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Experimental Study of Fast Orthogonal Frequency Division Multiplexing Transmission over a Random Media Channel for Optical Wireless Communications

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Abstract: In this paper, a 4 amplitude shift keying (4-ASK) fast orthogonal frequency division multiplexing (FOFDM) scheme was experimentally investigated over a turbulent air–water channel for optical wireless communications. The experiment results showed that the 4-ASK-FOFDM modulated signals were not sensitive to weak atmospheric turbulence, and the bit-error rate (BER) was lower than the 7% forward error correction (FEC) limit of 3.8×10^{-3}. Under the condition of the same spectra efficiency, the 4-ASK-FOFDM scheme just had a tiny performance penalty compared to the 16-QAM-OFDM scheme. Consequently, the 4-ASK-FOFDM scheme is a promising alternative to the conventional 16-QAM-OFDM scheme in optical wireless communications.

Keywords: 4-ASK; fast-OFDM; turbulent air–water channel; OFDM

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1. Introduction

Over the last few years, optical wireless communications (OWC) have attracted more and more attention in both commercial and military society due to its wide unregulated bandwidth and insensitivity to interference from electro-magnetic waves. And the OWC played an important role in emergency communications for disaster resistance [1]. The research scope of OWC included free-space optical communications (FSO), visible light communications (VLC) and underwater optical wireless communications (UOWC). Taking available devices, cost and complexity into account, the transmission scheme in OWC primarily adopted intensity modulation and direct detection (IM/DD) except for a few coherent detections that were mainly used in long-distance FSO communications. With the simple transmitter and receiver, a single-carrier scheme (e.g., pulse amplitude modulation (PAM)) was researched in many fields. X. Li et al. [2] proposed a feed-forward pre-equalization together with a PAM modulation scheme to achieve the transmission of data rates >1 Gb/s in VLC. To mitigate multipath dispersion, Asanka Nuwanpriya et al. [3] proposed a PAM-modulated single-carrier system using frequency-domain equalization. Chao Shen et al. [4] demonstrated a high-speed UWOC link over a 12 m and 20 m underwater channel, which reached a data rate of 2 Gbps and 1.5 Gbps based on NRZ OOK modulation. Chung-Yi Li et al. [5] reported a 16 Gbps PAM-4 UWOC system using a laser diode (LD) with 488 nm wavelength. Ciulio Cossu et al. [6] reported a UOWC system based on the PAM scheme, which can be used in practical marine experiments.

Although the transmitters and receivers using PAM had low complexity, the spectra efficiency (SE) of PAM was low, which was not suitable for OWC systems with limited modulation bandwidth, like OWC systems using LED. When SE was a driving factor, OFDM, in conjunction with IM/DD, was more popular in OWC systems. Yifei Chen et al. [7] demonstrated a 26 m air–water link with an OFDM scheme and data rate of 5.5 Gbps based on a 520 nm laser diode. Yu-Chieh Chi et al. [8] achieved a high-speed VLC with 9 Gbps QAM-OFDM and 450 nm GaN laser diode. Lu Zhang et al. [9,10] reported an improved m-QAM-OFDM transmission and a two-path parallel OFDM scheme for OWC. Chen Chen et al. [11] proposed a non-Hermitian symmetry OFDM for multiple-input, multiple-output VLC. Hassan M. Oubei et al. [12] demonstrated a UWOC transmission with a 4.8 Gbps data rate based on a 16-QAM-OFDM-modulated 450 nm laser. Due to the high SE, a multiple-carrier scheme (e.g., OFDM), together with IM/DD, would contribute to the development of high-speed OWC over short- to medium-transmission distances.

As a promising multicarrier transmission technique, FOFDM, which has been theoretically proposed for wireless applications [13], has only half of the subcarrier space of the conventional OFDM [14,15]. It has been extensively investigated in optical fiber communications [16–19]. FOFDM can reduce the complexity of the transmitter when compared to a conventional OFDM system having the same spectral efficiency and total data rate [20,21]. For generic linear channels, in [15], a computationally efficient fast-OFDM scheme enabling simple single-tap equalization without sacrificing data rate was proposed.

To evaluate the performance of FOFDM signal transmitting over a complex media channel, this work, as far as we know, experimentally investigated the performance of FOFDM scheme for OWC over a complex media channel which was comprised of a weak turbulence channel generated by an atmospheric turbulence simulator, together with a water tank, for the first time. The feasibility of this scheme was validated by the experiment results, which showed that the 4-ASK-FOFDM scheme was not sensitive to the generated weak turbulence, and its BER performance was very close to the conventional 16-QAM-OFDM scheme under the same spectral efficiency. Hence, the 4-ASK-FOFDM technique can be a promising alternative to the conventional 16-QAM-OFDM technique for optical wireless communications.

The rest of the paper is organized as follows. In Section 2, the principle of FOFDM is presented. In Section 3, the experiment about FOFDM signal transmitting over a complex media channel is described. Section 4 shows the experimental results. In Section 5, the experimental results are discussed. Finally, Section 6 summarizes the work.

