Delay Compensated Quad-level Delta-sigma Modulation Dual-color DRoF System for Beyond 5G Mobile Fronthaul

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Abstract: We demonstrated a high-performance dual-color B5G DRoF system using delay compensation. A quad-level 6-Gbit/s 64-QAM OFDM signal was successfully transmitted over the proposed system, showing a much better performance compared to the conventional 1-bit system.

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1. Introduction

To establish ubiquitous network connection for meeting the thriving demand of considerable data traffic, research about beyond 5th generation (B5G) or 6th generation (6G) mobile networks have been widely demonstrated. One of the most important targets of B5G/6G mobile fronthaul (MFH) was transmitting radio frequency signals from central offices (COs) to numerous remote radio heads (RRHs) in a robust and cost-effective way. Under this circumstance, radio-over-fiber (RoF) links were regarded as the indispensable approach for the fusion of wireless connection and ultra-fast networks. Among various RoF interfaces, digital RoF (DRoF) links were considered the appropriate solution, where the digital-to-analog convertor (DAC) was shifted from the CO to RRHs, making the n-bit signal transmit through optical links and significantly relieve the impact of optical devices' nonlinearity [1]. Nevertheless, the drawback of traditional DRoF has become obvious as the MFH progressing to B5G/6G. Based on the B5G/6G roadmap [2], the frequencies of employed RF carriers were shifted to millimeter-wave (mm-wave) or sub-THz bands, which meant that the severe attenuations in free-space or the extreme weather issue would strongly impact the transmission distances [3]. Hence, if directly implementing the traditional DRoF to B5G/6G scenarios, the constructing cost of RRHs would increase tremendously because the DAC components in every RRHs needed to support high frequencies from mm-wave to sub-THz bands. Moreover, the complicated digital signal processing (DSP) circuits in each RRH also made traditional DRoF hard to implement in a cost-effective way. To achieve robustness and cheapness simultaneously, the delta-sigma modulation based DRoF links are possible solutions, which replace the expensive DAC components in RRHs with simple lowpass or bandpass filters [4, 5]. Besides, only few quantization bits (normally 1 or 2) were required for the analog-to-digital convertor in COs, which improve the robustness to the nonlinearity in the optical links at the same time. In a delta-sigma modulation based DRoF link, a 2-bit delta-sigma modulated signal can exhibit a better transmission performance compared to the 1-bit one did owing to the signal-to-noise ratio (SNR) improvement [6]. Nevertheless, the 2-bit signal does not always outperform the 1-bit one due to the lower anti-nonlinearity in optical devices. To resolve this problem, we proposed a DRoF system using an optically constructed 2-bit delta-sigma modulation [7]. However, the timing synchronization issue became a bottleneck to achieve a high-performance system in the previous study. In this scenario, the optical group delay compensation, which effectively improved the frequency-shift-keying transmission [8], could be an appropriate solution for improvement of the proposed system.

In this work, we demonstrated a high-performance quad-level delta-sigma modulated 64-QAM OFDM based dual-color B5G DRoF system using an optical group delay compensation. In the proposed system, the quad-level (2-bit) signals were optically combined from two optical carriers with independently delay adjustment. Using the proposed system, we successfully transmitted 6-Gbit/s 64-QAM OFDM signal with a much better performance compared to the conventional 1-bit modulation system. The proposed system can provide a cost-effective solution to facilitate the deployment of B5G/6G mobile networks.

2. Experimental Setup

Fig. 1(a) illustrated the experimental setup of the proposed optical delay compensated quad-level delta-sigma modulated QAM-OFDM based dual-color B5G DRoF link. The original QAM-OFDM data was firstly generated and then modulated by a 3rd order 2-bit delta-sigma modulator. Afterwards, a 1-bit splitter was added for separating the 2-bit QAM-OFDM data into two 1-bit data streams (MSB: most significant bit and LSB: least significant bit).

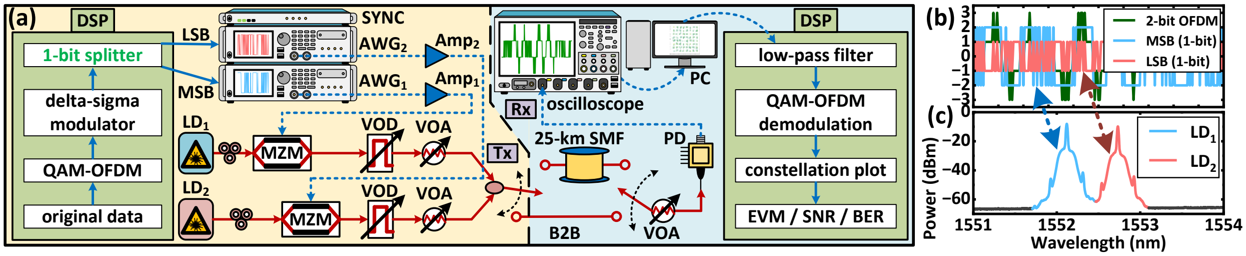

Fig. 1. (a) Experimental setup of the proposed B5G DRoF link. (b) Time domain waveforms of the generated 2-bit OFDM and the split 1-bit data streams. (c) Optical spectrum of the dual-color optical carrier with the modulated MSB/LSB data streams.

