Low-Bandwidth Sub-Nyquist A/D Conversion in Delay-Division Multiplexing OFDM PONs Enabled by Optical Shaping

Wei-Lun Chen[1], Min Yu[1], Lu-Yi Yang[1], Chia-Chien Wei[1,*] and Chun-Ting Lin[2]

[1] *Department of Photonics, National Sun Yat-sen University, Kaohsiung 804, Taiwan*
[2] *Institute of Photonic System, National Chiao Tung University, Tainan 711, Taiwan*
**ccwei@mail.nsysu.edu.tw*

Abstract: Optical shaping is proposed to reduce the required analog bandwidth of low-sampling-rate A/D conversion in a DDM-OFDM-PON. It successfully enabled the detection of 7.5-GHz/28-Gb/s downstream using low-bandwidth (1.7 GHz) and sub-Nyquist-sampling (3.75 GS/s) A/D conversion.

OCIS codes: (060.4230) Multiplexing; (060.4510) Optical communications.

1. Introduction

As the development of passive optical networks (PONs) is one of the most important fundamental network infrastructures [1], orthogonal frequency-division multiplexing (OFDM)-PON can provide high flexibility in capacity sharing to enable high-quality network services, in addition to the high spectral efficiency and ISI tolerance [2]. However, the single-channel aggregated capacity in OFDM-PONs needs to be more than ten times the capacity dedicated to a single optical network user (ONU). In other words, even though an ONU needs a small portion of aggregated data, the hardware at an ONU is required to be able to detect high-speed aggregated OFDM signals; in particular, an analog-to-digital (A/D) converter must be provided with a high sampling rate and high analog bandwidth (BW). By implementing preprocessing in the central office (CO) of an OFDM-PON, the delay-division multiplexing (DDM) technique allows an ONU to detect the demanded data after spectral aliasing caused by sub-Nyquist sampling, thereby significantly reducing the required sampling rate of A/D conversion [3, 4]. When the ONUs in a DDM system are divided into M virtual groups, the required sampling rate of A/D conversion at each ONU can be only $1/M$ of the Nyquist rate (NR), and the ONUs in the same group would share $1/M$ of the downstream data. However, the DDM scheme does not reduce the requirement of analog BW of A/D conversion because all sent subcarriers have to be retained before spectral aliasing.

In this work, the optical shaping technique is proposed to lower the required analog BW of A/D conversion in a DDM-OFDM-PON. An optical pulse carver was used to realize optical shaping, which equivalently induces significant spectral aliasing before A/D conversion; thus, a high analog BW is unnecessary in A/D conversion. Enabled by the proposed scheme, the experiment successfully demonstrated the detection of a 28-Gb/s OFDM signal, of which the NR is 15 GS/s, using low-BW (1.7 GHz) A/D conversion at the sub-NR of 3.75 GS/s. In addition, different shaping pulses are examined to show that an unconventional pulse could carry out better performance.

2. Concept

Fig. 1(a) schematically depicts the effects of A/D conversion using different BWs and sampling rates. The A/D conversion above the NR together with high analog BW enables the detection of a complete spectrum without spectral aliasing, as shown in Fig. 1(a1), where $\star$ denotes the convolution. Besides, the sub-Nyquist sampling with a high analog BW generates significant spectral overlapping, as shown in Fig. 1(a2). The spectral overlapping makes it possible for the DDM scheme to realize preprocessing [4]. Note that the group number (M) in Fig. 1 is set to 4. However, this is not the case in common A/D conversion. In fact, an A/D converter is generally equipped with an anti-aliasing filter, of which the BW is less than the half sampling rate of the converter. Once the BW of A/D conversion decreases with its sampling rate, as shown in Fig. 1(a3), the detected signal would not comprise high-frequency subcarriers of sufficient power, resulting in the failure of the DDM scheme. In addition to a lower sampling rate, a lower BW is also beneficial in terms of hardware cost; thus, we propose the optical shaping to achieve the feasibility of low-BW sub-Nyquist sampling in a DDM system. The concept of optical shaping is plotted in Fig. 1(b). Employing an optical pulse carver, an OFDM signal will be periodically switched in the time domain. A periodic pulse train corresponds to harmonics in the frequency domain, and it should be noted that a narrower pulse will yield more high-frequency harmonics. As a consequence, the optical shaping equivalently induces the convolution between the OFDM signal and harmonics. When the repetition rate of optical shaping is the sub-NR (i.e., $1/M$ of the NR), the fundamental frequency of harmonics is the sub-NR, leading to sufficient spectral overlapping. In this case, high-BW A/D conversion is unnecessary in the DDM system.