2. Principle of FOFDM

The detailed theory of FOFDM used in this paper can be found in [15]. The equations of FOFDM were briefly summarized as follows. It is assumed that N subcarriers are available, and we modulated the k-th subcarrier by $x(k)$; the time domain signal $s(n)$, $n = 0, \ldots, N-1$, can be written as

$$s(n) = \sqrt{\frac{2}{N}} \sum_{k=0}^{N-1} \varepsilon(k) x(k) \cos\left[\frac{\pi}{N} k \left(n + \frac{1}{2}\right)\right] \tag{1}$$

where $\varepsilon(k) = \sqrt{0.5}$ for $k = 0$, and 1 for $k = 1, \ldots, N-1$. To enable the use of single-tap equalizers, $s(n)$ is zero-padded and represented by $s_{ZP}(n)$, where $s_{ZP}(n) = s(n)$ for $0 \le n \le N-1$, and $s_{ZP}(n) = 0$, for $N \le n \le N+L-1$.

After passing through an LTI channel, the received signal is written as

$$r(n) = h(n) * s_{ZP}(n) + z(n), 0 \le n \le N+L-1 \tag{2}$$

where $*$ is the convolution operator, and $z(n)$ is the additive noise.

At the receiver, $r(n)$ are zero-padded to obtain $r_{2N}(n)$. A DFT with a length of 2N is applied to obtain a frequency domain signal $y(m)$. And there is

$$\begin{aligned} y(m) &= F_{2n}[r_{2N}(n)] = F_{2n}[h_{2N}(n) \cdot s_{2N}(n)] \\ &= F_{2n}[h_{2N}(n)] \cdot F_{2n}[s_{2N}(n)] \\ &= H(m) \cdot S(m) \end{aligned} \tag{3}$$

where $m = 0, 1, \ldots, 2N-1$,$F_{2n}[\cdot]$ denotes the DFT with a length of 2N, $h_{2N}(n)$ is the zero-padded signal of $h(n)$, and $s_{2N}(n)$ is the zero-padded signal of $s(n)$. $y(m)$ can be written as

$$y(m) = e^{j\frac{2\pi}{2N}m\cdot\frac{1}{2}}H(m)\cdot e^{-j\frac{2\pi}{2N}m\cdot\frac{1}{2}}S(m) = \hat{H}(m)\cdot\hat{S}(m) \tag{4}$$

where $\hat{S}(m)$ can be extended as

$$\begin{aligned} \hat{S}(m) &= \sqrt{\tfrac{1}{2N}}\sum_{n=0}^{N-1} s(n)e^{-j\frac{2\pi}{2N}m(n+\frac{1}{2})} \\ &= \sum_{k=0}^{N-1} x(k)G(m,k) \end{aligned} \tag{5}$$

and there is

$$G(m,k) = \frac{\varepsilon(k)}{N}\sum_{n=0}^{N-1}\cos\frac{\pi}{N}k\left(n+\frac{1}{2}\right)\cdot e^{-j\frac{\pi}{N}m(n+\frac{1}{2})} \tag{6}$$

The real part of $G(m,k)$ was derived as

$$\begin{aligned} G_R(m,k) &= \tfrac{\varepsilon(k)}{N}\sum_{n=0}^{N-1}\cos\tfrac{\pi}{N}k\left(n+\tfrac{1}{2}\right)\cdot\cos\tfrac{\pi}{N}m\left(n+\tfrac{1}{2}\right) \\ &= \begin{cases} 1 & m=0 \\ 0.5\cdot\delta(m-k) & m=1,\ldots,N-1 \\ 0 & m=N \\ -0.5\cdot\delta(2N-m-k) & m=N+1,\ldots,2N-1 \end{cases} \end{aligned} \tag{7}$$

To recover the transmitted symbols, the phase can be compensated by multiplying the conjugate of the estimated channel frequency response $\hat{H}(m)$ to $y(m)$; then, the real part is

$$\begin{aligned} y'(m) &= \left|\hat{H}(m)\right|^2\cdot\sum_{k=0}^{N-1} x(k)G_R(m,k) \\ &= \left|\hat{H}(m)\right|^2\cdot\begin{cases} x(m) & m=0 \\ 0.5\cdot x(m) & m=1,\ldots,N-1 \\ 0 & m=N \\ -0.5\cdot x(2N-m) & m=N+1,\ldots,2N-1 \end{cases} \end{aligned} \tag{8}$$

To make full use of the above equation, there is a further definition as follows:

$$\hat{H}_c(m) = \frac{1}{2}\left(\left|\hat{H}(m)\right|^2 + \left|\hat{H}(2N-m)\right|^2\right) \tag{9}$$

So, the transmitted data can be obtained as

$$x'(m) = y'(m) - y'(2N-m) = \hat{H}_c(m)\cdot x(m) \tag{10}$$

After removing $\hat{H}_c(m)$ by single-tap equalizers, the transmitted data $x(m)$ can be recovered.

