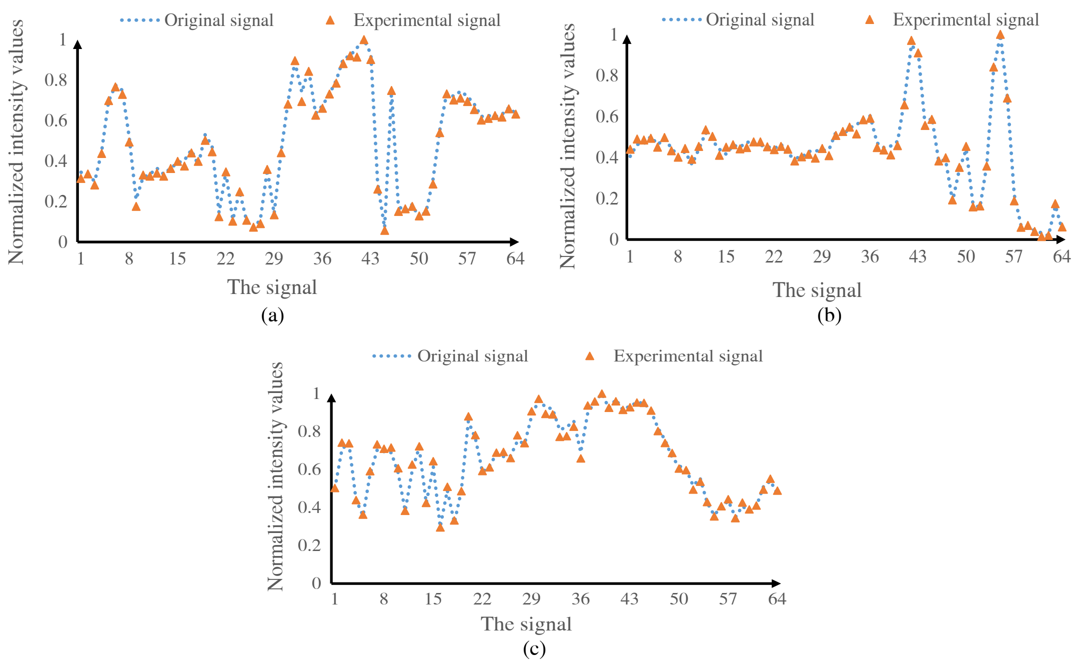

Fig. 8. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when milk of 100 ml and clean water of 850 ml are placed in the water tank.

MSE values almost maintain in the same level. These results mean that high-fidelity and high-robustness optical transmission can be realized even if the turbid medium exists in the wave propagation path.

C. Water with Salt

Salinity inhomogeneity leads to irregular changes in the refractive index of water and significantly affects signal transmission quality. Therefore, it is necessary to further study the impact of salt on the proposed method. In Fig. 1, the wave propagation distance d through water is fixed as 160 mm. The single-pixel detector is placed 50 mm away from water tank and 260 mm away from the SLM. In our experiment, clean water of 850 ml is mixed with three different weights of salt, i.e., 60, 90, and 120 g. Typical experimental results are shown in Fig. 9. As can be seen in Fig. 9, the signals are still retrieved with high fidelity. The

Table 2. Quantitative Comparisons about the Effect of the Turbidity of Turbid Water

Signal	Turbidity	MSE	SNR (dB)
Signal	850 ml clean water + 80 ml milk	2.29×10^{-4}	31.36
a	850 ml clean water + 90 ml milk	4.03×10^{-4}	28.90
	850 ml clean water + 100 ml milk	3.34×10^{-4}	29.72
Signal	850 ml clean water + 80 ml milk	1.40×10^{-4}	32.12
b	850 ml clean water + 90 ml milk	3.17×10^{-4}	28.58
	850 ml clean water + 100 ml milk	3.29×10^{-4}	28.42
Signal	850 ml clean water + 80 ml milk	2.70×10^{-4}	32.44
c	850 ml clean water + 90 ml milk	1.91×10^{-4}	23.95
	850 ml clean water + 100 ml milk	3.53×10^{-4}	31.28