The aforementioned processes were completed by DSP in MATLAB program. The generated 2-bit OFDM (green), 1-bit MSB (blue), and 1-bit LSB (red) waveforms were depicted in Fig. 1(b). Two synchronized arbitrary waveform generators were employed for outputting the 1-bit data streams with precisely controlling the timing synchronization through a synchronization board at 24 GS/s. Two RF amplifiers with adjusted gain of 6 dB were added to amplify the output data streams. For the optical carriers, two C-band laser diodes (LDs) were adopted. After adjusting the polarization through two polarization controllers, LD_1 and LD_2 were respectively encoded by the amplified MSB and LSB data streams using two Mach-Zehnder modulators. To control the optical path lengths and adjust the output powers of the two carriers, two pairs of variable optical delay lines and variable optical attenuators (VOAs) were inserted into the two MZM output arms. Afterwards, a 50%-50% optical coupler was connected to the two arms for generating the dual-color optical carrier. Fig. 1(c) shows the optical spectrum of the modulated dual-color optical carrier with peak powers of -8.9 (MSB carrier at 1552.12 nm) and -12.2 dBm (LSB carrier at 1552.73 nm). After the transmission, a 12.5-GHz photodetector was used to detect the dual-color optical carrier at an overall receiving power of -9 dBm. Besides, another VOA was added to control the adequate receiving powers. Finally, the received delta-sigma modulated QAM-OFDM data were sampled in an oscilloscope at a sampling rate of 100 GS/s. The captured quad-level waveforms were filtered and demodulated in MATLAB. Constellation plots, error vector magnitudes (EVMs), SNRs, and bit-error-rates (BERs) were calculated to evaluate the system performances.

3. Results and Discussions

For evaluating the system performance and the effectiveness of the optical group delay compensation, a quad-level 400-MHz 16-QAM OFDM signal was first transmitted over the system. Fig. 2(a) shows the BERs of the demodulated 2-bit 1.6-Gbit/s 16-QAM OFDM data before and after 25-km SMF transmission with different optical delay adjustments. From Fig. 1(c), the MSB carrier would travel faster in the optical fiber than the LSB carrier because the optical pulse at a shorter wavelength experiences a lower refractive index than the one at a longer wavelength. In other words, increasing the optical path to the MSB carrier could make the arriving time the same for the two carriers after the fiber propagation. Hence, the optical path difference in the Fig. 2(a) X-axis could be defined as the additional optical path for the MSB carrier comparing with the LSB carrier. For the B2B case, as shown in Fig. 2(a), the received 1.6-Gbit/s 16-QAM OFDM data exhibited the best BER of 5.15×10^{-20} (EVM of 4.94%) at a delay difference of 0 and deteriorated either lengthening or shortening the MSB optical path, meaning that the two optical carriers arrived at the same time without a long fiber propagation. In other words, even a little optical path difference can make the two optical carriers unsynchronized and degrade the signal quality. After the 25-km SMF transmission, the BER of the 400-MHz 16-QAM OFDM data drastically deteriorated to 4.45×10^{-4} (EVM of 13.79%) without adjusting the optical path difference owing to the timing asynchronization between the two optical carriers after a long fiber propagation. By increasing the additional optical path for the MSB carrier to 70 mm, the BER of the same transmitted data could be optimized to 3.39×10^{-18} (EVM of 5.21%) because the optical group delay was effectively compensated. Fig. 2(b) shows the SNRs of the demodulated data in Fig. 2(a). From the figure, the SNRs at the higher frequencies could be improved to nearly the B2B case after appropriately increasing the optical path of MSB carrier. Fig. 2(c) shows the SNR degradations obtained by subtracting the SNRs after 25-km SMF transmission to the B2B case. It is shown that the subcarrier SNRs degraded more severely at the high frequencies than the ones at the low frequencies because the former experienced a larger timing asynchronization than the latter. By appropriately adjusting the delay compensation (70 mm to MSB carrier), the SNR degradations could be improved to nearly 0 dB compared to the B2B case.

After compensating the optical group delay, we successfully transmitted the quad-level 6-Gbit/s 64-QAM OFDM signal over 25-km SMF with an EVM value of 7.13% which met the forward error correction (FEC) criterion. The corresponding EVMs and constellation plots with (green) and without (red) delay compensation are plotted in Fig. 3(a). It shows a significant performance improvement compared to the case of without using a delay compensation. Finally, we compared the performance of the proposed system with the conventional 1-bit delta-sigma system.

