C-band PS 4096QAM OFDM FSO Transmission with 6.98bit/s/Hz Net SE Based on Kramers-Kronig Detection

Yiran Wei, Yingjun Zhou, Cuiwei Liu, Feng Wang, Kaihui Wang, Junting Shi, Nan Chi and Jianjun Yu*
Key Laboratory for Information Science of Electromagnetic Waves (MoE), Department of Communication Science and Engineering, Fudan University, No. 220, Handan Road, Shanghai, China
**e-mail: jianjun@fudan.edu.cn*

Abstract: We experimentally demonstrate 10Gbaud PS 4096QAM OFDM with KK detection over 25m FSO transmission. As far as we know, this is the highest QAM delivery in a FSO communication system.

1. Introduction

Free space optic (FSO) communications have been proposed for indoor links, last-mile connection in wireless networks and inter-satellite transmission, which have attracted much attention for both academies and industries [1]. Especially, C-band laser is relatively safe because most of the laser energy is obstructed before being sent into retinas [2]. Thus, a higher transmitting power is available in a C-band FSO system. Direct detection (DD) scheme is highly preferable for short-reach communication due to its low cost. Nevertheless, the recommended modulation formats such as pulse-amplitude modulation (PAM) and discrete multitone (DMT) in DD system will occupy more spectrum compared that in a coherent systems, since the phase information cannot be detected by the single photodiode (PD). A feasible method to convey complex signal by allocating the carrier at the edge of the signal is presented in [3]. However, this method suffers much from the signal-signal beating interference (SSBI). Recently, a so called Kramers-Kronig (KK) scheme is proposed to mitigate SSBI under the minimum phase condition [4], which can reconstruct the complex optical field from the PD detected amplitude. On the other hand, probabilistic shaping (PS) has been proved as an effective technology in optical communication [5], which can improve receiver sensitivity by an easy control of the system spectral efficiency (SE) by adjusting the shaping coefficient v of Maxwell-Boltzmann distribution. Thus, the combination of PS and KK is a promising candidate to achieve a FSO system with high SE based on DD.

In our previous work, 256QAM transmission in a 25GHz grid was carried out with KK detection, and a SE of 5.12bit/s/Hz was obtained [6,7]. In this work, we further increase the modulation order to 4096QAM OFDM, and we introduce PS to improve the system performance, and achieve a SE of 6.98bit/s/Hz in 25m C-band FSO link. To the best of our knowledge, this is the highest QAM delivery in a FSO communication system with net SE up to 6.98bit/s/Hz.

2. Experimental setup

The experimental setup and digital signal processing (DSP) of the FSO system is shown in Fig. 1 The initial binary sequence is firstly transformed to PS symbols, including a constant composition distribution matching (CCDM), a forward error correction (FEC) encoding and quadrature amplitude modulation (QAM) Gray mapping. After serial to parallel and inverse fast Fourier transform (IFFT), the OFDM signal is generated. Then the cyclic prefix (CP) of 16 length is added. The up-sampling by a factor of 8 is implemented to form a 10Gbaud signal in the 80GSa/s digital analog convertor (DAC). Before being sent into DAC, the signal is up-converted to construct a single-sideband (SSB) signal. The signal is then modulated on a C-band optical carrier operating at 1565.35nm by an IQ modulator of 30GHz