3. Experiments

The experimental setup of the 4-ASK-FOFDM transmission through a random media channel is shown in Figure 1. The picture of the experimental setup is displayed in Figure 2. At the transmitter, a 4-ASK-FOFDM time domain signal was first generated by an offline Matlab program. In the offline digital signal processing (DSP) which was marked by the dashed rectangles in Figure 1, firstly, a pseudorandom binary sequence (PRBS 2^{15}-1) was mapped into 4-ASK symbols. Then, DCT pre-coding [22] was adopted to lower the peak-to-average power ratio. Due to the restriction of the 500 MHz bandwidth of the digital oscilloscope used, the pre-coded 4-ASK symbols were just modulated onto 112 subcarriers by inverse discrete cosine transform (IDCT) with a length of 256. To avoid DC coupling, the first six subcarriers were set to be zeros. And the guard interval with the length of 16 was added to prevent inter-symbol interference (ISI). Thus, the time domain FOFDM signal was generated. After parallel-to-serial (P/S) conversion, we uploaded the sequence to an arbitrary waveform generator (AWG, Agilent 81180A), and the sampling rate was set to 2.5 GSa/s. For the baseband signal, the bandwidth was calculated as $2.5 \times (6 + 112)/256/2 \approx 576$ MHz, the net data rate was 965.5 Mb/s and the spectral efficiency (SE) was 1.68. After AWG, an RF amplifier (SHF 100AP) was used to amplify the baseband 4-ASK-FOFDM signal, and a Bias-tee (PE1611) was used to superimpose the amplified signal on the DC bias current. An LD outputting blue light was directly modulated by the mixed signal. A curve of optical power versus bias current for the blue LD is shown in Figure 3a. And when the DC current was set to 65 mA, we measured the optical spectra by an Andor SR-500i spectrometer, and the spectra are shown in Figure 3b. When the current was 65 mA, the optical power of 30 mW was output by the LD, and the emission wavelength was around 451 nm.

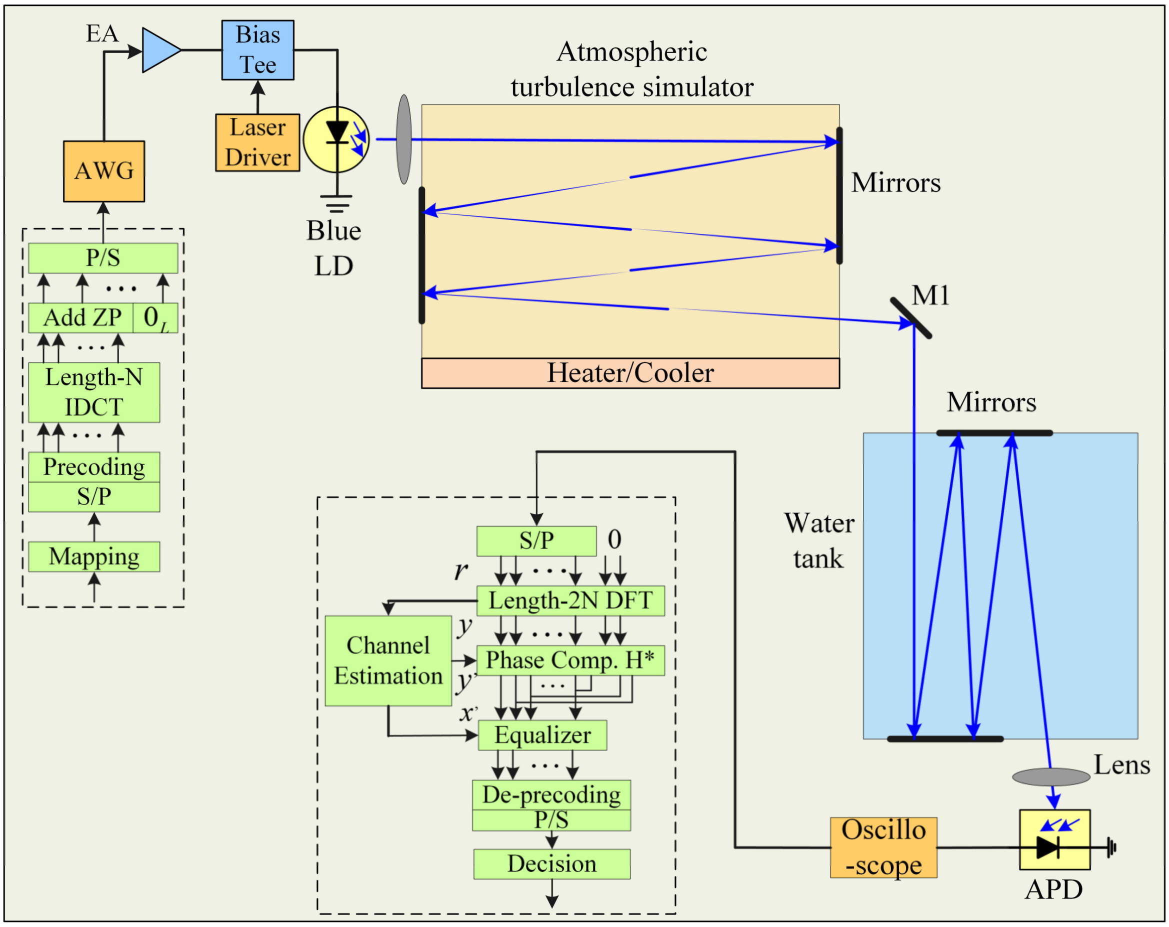

Figure 1. Experimental setup of 4-ASK-FOFDM transmission over a simulated turbulent air channel followed by a water channel for OWC: arbitrary waveform generator (AWG), electrical amplifier (EA), laser diode (LD), mirror (M1), avalanche photodiode (APD).