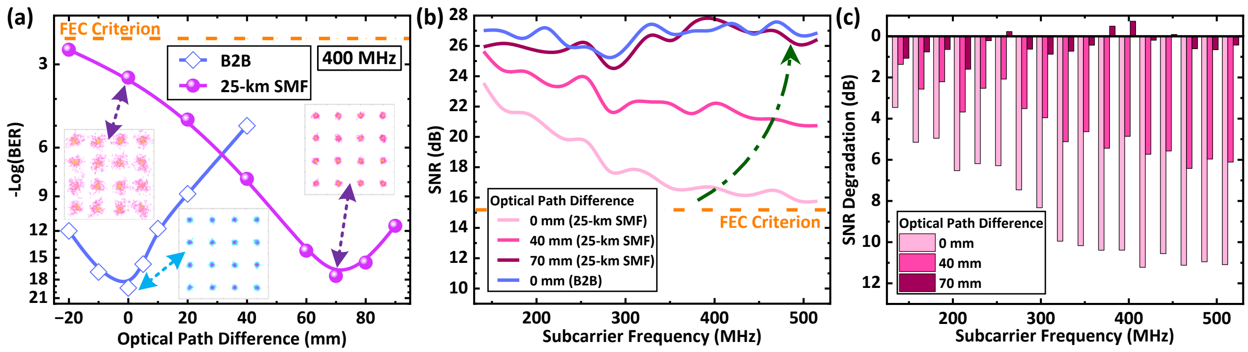

Fig. 2. (a) BERs and constellation plots of the transmitted 400-MHz 16-QAM OFDM with different optical path differences. (b) Subcarrier SNRs. (c) Subcarrier SNR degradations of different compensating conditions comparing with the B2B case.

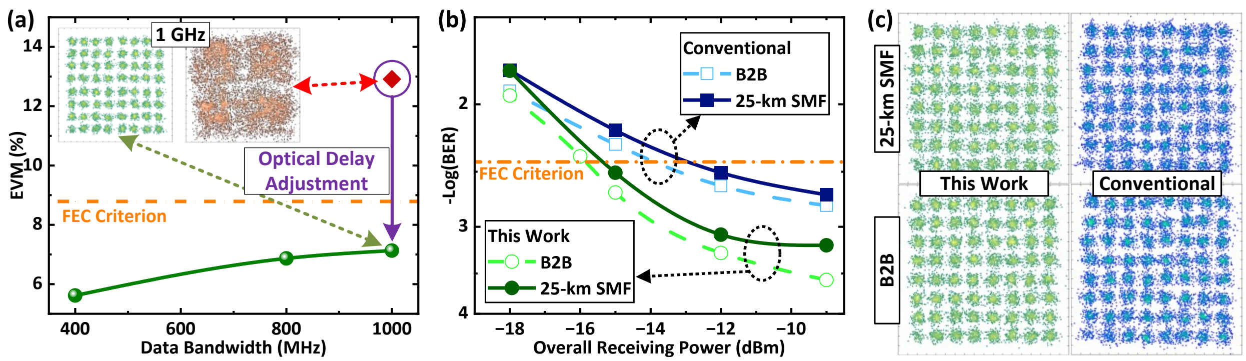

Fig. 3. (a) EVMs of the 64-QAM OFDM after 25-km SMF transmission. (b) BERs of the 6-Gbit/s 64-QAM OFDM at different receiving powers in the proposed system and the conventional system. (c) Constellation plots at -15 dBm receiving power.

Fig. 3(b) shows the BERs of the transmitted 1-GHz 64-QAM OFDM signal for different receiving optical powers. As shown in the figure, our proposed system can provide a much better performance compared to the conventional one. To meet the FEC criterion (BER of 3.8×10^{-3}), the lowest available receiving powers were -15.88 and -15.38 dBm for B2B and 25-km SMF case in the proposed system, respectively. This resulted in a power penalty of only 0.50 dB. However, the conventional system only respectively supported the lowest receiving powers of -13.89 and -12.98 dBm for B2B and 25-km SMF cases with power penalty of 0.91 dB. Fig. 3(c) shows the constellation plots of the demodulated 6-Gbit/s 64-QAM OFDM data at receiving power of -15 dBm. From Fig. 3(c) (left green ones), the calculated BERs were 2.1×10^{-3} and 3.1×10^{-3} for B2B and 25-km SMF cases in the proposed system, respectively. However, in the 1-bit conventional system (blue constellations), the calculated BERs were 5.2×10^{-3} and 6.6×10^{-3} for the same transmission cases, where neither of them passed the FEC criterion. In other words, the proposed system in this work performed much better in low receiving power conditions compared to the conventional 1-bit system.

4. Conclusion

We proposed and experimentally demonstrated a high-performance delay compensated dual-color quad-level delta-sigma B5G DRoF system. We confirmed that adding a proper delay compensation to one the signals significantly improved the signal performance. Using the system, we successfully transmitted 6-Gbit/s 64-QAM OFDM signal over 25-km SMF with a much better performance compared to the conventional 1-bit delta-sigma system.

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