OFDM-1024QAM transmission over 400m at THz band with Delta-Sigma-Modulation

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Abstract: For the first time, we successfully transmit 1.25GBaud OFDM-256QAM/1024QAM signals over 20km SMF and 400m wireless link at the terahertz band with 1-bit DSM. The BER of OFDM-256QAM/1024QAM can satisfy the FEC threshold of $3.8\times10^{-3}/4.0\times10^{-2}$.

1. Introduction

Nowadays, the emergence of new digital services such as cloud computing, ultra-high-definition video, and virtual reality (VR), has driven the explosive growth of network traffic, which bring challenges to the capacity of mobile communication systems. The terahertz (THz) band has a huge available bandwidth resource, so it has received extensive attention and is considered a potential band for future mobile communications. In recent years, the optical heterodyne using two optical resources is regarded as the most promising technique for THz signals generation in a uni-traveling carrier photodiode (UTC-PD) [1-4]. Up to now, many researches about the transmission of the THz signals have been reported: optical THz system over 54 m wireless link by using PS technique and 104 m without a THz amplifier, as well as 400m long-range THz link is achieved [1-3].

However, limited by the maturity of the device and the signal-to-noise ratio (SNR) of the system, the modulation format orders reported on terahertz signal transmission are often not very high. Nowadays, the high-order QAM technique is widely used in wireless communication. Up to now, 1024QAM and 2048QAM have been adopted in practical applications. 4096QAM and higher-order QAM are also being investigated for the future wireless network. For such high-order QAM signal transmission, the current THz system is difficult to support. Considering the abundant bandwidth resources of the THz band, the delta-sigma modulator (DSM) with oversampling could be a good solution. Usually, low resolution DSMs with oversampling are used to quantize the baseband signal and the in-band noises are reduced by noise shaping technique [5-7]. In this way, the high-performance digital-to-analog converter (DAC) can be avoided and the generated OOK/PAM4 signal could directly drive the nonlinear lasers. At the receiver, an LPF and down-sample operation are adopted to recover the baseband signals. In such a system, the high-order signals can be converted into low-order ones so that a high receiver sensitivity can be obtained. Moreover, the receiver can use an ADC with a lower resolution for low-order signal reception.

In this paper, we propose and demonstrated a DSM-based THz-over-fiber system for high-order OFDM signal transmission. Two 1-bit DSMs are used to quantize the baseband OFDM signals into QPSK single carrier signals. Based on the experimental results, 1.25 GBaud OFDM-256QAM~1024QAM signals can be successfully transmitted over 20km SMF and 400m wireless link at the terahertz band. The BER of the OFDM-256QAM and OFDM-1024QAM after the transmission can satisfy the SD-FEC threshold of 4.0×10^{-2} and HD-FEC threshold of 3.8×10^{-3}, respectively.

2. Principles and Experimental Setup

The experimental setup is demonstrated in Fig.1. At the Tx side, the external cavity laser-1 (ECL1) with the 100 kHz linewidth is employed as the optical carrier source at 1550nm. The baseband electric signal, delivered by the 10-Gsa/s arbitrary waveform generator (AWG) and amplified by the electric amplifier (EA) before, is modulated via the I/Q modulator with 30-GHz bandwidth. After the polarization-maintaining erbium-doped optical fiber amplifier (PM-EDFA), the modulated signal is coupled with the optical oscillator signal generated by the 100 kHz linewidth ECL2. The frequency space between two signals is set as 335 GHz. The polarization and power of the coupled signal are strictly controlled through the EDFA, polarization controller (PC), and variable optical attenuation (VOA). Heterodyne beaten by the uni-traveling-carrier photodiode (UTC-PD) and amplified by the 25-dB gain low-noise amplifier (LNA), the wireless 335 GHz signal at -10 dBm is delivered by the 25-dBi gain antenna.

At the transmitter, the 1.25 Gbaud OFDM signal is used as the baseband signal for transmission. We use two 1-bit fourth-order DSMs with an OSR of 8 to quantize the real and imaginary parts of the baseband OFDM signal. The