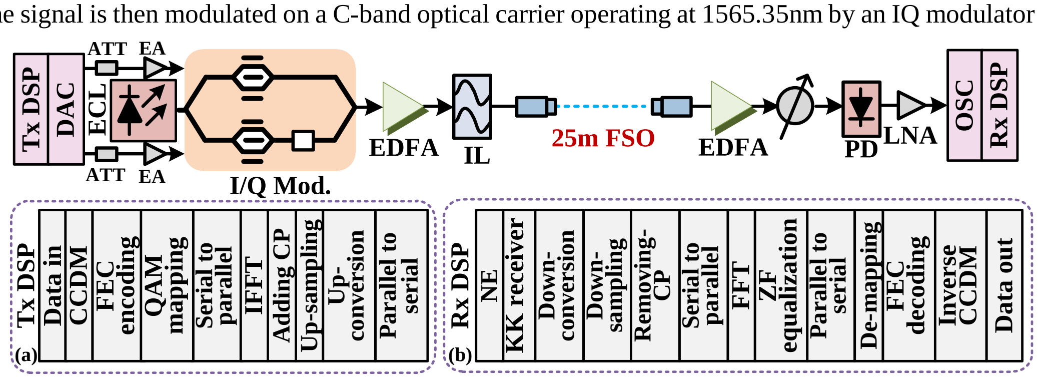

Fig. 1. Experimental setup for C-band FSO, (a) block diagram of Tx DSP, (b) block diagram of Rx DSP.

bandwidth. An Erbium-doped fiber amplifier (EDFA) is used before the 12.5GHz interleaver (IL). After that, the optical signal is sent into the FSO transmitter. The Tx and Rx of the FSO system are shown in Fig. 2(a).

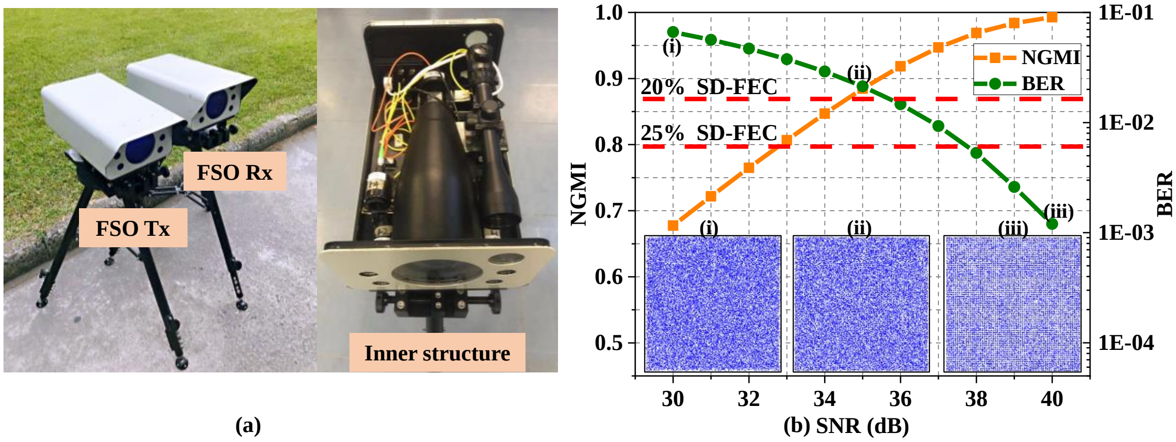

Fig. 2. (a) FSO Tx, Rx and inner structure, (b) NGMI and BER versus SNR, Insets: constellations with (i) 30dB, (ii) 35dB and (iii) 40dB SNR.

After 25m FSO transmission, the optical signal is absorbed by the FSO receiver. The measured power loss of 25m FSO link is about 18dB. The combination of EDFA and variable optical attenuator (VOA) is employed to adjust the optical power in the receiver side. The electrical signal is detected by a PD and amplified by a low noise amplifier (LNA) with 3dB bandwidth of 20GHz. Then a 33GHz bandwidth oscilloscope (OSC) operating at 100GSa/s is set to acquire the amplified electrical signal. The signal is then recovered by the nonlinear equalization (NE) and reconstructed to a SSB signal after KK detection. The KK scheme is worked as follows. A positive value is added to the detected signal as a virtual DC component due to the usage of an AC-coupled PD. Assuming the PD detected signal is $S(t)$. Then the signal with the virtual DC can be express as:

$$S'(t)=V_{DC}+S(t) \tag{1}$$

The phase can be derived as:

$$\varphi(\mathrm{t})=\mathrm{Hilbert}[\ln(\sqrt{S'(t)})] \tag{2}$$

Subsequently, the reconstructed SSB signal is:

$$S_{SSB}(t)=\sqrt{S'(t)}e^{i\varphi(t)} \tag{3}$$

Following the down-conversion and down-sampling, the CP is removed and the serial signal is converted into a parallel signal. After fast Fourier transform (FFT) and zero-force (ZF) equalization, the signal is set back to serial. With de-mapping, FEC decoding and inverse CCDM, the binary sequence is recovered.