The blue light from the LD was launched into a simulated turbulent air channel by a Plano-Convex lens with a focal length of 49.8 mm, and the radius of curvature was 25.8 mm. The atmospheric turbulence simulator consisted of a chamber, heater, cooler and fans. Its length was 2.5 m. When the fans and heater in the chamber work, the simulator can generate turbulent airflow. The blue light was reflected four times by mirrors mounted on the chamber side. After reflection, the transmission distance was extended to 12.5 m. If we disabled the fans and the heater, the simulator just produced a 12.5 m free-space atmospheric channel. After passing through the simulated atmospheric turbulence, the blue light was reflected into a water tank with a length of 1.6 m and was filled with tap water. The estimated attenuation coefficient of the tap water was about 0.23 m^{-1} [23]. When the blue light was propagating in the water tank, it was reflected four times by mirrors mounted on the side of the tank. The transmission distance in the water tank could be increased to 8 m after reflection. Lastly, the output blue light from the water tank was focused onto an APD (APD210, Menlo Systems) by a lens which was the same as the lens used at the transmitter side. The bandwidth of the APD210 was 1 GHz, and its active diameter was 0.5 mm.

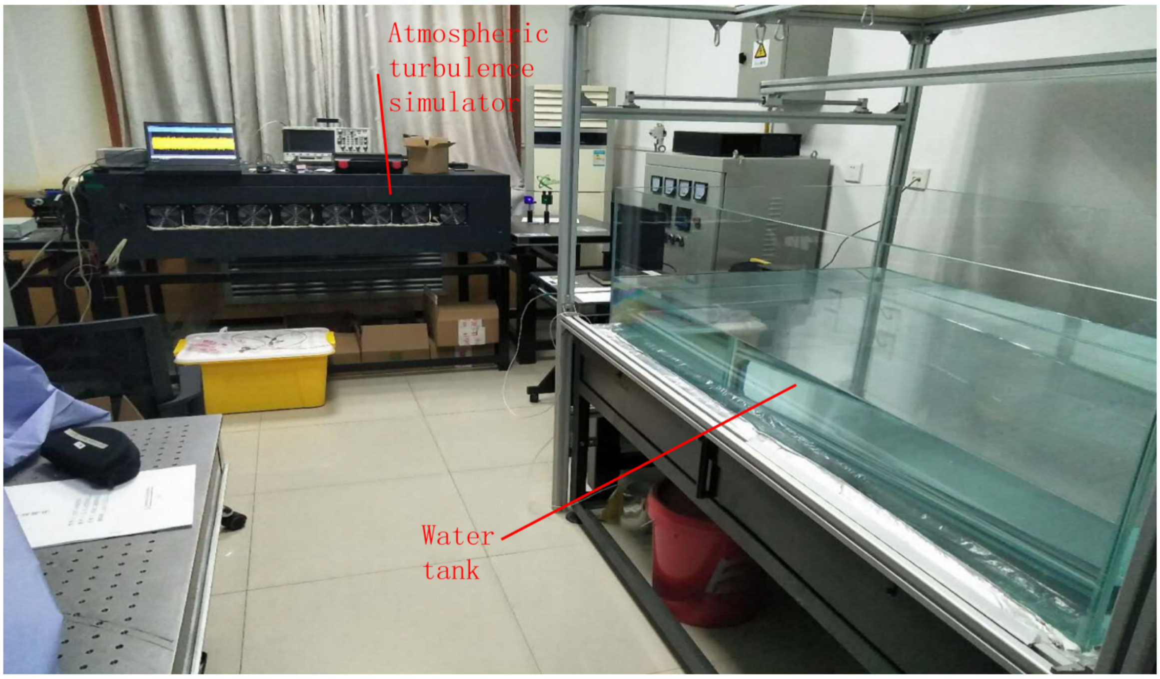

Figure 2. Photograph of the experimental setup.