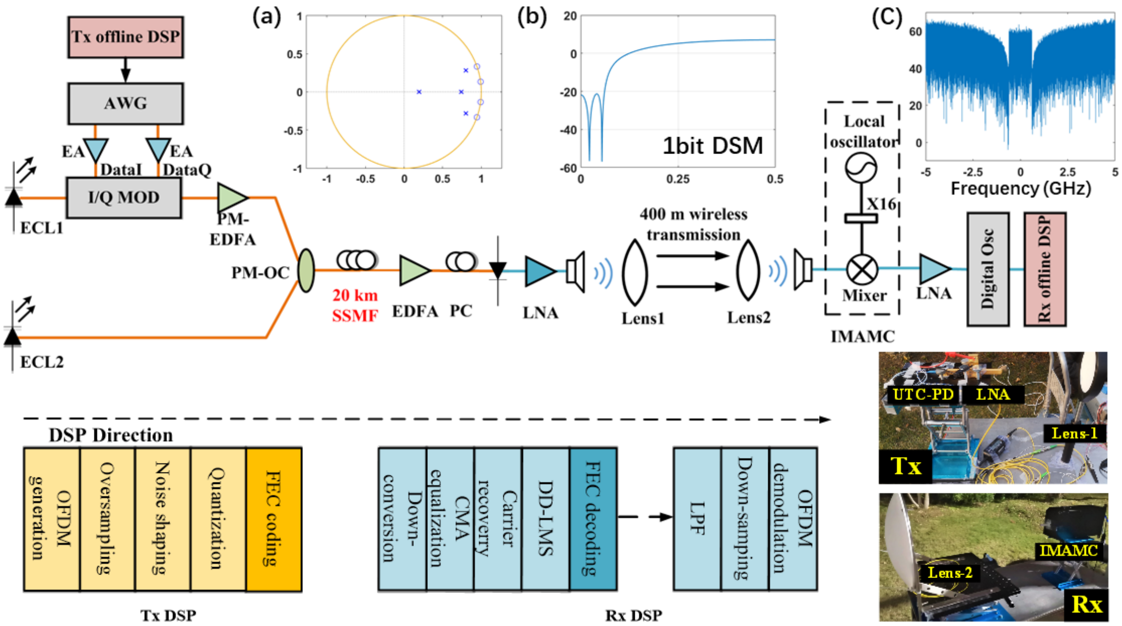

Fig. 1. The experimental setup of the DSM-based THz-over-fiber transmission system: (a) the zero-poles and (b) magnitude-frequency response for the 2-bit DSMs; (c) spectrum of the QPSK signal after DSMs.

zero-poles and magnitude-frequency response for the 1-bit DSMs are presented in Fig. 1 (a) and (b). Fig. 3(c) shows the spectrum of the signal after DSMs. The two 1-bit DSMs can generate two OOK signals, which can be combined as an 8 Gbaud single carrier (SC) QPSK signal and then used to drive I/Q modulator for optical modulation.

A pair of polytetrafluoroethylene (PTFE) lenses are deployed for the signal beam aggregation to support a 400-m wireless transmission link. Meanwhile, the long-distance transmission of the wireless THz wave requires strict beam alignment. Two tripod heads are deployed to adjust the elevation, azimuth, and height of the Tx and Rx for better performance. At the Rx side, the signal down-conversion is realized via an integrated mixer/amplifier/multiplier chain (IMAMC) consisting of a 20.625-GHz radio frequency (RF) source, a ×16 frequency multiplier, and a mixer. The EA is adopted to improve the receiver sensitivity. The 5 GHz (335-20.625×16=5) intermediate-frequency (IF) signal is captured by a 50 GSa/s OSC for following offline digital signal processing.

The DSP in the receiver includes two parts: the equalization for QPSK and the DSM demodulation. The sampled signals are firstly down-converted to the baseband for the following DSP. In this experiment, a 73-tap CMA equalizer is adopted to compensate for the linear distortions during the transmission. Subsequently, the carrier recovery operation including frequency offset estimation (FOE) and carrier phase estimation (CPE) is conducted. Moreover, a decision-directly least-mean-square (DD-LMS) equalizer with 133 taps is adopted to further improve BER performance. Before DSM demodulation, the equalized signals are decided into the standard QPSK constellations. After LPF and down-sampling operation, the baseband OFDM signal can be recovered. Finally, we can simply recover the original high-order QAM signals by reversing the operations of the OFDM generation at the transmitter [8].

3. Experimental results and discussions

In such a DSM-based system, even a small number of misjudgments of constellation points can lead to performance degradation of the recovered signal. Fig. 2(a) presents the relationship between the BER of the recovered OFDM-QAM and the BER of the QPSK signal after DSM. It can be seen that when the BER of the DSM-QPSK signal is lower than 1E-5, the BER performance of the recovered OFDM-QAM signal tends to be stable. Therefore, we add LDPC coding with a code of 5/6 for the QPSK signals at the transmitter. At the receiver, FEC decoding can help reduce the BER of the DSM-QPSK signals. We can also use the commonly used FEC threshold. Usually, FEC coding can reduce the BER of the DSM-QPSK signal to 1E-6 or even lower so that the original OFDM-QAM can be recovered.