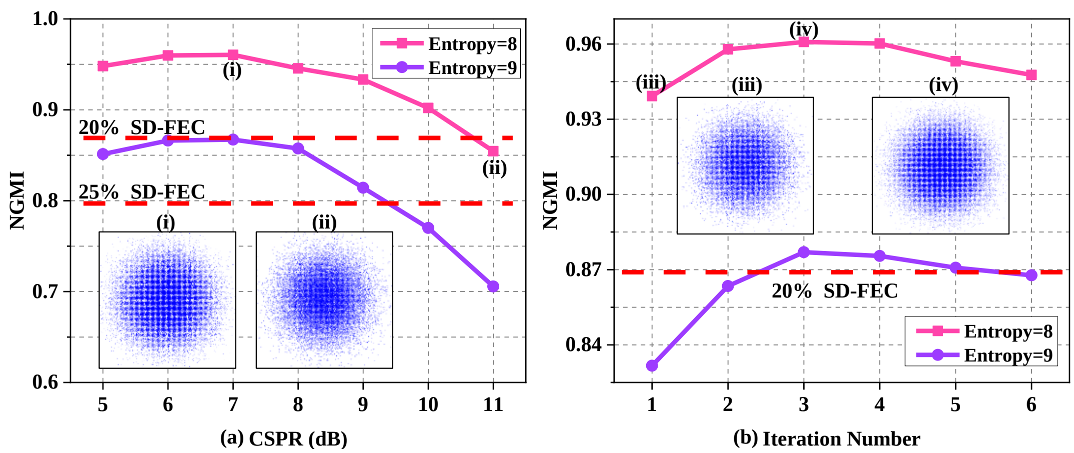

Fig. 3. (a) NGMI versus CSPR, (b) NGMI versus iteration numbers, Insets: constellations with (i) 7 and (ii) 11 dB CSPR, constellations with (iii) 1 and (iv) 3 iteration numbers.

2. Results and Discussion

We also simulate the uniform 4096QAM OFDM with additive white Gaussian noise (AWGN) channel. The bit error rate (BER) and normalized generalized mutual information (NGMI) against signal-noise ratio (SNR) is shown as Fig. 2(b). The FEC threshold is set at NGMI scale. The NGMI is calculate as follows [8]:

$$NGMI = 1\text{-}[H(X) - GMI]/m \tag{4}$$

where m represents modulation order and $H(X)$ is the entropy of the signal. The entropy of the PS 4096QAM OFDM signal is adjusted by the shaping coefficient v. Based on the simulation results in Fig. 2(b), 20% and 25% SD-FEC NGMI thresholds are calculated.