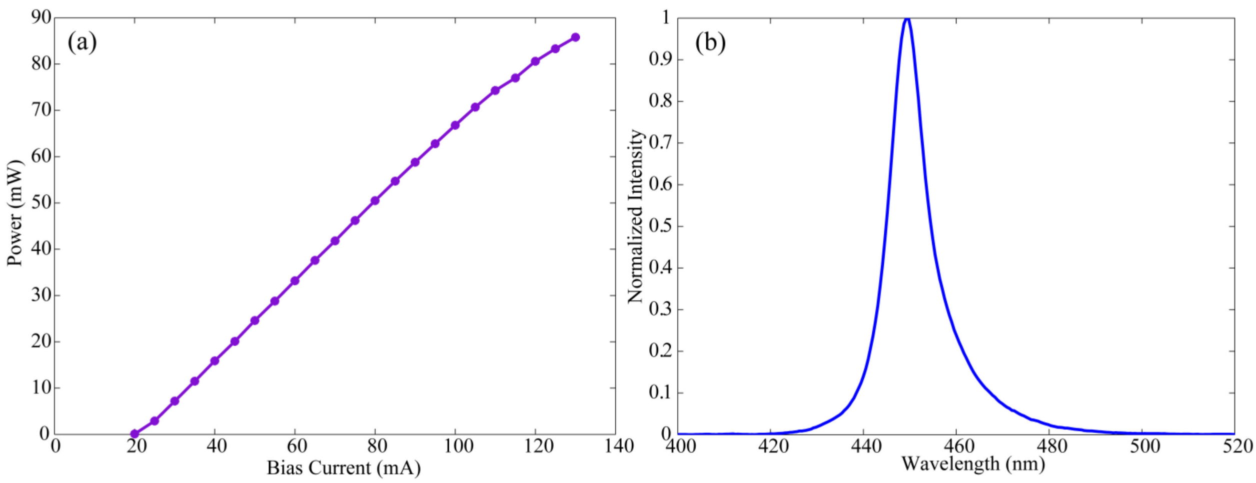

Figure 3. (**a**) Power vs. current for an LD working at 25 °C. (**b**) Optical spectrum of the LD working at bias current of 65 mA and temperature of 25 °C.

The APD converted the received light to an analog electrical signal, then the electrical signal was sampled by a digital oscilloscope (Keysight DSO-X 4054A), which had a bandwidth of 500 MHz, a sampling rate of 5 GSa/s and a resolution of 8 bits. The sampled baseband FOFDM signal was processed by an offline algorithm, which was surrounded by a dashed rectangle in Figure 1. The baseband FOFDM signal had 8 pilot symbols and

256 FOFDM payload symbols in every signal frame. For the offline algorithm, symbol synchronization identifying the start of each frame was first performed. Following the serial-to-parallel (S/P) conversion, a discrete Fourier transform (DFT) with a length of 512 points was performed to obtain the frequency domain signal. Next, the channel was estimated using the pilot symbols, and single-tap equalization was carried out. After IDCT de-precoding and parallel-to-serial (P/S) conversion, the decision was made to recover the binary bit sequence. The error bits in the recovered binary bit sequence were counted directly, then BER was calculated.

4. Experimental Results

We performed two experiments to evaluate the performance of 4-ASK-FOFDM. In the first experiment, the atmospheric turbulence simulator was enabled; thus, it provided a turbulent atmospheric channel with a length of 12.5 m. Before transmitting the 4-ASK-FOFDM signals, we measured the fluctuated signal when a blue light with constant power was transmitted. Because the coherent time of atmospheric turbulence was 1~100 ms, a Si amplified detector (PDA100A-EC, Thorlabs) with bandwidth from DC to 2.4 MHz was used in the measurement. The transmission distance in the water tank was fixed to 1.6 m because the tap water channel did not make the signal fluctuate. The statistical histogram of the captured signal was shown in Figure 4a, and the statistical histogram was fitted according to lognormal distribution; the fit curve was also presented in Figure 4a. Based on the fitted curve, we found that the mean of the captured signal was 0.0313 V, the variance was 0.007, and the scintillation index was 0.007. According to the parameters obtained, we can conclude that the simulated atmospheric turbulence was weak. The power spectra density (PSD) of the fluctuated signal was plotted in Figure 4b. It can be seen from Figure 4b that the power of the fluctuated optical signal was mostly below 19 Hz, which also meant that the simulated turbulence was weak.