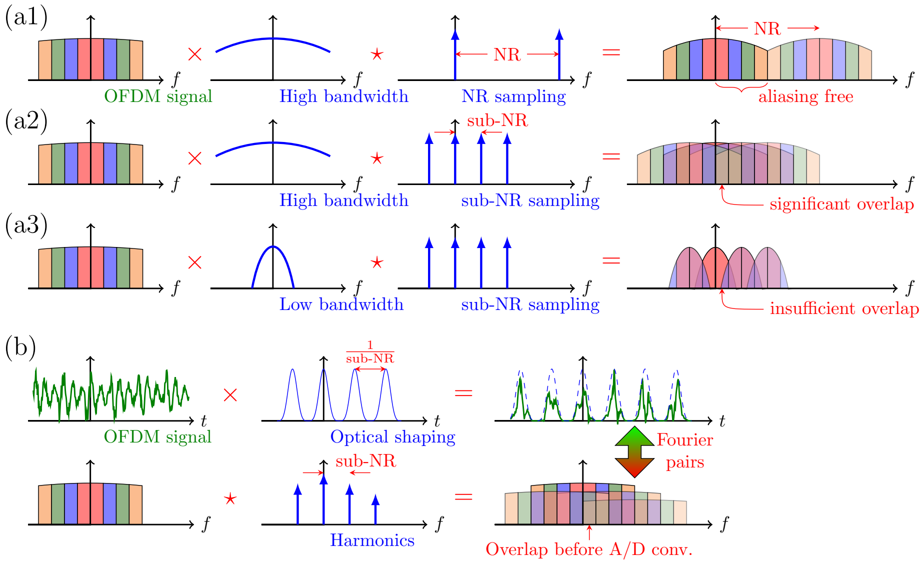

Fig. 1: Concepts of (a) A/D conversion and (b) optical shaping.

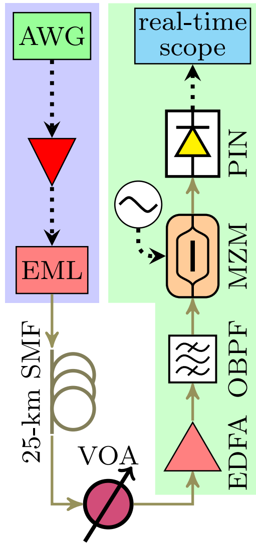

Fig. 2: Experiment setup.

