Integrated Coherent Optical Fiber Communication System with Discrete-Time Analog Transmission

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Abstract: We propose and experimentally demonstrate an integrated coherent optical fiber communication system based on discrete-time analog transmission (DTAT-IOFC). The experimental results indicate that DTAT-IOFC exhibits better performance and achieves 6 dB optical signal-to-noise ratio gain. © 2024 The Author(s)

1. Introduction

Currently, point-to-point coherent optical fiber communication systems are based on the digital communication structure (D-OFC). In digital optical communication, information sources (such as text, images, and videos) are encoded into bits by source coding. Channel coding is utilized to overcome bit errors in transmission by adding redundant bits. Then, the bits are modulated into symbols for the transmission [1]. However, D-OFC has the "cliff effect" problem, which means that when the channel state deteriorates, the bit error rate exceeds the feedforward error correct (FEC) code threshold, and the system reliability drops like a cliff [2]. Thus, for the first time, we propose an integrated coherent optical fiber communication with discrete-time analog transmission (DTAT-IOFC). Specifically, by replacing the separated source coding, channel coding, and modulation with joint source-channel coding and modulation (JSCCM), DTAT-IOFC achieves end-to-end coding and modulation optimization, which can effectively prevent the "cliff effect" [3]. Moreover, the deep learning-based JSCCM codes the information sources into discrete-time continuous amplitude signals, yielding more degrees of freedom than discrete constellations [4].

In this paper, coherent DTAT-IOFC is proposed and experimentally demonstrated. In the experiment, the transmission of images is investigated. The transformer-based JSCCM network is utilized to encode the images into discrete-time analog symbols. Then, the signals are transmitted through a dual-polarization coherent optical communication system. The experimental results show that when the optical signal-to-noise ratio (OSNR) decreases, DTAT-IOFC provides a graceful and gradual performance degradation similar to analog communication. Therefore, DTAT-IOFC can automatically adapt to the channel noise variation, while D-OFC needs to adjust the coding parameters and modulation formats according to the channel noise level variation. Meanwhile, DTAT-IOFC shows a better image transmission performance. Compared to D-OFC with practical channel coding and modulation, DTAT-IOFC achieves 6 dB OSNR gain under the same image transmission rate. DTAT-IOFC even outperforms D-OFC with capacity-achieving channel code and modulation in many cases.

2. Principle of DTAT-IOFC

The structure of the proposed DTAT-IOFC is shown in Fig. 1. In DTAT-IOFC, the transmitted images are encoded into discrete-time analog symbols by JSCCM. The JSCCM network is based on the Swin Transformer [5]. The RGB images $x \in R^{H\times W\times 3}$ are split into $l_1 = \frac{H}{2}\times\frac{W}{2}$ non-overlapping patches. The patches are input into the network in order from top left to bottom right. After patch embedding, the Swin Transformer blocks are utilized for encoding. After four stages of encoding and a fully connected layer, the images are encoded into discrete-time analog symbols. The constellation of DTAT-IOFC is shown in Fig. 1, which is irregular and has a Gaussian distribution of amplitude. After optical fiber channel transmission, the images are recovered by the joint demodulation decoding (JDD) network. The JDD network is the inverse process of JSCCM. In the training process, the DIV2K dataset is used. An Adam optimizer with a learning rate of 1×10^{-4} is utilized. The JSCCM and JDD network models are trained end-to-end under the additive white Gaussian noise (AWGN) channel with a uniform distribution of SNR from 3 dB to 13 dB.

A reasonable signal peak-to-average power ratio (PAPR) value is important to the transmission over the optical physical link. The large PAPR gives rise to distortions caused by nonlinear devices, such as an A/D converter, modulator, and transmission fiber [6]. To ensure the performance of image encoding and control the PAPR of the output discrete-time analog symbols simultaneously, we design the loss function for the DTAT-IOFC model training.

$$Loss = (1 - \text{MS-SSIM}) + \lambda PAPR \tag{1}$$

The MS-SSIM evaluates the performance of the received images, which is a multi-scale perceptual metric that approximates human visual perception well [7]. The term $\lambda PAPR$ of loss function could limit the PAPR of the output discrete-time analog symbols, where λ is a tunable parameter. In our experiments, λ is set to 1×10^{-3}.