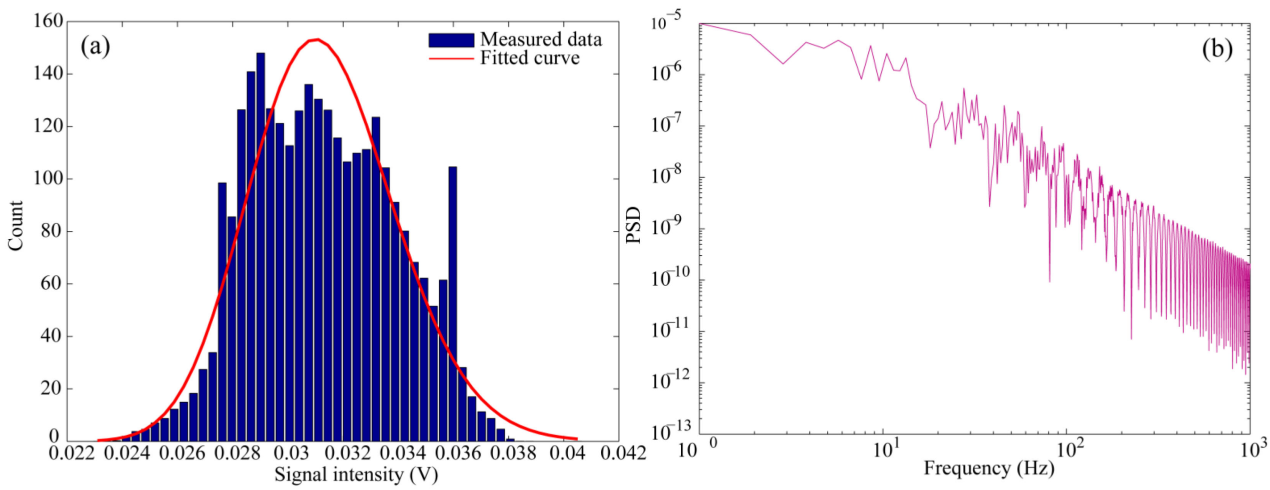

Figure 4. (**a**) Statistical histogram and (**b**) power spectra density of the received signal at the receiver when the light with constant optical power propagated over a simulated turbulence channel.

4.1. Comparison of Performance When 4-ASK-FOFDM Signal Transmitted over a Simulated Air Turbulence Channel Followed by a Water Channel or a Free-Space Air Channel Followed by a Water Channel

After the fluctuated channel measurement, the 4-ASK-FOFDM signal was transmitted. To compare with the results obtained in the first experiment, in the second experiment, the atmospheric turbulence simulator was disabled, so it was just a free-space atmosphere channel with a length of 12.5 m. In the two experiments, when the transmission distance through the tap water tank was 3.2 m, we captured the time domain waveforms of 4-ASK-FOFDM. The waveforms and the corresponding spectra are shown in Figure 5. The waveform in Figure 5a and its spectrum in Figure 5b were obtained over the turbulent air–water channel in the first experiment. The waveform in Figure 5c and its spectrum in Figure 5d were obtained over the free-space air channel, followed by a water channel in the second experiment.

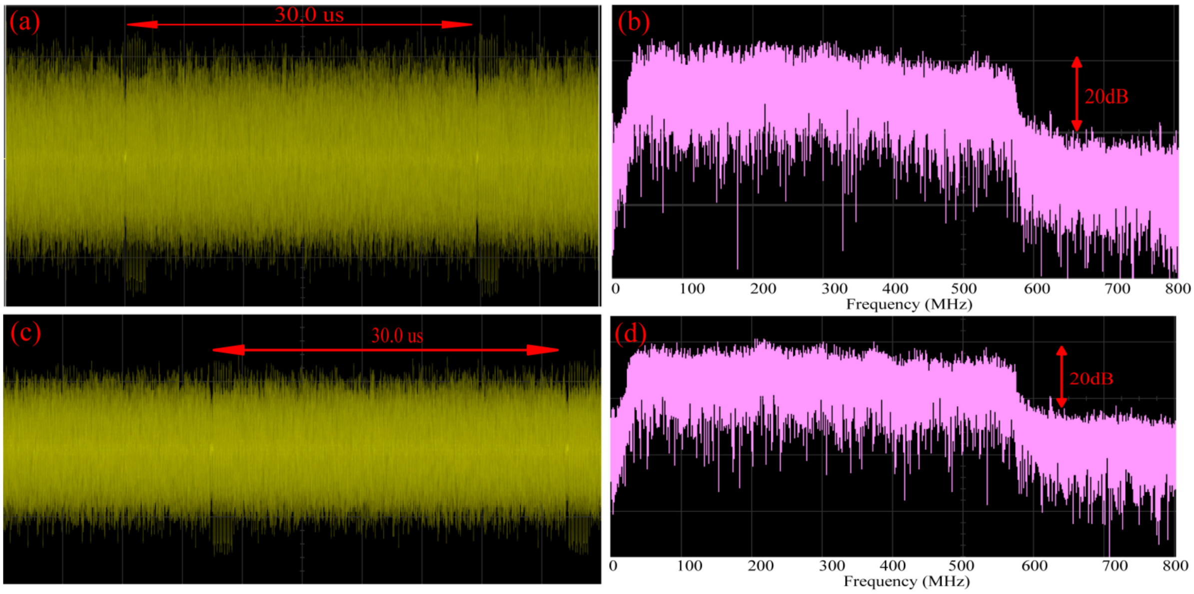

Figure 5. Waveforms and spectra captured over a simulated air turbulence channel followed by a water channel (**a**,**b**) and over a free-space air channel followed by a water channel (**c**,**d**).

In the two experiments, the effect of the link distance in the water tank on the BER performance was investigated. The link distance through the water tank was changed from 1.6 m to 8 m. The measured BER for 4-ASK-FOFDM at different link distances is shown in Figure 6. As seen from Figure 6, as the link distance increases from 1.6 m to 8 m, the BER of 4-ASK-FOFDM were all below a 7% FEC limit of 3.8×10^{-3}, whether the turbulent air channel was enabled or disabled. Furthermore, the difference between 4′-ASK-FOFDM-turbulent′ and 4′-ASK-FOFDM-non-turbulent′ was tiny, which meant the turbulent air channel had a negligible effect on the 4-ASK-FOFDM signal. This was because the simulated turbulence by the atmospheric turbulence simulator was too weak, and the power of the fluctuated signal was below 19 Hz; thus, the coherent time of the simulated air turbulence was up to 53 ms. The coherent time was much longer than the period of one OFDM data frame (30 µs); consequently the turbulent air channel just led to limited fade. In addition, because the IM/DD transmission scheme was adopted, the phase fluctuation brought by the turbulent air cannot affect the 4-ASK-FOFDM signal. Figure 7 shows the constellations of the 4-ASK-FOFDM signal when the link distance through the water tank was 1.6 m and the atmospheric turbulence simulator was either enabled or disabled. The insets in Figure 7 presented the histogram of constellation points.