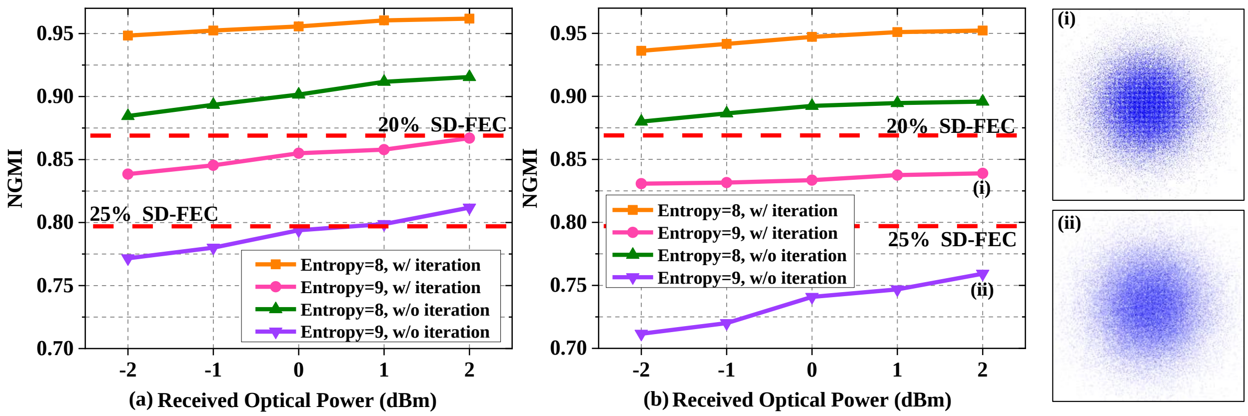

Fig. 4. NGMI versus ROP in (a) BTB case and in (b) FSO transmission, Insets: the received constellation (i) with and (ii) without iteration

In the experiment, we send the PS 4096QAM OFDM with two different entropy, 8 and 9 respectively. And we transmit the signal over 25m FSO link. Fig. 3(a) shows the NGMI at different carrier signal power ratio (CSPR). The CSPR is modified by the bias voltage of the IQ modulator, and measured by turning on/off the electrical signal. The optimal CSPR in the system is around 7dB. Thus, the following experimental results are all based on 7dB CSPR. The constellation of 8 entropy signal is quite clear at the optimum point. In order to realize the high-order format communication, we iterate the training signal for several times so as to release the noise penalty. Fig. 3(b) presents the NGMI versus the iteration number. The test iteration number is 3 and an excess of iteration will cause noise overfitting.

Fig. 4(a) depicts the BTB NGMI with various received optical power (ROP). The iteration method significantly improves the performance of PS signal with different entropy. The NGMI drops faster with the decrease of ROP when the iteration method is not employed. Relatively speaking, the performance becomes stable after employing training iteration. The FSO results are shown in Fig. 4(b). The constellation of the signal with 9 entropy shown in Fig. 4 is much clearer with iteration than that without iteration. Although the signal is attenuated by 18dB in the 25m FSO link, a higher than the 25% SD-FEC threshold NGMI can still be achieved based on a PS 4096QAM OFDM signal with 9 entropy and the training iteration. Thus, it is promising to be a transmission scheme for beyond 5G wireless communications. In this system, the CP overhead is 16/(16+512)=3.03%. Thus the SE is $9\times(4/5)\times$(1-3.03%)=6.98bit/s/Hz.

3. Conclusions

We have achieved 10Gbaud PS 4096QAM OFDM transmission over a 25m FSO link with the training iteration scheme. To the best of our knowledge, this is the first time that a net SE of 6.98 bit/s/Hz is achieved based on KK detection in a C-band FSO communication system. Since C-band laser is relatively safe to eyes, it is a potential candidate for beyond 5G wireless communication systems.

This work is supported by National Key R&D Program of China (2018YFB1801004) and National Natural Science Foundation of China (61527801, 61675048, 61720106015, 61805043, 61835002).

Reference

[1] M. Alzenad, et al, IEEE Commun. Mag. (2018), Vol. 56, Num. 1, pp. 218-224.
[2] M. A. Khalighi, et al, IEEE Commun. Surv. Tuts. (2018), Vol. 16, Num. 4, pp. 2231-2258.
[3] M. Schuster, et al, IEEE Photonics Technol. Lett. (2008), Vol. 20, Num. 9, pp. 670-672.
[4] F. Buchali, et al, Proc. of Eur. Conf. Opt. Commun. 2015,1-3.
[5] Y. Zhou, et al, Proc. of Opt. Fiber Commun. Conf. 2019, Th2A. 46.
[6] Y. Zhou, et al, J. Light. Technol. (2019), Early Access Article, DOI: 10.1109/JLT.2019.2943122.
[7] J. Cho, et al, Proc. of Eur. Conf. Opt. Commun. 2017,1-3.