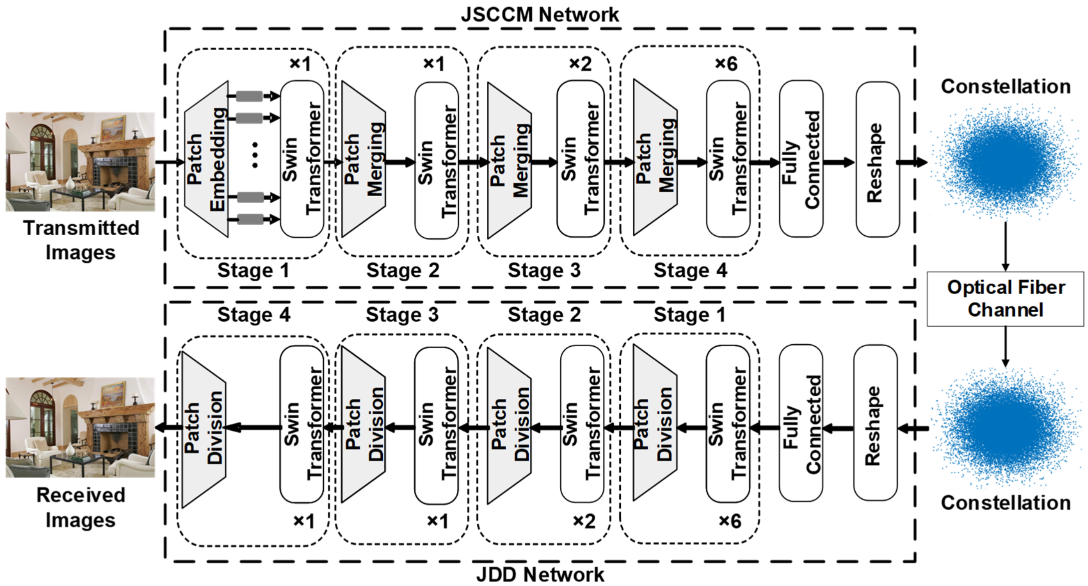

Fig. 1. Structure of the proposed DTAT-IOFC.

3. Experiments and results

The experimental setup of the optical transmission system is shown in Fig. 2. At the transmitter, the symbols are processed by a square-root-raised cosine (SRRC) filter with a 0.1 roll-off factor. The signals are then sent to the arbitrary waveform generator (AWG, Keysight M8195A). This AWG's highest sampling rate and analog bandwidth are 65 GSa/s and 25 GHz, respectively. The electrical analog signals generated by the AWG are amplified by a four-channel amplifier. The electrical signals are then modulated into optical signals by a dual-polarization (DP) IQ modulator. The input fiber optical power is 0 dBm, with the amplification of the erbium-doped fiber amplifier (EDFA). At the receiver, the optical signals are converted into electrical signals by an integrated coherent receiver. The received electrical signals are sampled at 100 GSa/s using the digital sampling oscilloscope (DSO) with an analog bandwidth of 25 GHz (Tektronix DSA72504D). Then, the electrical signals are processed by the digital signal process (DSP) at the receiver. The constellation of the DTAT-IOFC is irregular, so the training-sequence-based 4 × 4 multiple-input multiple-output (MIMO) is used for depolarization and channel equalization. The pilot-aided algorithm is used for carrier phase recovery. They are not sensitive to modulation formats.

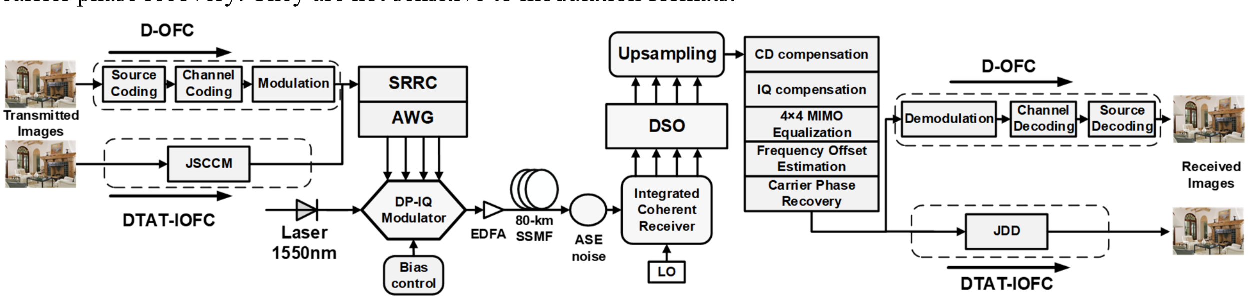

Fig. 2. Experiment setup of the coherent optical fiber communication system. ASE: amplifier spontaneous emission; LO: local oscillator; CD: chromatic dispersion.