4.2. Comparison of BER Performance between 4-ASK-FOFDM and 16-QAM-OFDM in a Simulated Air Turbulence Channel Followed by a Water Channel

To better evaluate the performance of 4-ASK-FOFDM, the BER of 4-ASK-FOFDM was compared with that of conventional 16-QAM-OFDM under the same SE of 1.68. The measured BER for 4-ASK-FOFDM and conventional 16-QAM-OFDM at different link distances is shown in Figure 8. As seen in Figure 8, as the link distance increases from 1.6 m to 8 m, the BER of 4-ASK-FOFDM were all below 3.8×10^{-3}, which was the 7% FEC limit. The BER performance of conventional 16-QAM-OFDM was a little better than 4-ASK-FOFDM. But the performance penalty of 4-ASK-FOFDM was tiny. Figure 9 shows the constellations of the 4-ASK-FOFDM signal and 16-QAM-OFDM signal when the link distance through the water tank was 1.6 m and the atmospheric turbulence simulator was enabled.

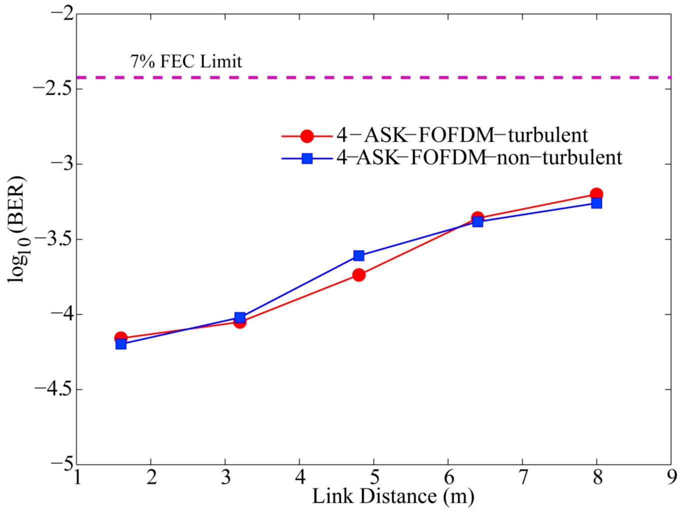

Figure 6. Curves of BER vs. link distance over a simulated air turbulence channel followed by a water channel and a free-space air channel followed by a water channel.

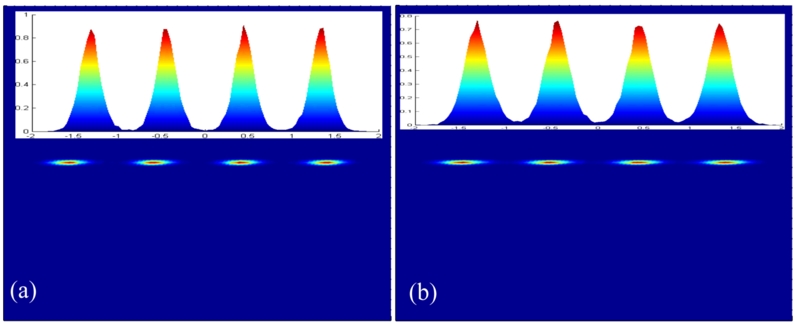

Figure 7. Constellations of the 4−ASK−FOFDM signal when the link distance through water tank was 1.6 m and (**a**) the atmospheric turbulence simulator was disabled or (**b**) the simulator was enabled. The insets showed the histogram of constellation points.

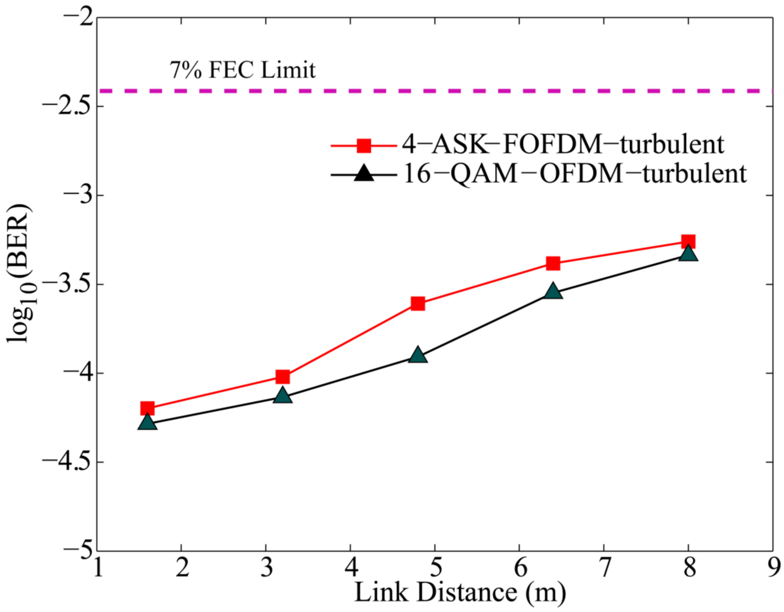

Figure 8. Curves of BER versus link distance over a simulated air turbulence channel followed by a water channel for 4-ASK-FOFDM and 16-QAM-OFDM signals.