3. Experiment and Discussion

The experiment setup of optical shaping is plotted in Fig. 2. The optical transmitter was a 10-GHz electro-absorption modulated laser (EML, Alcatel 1915LMM). The electrical OFDM signals were generated by an arbitrary waveform generator (AWG, Tektronix 70001A) with the sampling rate of 50 GS/s. The total signal BW was 7.5 GHz, corresponding to the NR of 15 GS/s. The cyclic prefix (CP) was 1/32; 508 subcarriers were used to carry 16-QAM, and the symbol rate of the OFDM signal was 14.65 MBaud. Thus, the data rate excluding the CP was 28 Gb/s. The number of groups was 4 (i.e., $M = 4$), corresponding to the sub-NR of 3.75 GS/s. After the transmission over 25-km single-mode fiber (SMF), a pulse carver based on a Mach-Zehnder modulator (MZM) was used to realize the optical shaping. To examine the effects of pulse shape, three different operating conditions of MZM were applied to realize optical switching at the repetition rate of 3.75 GHz. When the MZM was biased at a 50% transmission point and modulated by a 3.75-GHz sinusoidal wave, the shaping pulse was of 50% duty cycle (named 50% shaping). When the bias was set at its maximum transmission, the modulation using a 1.875-GHz sinusoidal wave generates the pulses of 33% duty cycle (named 33% shaping). In addition, unconventional pulses were generated using ~11% transmission bias 3.75-GHz modulation with the peak-to-peak amplitude of 0.73 V_π (named unconventional shaping). The optical pulse trains and the corresponding electrical spectra were shown in Fig. 3. Compared to the 33% pulses, the 50% pulses show a faster drop in harmonic power, implying less spectral overlapping in the proposed optical shaping. However, some undesired harmonics at 1×, 3× and 5×1.875 GHz were generated due to the imperfect modulation in Fig. 3(b). Lastly, the unconventional pulses in Fig. 3(c) shows the slowest drop in harmonic power, in addition to avoiding the undesired harmonics. The received optical power was controlled by a variable optical attenuator (VOA) inserted before an optical preamplifier and a 10-GHz p-i-n

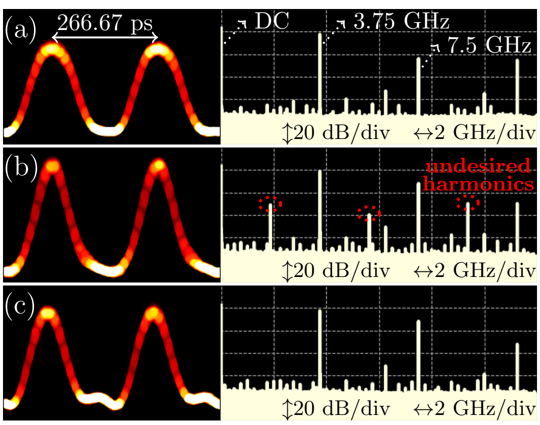

Fig. 3: The measured waveforms and electrical spectra of (a) 50%, (b) 33% and (c) unconventional pulses.

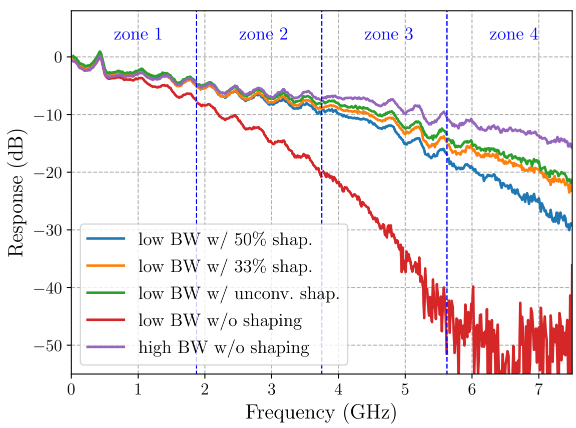

Fig. 4: Measured frequency responses.

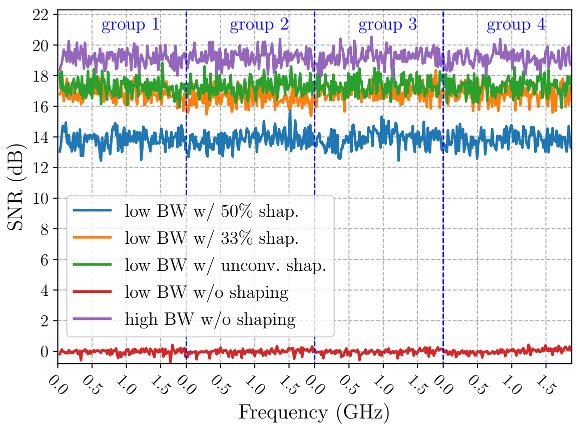

Fig. 5: SNR at the received power of −18 dBm.