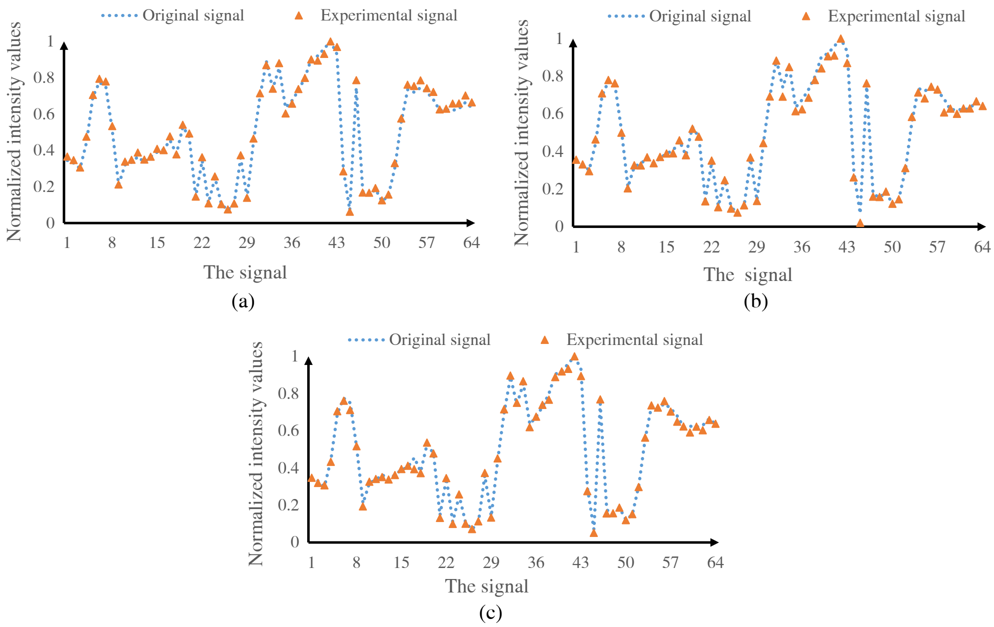

Fig. 9. (a)–(c) Comparisons between original signal and the experimentally retrieved signals when three different weights of salt (i.e., 60, 90, and 120 g) are respectively used with clean water of 850 ml. SNR values of the retrieved signals in (a)–(c) are 28.91, 27.86, and 30.81 dB, respectively. MSE values of the retrieved signals in (a)–(c) are 4.02×10^{-4}, 5.13×10^{-4}, and 5.10×10^{-4}, respectively.

MSE and SNR values of these retrieved signals are calculated and shown in Fig. 9.

In this case, the low MSE values and high SNR values also illustrate that the proposed method is feasible and effective. It can be seen in Figs. 9(a)–9(c) that salinity inhomogeneity does not affect high-fidelity signal transmission. Many kinds of signals have been tested in this study, and experimental results always illustrate that the retrieved signals overlap with original signals. With the increase of the salt, the MSE values and SNR values of the retrieved signals still remain steady.

D. Water with Milk and Salt

More complicated turbid-water environments are further studied, i.e., clean water with salt and milk. In this kind of turbid environment, the scattering medium becomes more complex and turbid, and it is found that our method can still resist the disorder of scattering media. In Fig. 1, a light wave propagates through turbid medium with axial distance d of 160 mm. The single-pixel detector in Fig. 1 is placed 50 mm away from the water tank and 260 mm away from the SLM. Typical experimental results are shown in Figs. 10(a)–10(c). To experimentally demonstrate feasibility of the proposed approach, three different kinds of irregular analog signals are used and tested through turbid medium, in which clean water of 850 ml is mixed with salt of 120 g and milk of 70 ml. It can be seen from Figs. 10(a)–10(c) that the signals retrieved at the receiving end almost overlap with original signals. Therefore, the proposed method can still realize high-fidelity optical transmission in free space even if the turbid medium becomes more complex. The calculated MSE and SNR values given in Fig. 10 further demonstrate that the proposed method can realize high-robustness and high-fidelity optical transmission through turbid water.

E. Seawater Samples

Real seawater samples, which are obtained from the Star Venue in Hong Kong, are also tested by using the proposed method, and several 2D images are utilized as original signals. The optical experimental setup in Fig. 1 is applied. The size of the signal (2D image) is 64×64 pixels, and that of the generated random