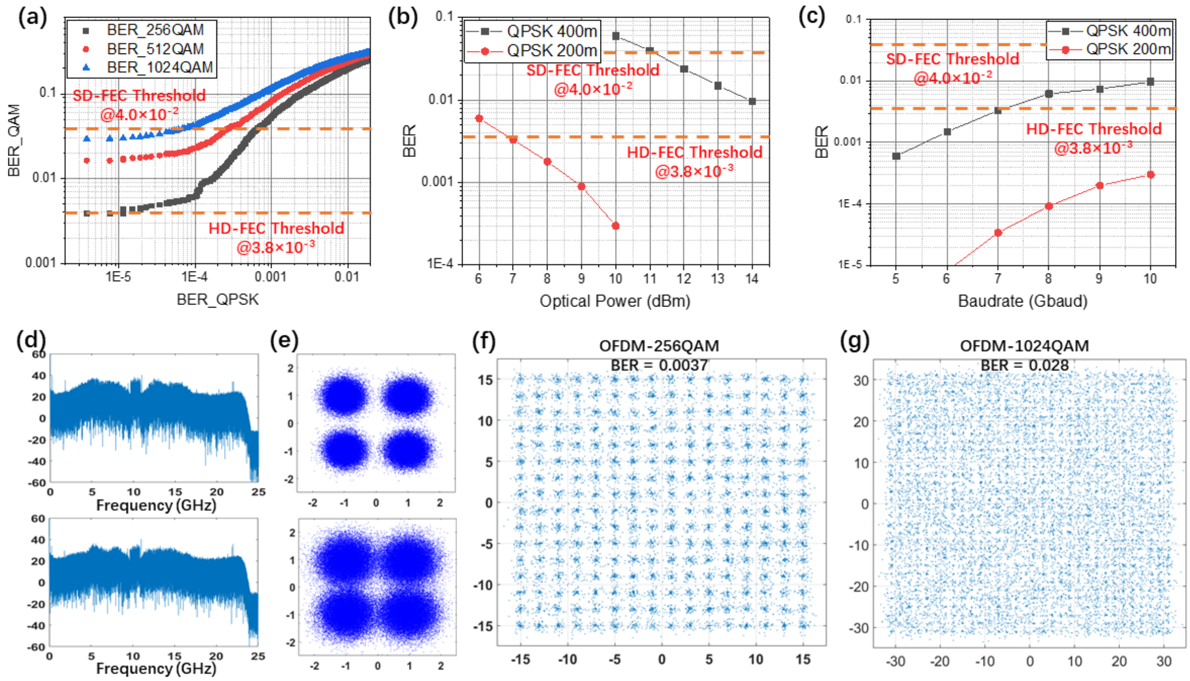

Fig. 2. The experimental results: (a) BER curves of the recovered OFDM-QAM versus the BER of the DSM-QPSK signals; measured BER of the DSM-QPSK with (b) different optical power and (c) different baud rate; (d) spectrum of the received IF signals and (e) the demodulated QPSK signals after 200m and 400m wireless transmission; constellations of the recovered (f) OFDM-256QAM and (g) OFDM-1024QAM.

Fig. 2(b) shows the measured BER of the 10 Gbaud DSM-QPSK signals with different optical power. In 200m and 400m wireless transmission cases, the 10Gbuad DSM-QPSK signals can satisfy the HD-FEC and SD-FEC threshold when the optical power is larger than 7.0 and 11.0 dBm. Fig. 2(c) present the measured BER of DSM-QPSK signals with different baud rate. Fig. 2(d) and (e) show the spectrums of the received IF signals and the demodulated QPSK signals after 200m and 400m wireless transmission, respectively. With the aid of the FEC technique, the bit errors in the transmission of the DSM-QPSK signal can be almost completely corrected so that the OFDM signal recovery can be ensured. The constellations of the recovered OFDM-256QAM and OFDM-1024QAM are also given in Fig. 2(f) and (g). The corresponding BER are 0.0037 and 0.028. Generally, such high-order QAM signals are hard to be transmitted in THz-over-fiber systems due to the nonlinearities and low SNR. However, the DSM-QPSK signals can overcome these limitations and can be a promising solution in future mobile networks.

4. Conclusions

In this experiment, we propose and demonstrated a DSM-based THz-over-fiber system for high-order OFDM signal transmission. Based on the experimental results, 1.25 Gbaud OFDM-256QAM~1024QAM signals can be successfully transmitted over 20km SMF and 400m wireless link at the terahertz band. The BER of the OFDM-256QAM and OFDM-1024QAM after the transmission can satisfy the SD-FEC threshold of 4.0×10^{-2} and HD-FEC threshold of 3.8×10^{-3}, respectively. This work was partially supported by Chinese National key R&D projects under grant number 2018YFB1800905, the fellowship of China National Postdoctoral Program for Innovative Talents under grants of BX2021071 and the National Nature Science Foundation of China (NSFC) under grant No 61935005, 61720106015, 61835002 and 62127802.

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