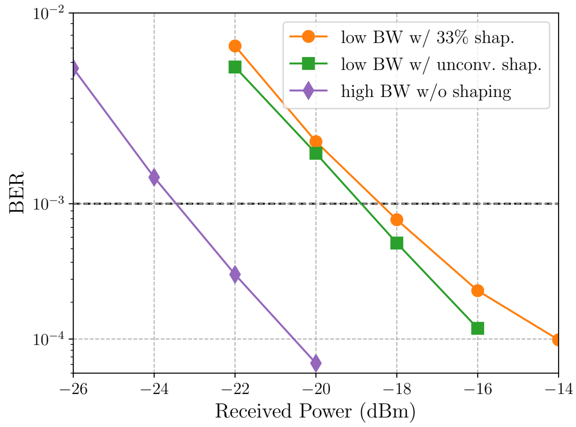

Fig. 6: BER curves.

receiver (PIN, Nortel Network PP-10G). Instead of using an A/D converter of sub-Nyquist sampling, the received signal was captured via a real-time oscilloscope (Keysight DSA-X93204A) at a sampling rate of 80 GS/s, and an off-line DSP was applied to emulate the sub-Nyquist sampling. For the cases of low-BW A/D conversion, the DSP includes low-pass filtering using an 11th-order Bessel filter with the 3-dB BW of 1.7 GHz before A/D conversion.

Fig. 4 plots the measured responses of the whole transmission system. Note that the responses at > 1.875 GHz (i.e., zone 2–4) were actually measured within 1.875 GHz (i.e., zone 1) due to the aliasing caused by sub-Nyquist sampling [5]; for instance, the response of the subcarrier at 4.25 ($= 1.875 \times 2 + 0.5$) GHz was measured by its contribution at 0.5 GHz. Thus, it is obvious that the low-BW case without shaping (schematic plot in Fig. 1(a3)) has an insignificant contribution from high-frequencies subcarriers. Applying the proposed optical shaping, the responses can be significantly improved, implying a better performance in a DDM system. In particular, using the unconventional shaping achieves the highest response in the three cases with shaping, and the 50% shaping leads to the worst one. These results are consistent with the spectra in Fig. 3. On the other hand, the high-BW case without shaping (schematic plot in Fig. 1(a2)) shows the highest responses mainly due to the 32-GHz BW of the oscilloscope. After preprocessing based on the responses in Fig. 4, we measured the signal-to-noise ratios (SNRs) of different DDM groups by controlling the delays of shaping and A/D conversion, and they are aggregated in Fig. 5, where the received optical power was −18 dBm. Without sufficient contribution from high-frequency subcarriers, the low-BW case without shaping cannot work at all; after applying the proposed shaping, the average SNR was significantly enhanced to 13.8, 16.8 and 17.3 dB using 50%, 33% and unconventional shaping, respectively. Obviously, the SNR performance is closely related to the responses in Fig. 4. Thus, more than $\sim$14-dB improvement in SNR can be realized by the proposed technique. Similarly, the SNR of the high-BW case is the best due to its highest response. Moreover, the bit-error rate (BER) performance of various cases was measured and compared, as shown in Fig. 6. Since the signal using 50% shaping shows worse performance, only the cases with 33% or unconventional shaping are shown, and the required powers to reach the BER of 10^{-3} are −18.5 or −19 dBm, respectively. Compared to the high-BW case, however, there is a $\sim$ 4 dB penalty at the BER of 10^{-3} mainly because of the high-frequency loss of low-BW A/D conversion.

4. Conclusions

We proposed the optical shaping to avoid the necessity of high analog BW in sub-NR A/D conversion in a DDM system. Using only 1.7-GHz-BW A/D conversion at the sampling rate of 3.75 GS/s (i.e., 1/4 of NR), the experiment shows that the optical shaping can significantly improve the performance, thereby successfully demonstrating the detection of a 28-Gb/s OFDM signal. In addition, we also experimentally demonstrate that the performance can be improved by varying a pulse train.

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