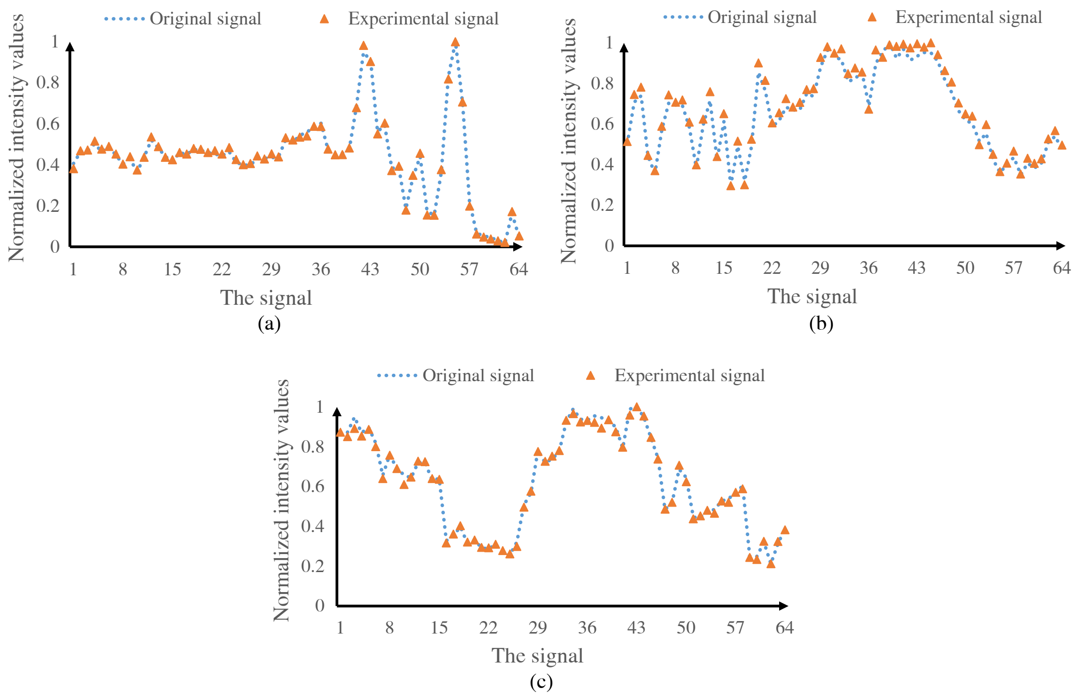

Fig. 10. (a)–(c) Comparisons between three different kinds of original analog signals and the signals experimentally obtained at the receiving end when salt of 120 g, milk of 70 ml, and clean water of 850 ml are placed in the water tank. SNR values of the retrieved signals in (a)–(c) are 32.91 dB, 26.23 dB, and 30.65 dB, respectively. MSE values of the retrieved signals in (a)–(c) are 1.17×10^{-4}, 1.13×10^{-4}, and 3.85×10^{-4}, respectively.

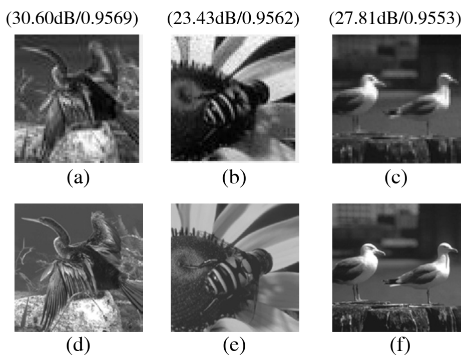

Fig. 11. (a)–(c) 2D images obtained at the receiving end in optical experiments and (d)–(f) original images. The PSNR and SSIM values are given inside the brackets.

pattern is 512 × 512 pixels. The experimental results retrieved at the receiving end are shown in Figs. 11 and 12.

We use peak signal-to-noise ratio (PSNR) and structural similarity index measure (SSIM) [29] to quantitatively evaluate quality of the retrieved images as given in Figs. 11(a)–11(c). It is also observed that there is always a steady scaling factor γ between original analog signal and the experimentally retrieved signal. As can be seen in Fig. 12(b), the scaling factor distribution is within a small range. Our study demonstrates that the proposed method can resist scattering, absorption effect, and environmental noise, and it can realize high-robustness and high-fidelity optical signal transmission in free space through turbid water.

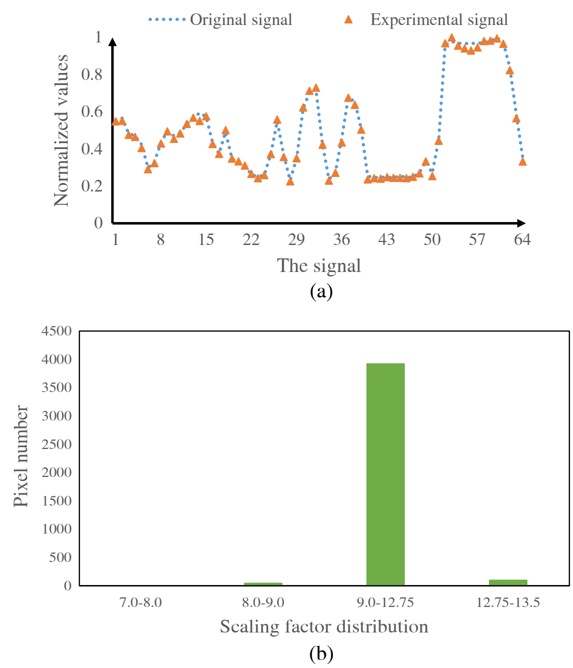

Fig. 12. (a) Typical comparison between pixel values along the 30th row of the retrieved image in Fig. 11(b) and those in original image, and (b) a typically statistical result about scaling factor distribution (magnitude of the coefficients: 2.0×10^{-12}) for the retrieved image in Fig. 11(b).

4. CONCLUSION

We have proposed to build a high-fidelity and high-robustness optical signal transmission channel in free space through turbid water. We have demonstrated a versatile approach to encoding analog signals into random amplitude-only patterns in order to realize high-robustness and high-fidelity optical transmission in free space through turbid water. A number of experimental results have demonstrated that for different kinds of analog signals, the proposed method is able to realize high-fidelity information transmission through turbid water. Compared with conventional methods, the proposed method is easier to implement, and prior knowledge about turbid water is not required. In terms of the higher data rate, other devices may be applied to replace the SLM used here, e.g., digital micromirror device or LED array. This work is meaningful to offer an insight into optical signal transmission in free space through turbid water, and the proposed method could be of value in many applications.

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