In the experiment, the high-resolution images from the Kodak dataset with 768×512×3 pixels are transmitted to investigate the DTAT-IOFC performance. The experiment system's baud rate and sampling rate are 30 Gbaud and 60 GSa/s, respectively. The image transmission rates of DTAT-IOFC and D-OFC are similarly controlled, which is 7.98×10^{5} images/s. The D-OFC system is used for comparison. The JPEG2000 and 3/4 code rate LDPC are used as source coding and channel coding, respectively [8]. The modulation format adopts QPSK and 16QAM. For QPSK

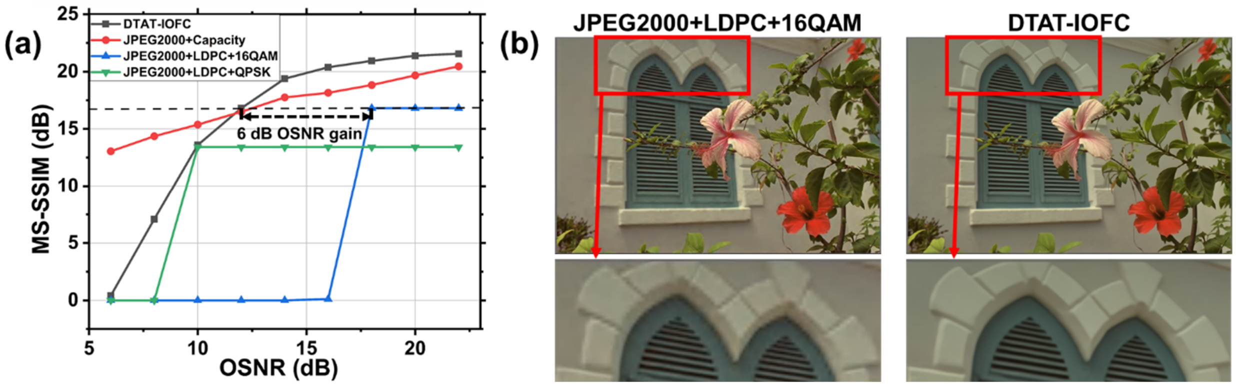

Fig. 3. (a) Experiment results of the coherent optical fiber communication system. (b) Visual results of the received image when OSNR is 18 dB.

and 16QAM transmission, the system keeps the same image transmission rate.

The experimental results are shown in Fig. 3(a), indicating the relationship between the OSNR and the MS-SSIM of the received images. For more intuitive observation and comparison, it is converted into dB form. The formula is MS-SSIM(dB) = −10log(1 − MS-SSIM). For D-OFC transmission, 16QAM is more suitable in the high-OSNR region (OSNR above 18 dB). In the low-OSNR region (OSNR below 18 dB), 16QAM cannot support reliable transmission, and QPSK is required. Due to the decrease in the bit transmission rate adopting QPSK, the compression ratio of the source coding (JPEG2000) needs to be increased to keep the same image transmission rate. A higher compression ratio of source coding will lead to increased image distortion. The image's transmission quality and the system's noise robustness have a trade-off relationship. For the DTAT-IOFC, channel noise will affect the quality of the received discrete-time continuous amplitude symbols, which will directly influence the performance of the received image. As the channel noise increases, the DTAT-IOFC provides a graceful and gradual performance degradation similar to analog communication. Therefore, DTAT-IOFC can automatically adapt to the channel noise level variation, while D-OFC needs to adjust the coding parameters and modulation formats according to the channel noise level variation. The transmission results indicate that the proposed DTAT-IOFC outperforms the D-OFC. DTAT-IOFC achieves up to 6 dB OSNR gain in the experiments. The results of ideal capacity-achieving channel code, modulation, and channel equalization are also considered during evaluation (marked "JPEG2000+Capacity"), obtained by numerical calculations. Notably, DTAT-IOFC performs better than D-OFC with JPEG2000+Capacity in the high-OSNR region. In the low-OSNR region, the performance of the channel equalization algorithm will degrade significantly, resulting in the transmission performance of DTAT-IOFC obtained in the low-OSNR region being worse than the JPEG2000+Capacity result obtained by theoretical numerical calculation. Fig. 3(b) visualizes the received images when OSNR is 18 dB. It can be observed that DTAT-IOFC can achieve better visual quality with the same OSNR and image transmission rate. Specifically, it produces higher-fidelity textures and details.

4. Conclusions

In this paper, we propose and demonstrate a coherent DTAT-IOFC. Compared with D-OFC with practical channel coding and modulation, DTAT-IOFC achieves 6 dB OSNR gain under the same information transmission rate. DTAT-IOFC outperforms D-OFC with capacity-achieving channel code and modulation in many cases. Meanwhile, DTAT-IOFC can automatically adapt to the channel and provide a graceful and gradual performance degradation as the channel noise increases.

5. References

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