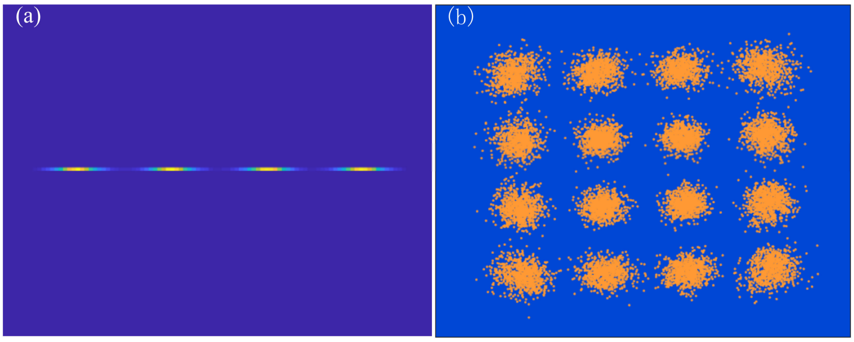

Figure 9. (**a**) Constellation of the 4-ASK-FOFDM signal and (**b**) constellation of 16-QAM-OFDM signal when the link distance through water tank was 1.6 m.

5. Discussion

The key components in our experiment included an RF amplifier (SHF 100AP) with a bandwidth of 30 KHz–25 GHz, Bias-Tee (PE1611) with a bandwidth of 10 MHz to 2.5 GHz, blue LD with a bandwidth of 1.25 GHz, and lens and avalanche photodiode (APD) with a bandwidth of 1 GHz. The bandwidth in the link was enough, so it was not the factor that affected the experiment's performance. The wavelength of the LD was 451 nm, and the output power was fixed to 30 mW. The wavelength of LD was one of the key factors that affected the performance. For underwater optical communications, the wavelengths of blue (around 450 nm) and green (around 532 nm) were two transmission windows; the light with these two wavelengths had less attenuation brought by the water and produced better BER performance than light with other wavelengths. Another key factor was the lens at the transmitter side. If the light beam is expanded by the lens, a big light spot will be produced; then, the optical power reaching the receiver lens will reduce, which will lead to worse BER performance.

In optical wireless communications, OFDM was widely researched because it could bring higher spectra efficiency and better tolerance of multipath effect. But in turbulent atmosphere channels, when it encountered the scintillation of light, OFDM was not superior to a single-carrier scheme. Because the high-order modulation format used by OFDM, like QAM, carried information both with amplitude and phase, when the light was distorted by the turbulence, both the amplitude and phase of information symbols were affected, which led to performance degradation.

For FOFDM, the information was mapped to ASK symbols; only the amplitude was used, so when distortion appeared, only the amplitude was affected. In order to investigate the performance of 4-ASK-FOFDM, we transmitted a 4-ASK-FOFDM signal over a turbulent air–water channel and a non-turbulent air–water channel. Through comparison, it can be concluded that the 4-ASK-FOFDM has a better tolerance in the turbulent channel. Moreover, because of low complexity and high SE, the FOFDM scheme could have more potential applications in future optical wireless communications.

6. Conclusions

In this paper, we experimentally investigated a 4-ASK-FOFDM transmission over a turbulent air–water channel, which was comprised of a weak turbulence channel generated by an atmospheric turbulence simulator, together with a water tank. The BER performance was compared when the 4-ASK-FOFDM signals were transmitted over a turbulent air–water channel and a free-space air–water channel, respectively. The results showed that the BER performance difference under these two kinds of channels was tiny; hence, the 4-ASK-FOFDM signals were not sensitive to weak turbulence. Moreover, the performance of the 4-ASK-FOFDM scheme was compared with a conventional 16-QAM-OFDM scheme under the condition of the same spectra efficiency. The results showed that there was a slight BER performance penalty for 4-ASK-FOFDM compared with the 16-QAM-OFDM scheme. Accordingly, the feasibility of the 4-ASK-FOFDM-based OWC system was validated. It is a promising alternative to conventional OFDM techniques in optical wireless communications. To further improve the performance of 4-ASK-FOFDM, more effective channel estimation and compensation algorithms will be researched in the future. With these more effective algorithms, it is believed that FOFDM will be a promising alternative to conventional OFDM techniques in optical wireless communications.

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Conflicts of Interest: The authors declare no conflicts of interest.

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