Spectrally Overlaid DDO-OFDM Transmission Enabled by Optical Power Division Multiplexing

Zhenhua Feng(1), Ming Tang(1), Xun Guan(2), Calvin Chun-Kit Chan(2), Qiong Wu(1), Xi Chen(1), Ruoxu Wang(1), Rui Lin(1,3), Songnian Fu(1), Lei Deng(1), Deming Liu(1)*

(1) Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, China, 430074.
*tangming@mail.hust.edu.cn

(2) Department of Information Engineering, the Chinese University of Hong Kong, Hong Kong, China.

(3) School of ICT, The Royal Institute of Technology (KTH), Electrum 229, Kista, Sweden.

ABSTRACT

Two 8.3-Gb/s spectrally overlaid DDO-OFDM signals are successfully transmitted along 50-km SMF using optical power division multiplexing and received by a successive interference cancellation (SIC) receiver. Spectral efficiency is doubled with optimized optical modulation index and optical power division ratio.

Keywords: *DDO-OFDM, power division multiplexing, SIC*

1. INTRODUCTION

In order to satisfy the ever-growing capacity requirements fueled by bandwidth-hungry applications such as next-generation ultra-high definition (UHD) 4K/8K videos and virtual reality (VR), five available physical dimensions have been exploited for modulation and multiplexing in optical communications including time, frequency, quadrature, polarization and space [1]. In these widely recognized technologies, orthogonality must be ensured to minimize the interference or crosstalk from other channels so that signals can be separated individually without impacting each other's detection performance, otherwise severe performance penalty occurs. Therefore, confined to the rigorous orthogonality, it seems impossible to reuse the frequency band to simultaneously transmit multiple parallel signals via the same polarization state, time slot and space channel. Recently, non-orthogonal multiple access (NOMA) emerges as a potential candidate for the upcoming 5G standard due to its superior spectral efficiency [2]. In NOMA, multiple users are multiplexed with different power levels using superposition coding at the transmitter side and successive interference cancellation (SIC) based multi-user detection algorithms at the receiver [3]. Previous work demonstrates that the non-orthogonal feature of NOMA can significantly improve the capacity and throughput in both wireless and visible light communication systems by allocating the entire bandwidth to different users simultaneously [3-5]. Inspired by the idea of NOMA, we proposed and experimentally demonstrated a downstream DDO-OFDM transmission by utilizing digital domain power division multiplexing (DDPDM) to transmit multiple independent signals and recover each one using SIC algorithm [6], which nearly doubles the spectral efficiency of the short-reach optical communication systems.

In this paper, we further investigate the uplink transmission scheme based on optical power division multiplexing, where multiple intensity-modulated OFDM signals with overlapped spectra add directly in optical domain. Simulation results show that spectrally overlaid DDO-OFDM transmission can be realized in conjunction with optical power division multiplexing and SIC by only using one laser and photodetector.

2. SYSTEM MODEL AND OPERATION PRINCIPLE

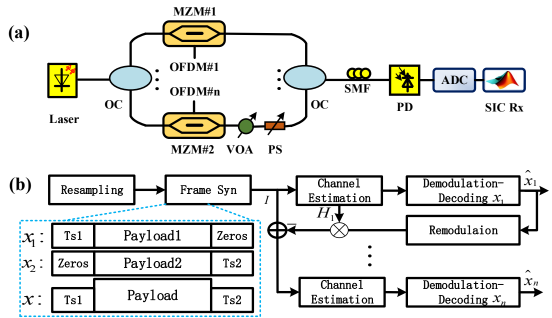

Fig. 1: (a) Schematic of proposed parallel DDO-OFDM transmission system using optical power division multiplexing and SIC; (b) digital signal processing in SIC receiver and the inset is the OFDM frame structure. (OC: optical coupler, VOA: variable optical attenuator, PS: phase shifter, SMF: single mode fiber, PD: photodetector, ADC: analog to digital converter, SIC: successive interference cancellation)

As shown in Fig. 1(a), a continuous wave (CW) is power split and launched into n Mach-Zehnder Modulators (MZM) on the parallel tributaries. The driving signals of the MZMs (bias at quadrature point) are independent

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baseband OFDM signals with properly aligned frame structure shown as inset in Fig. 1(b). After power control and phase shifting via the VOA and PS, respectively, the multiple intensity modulated optical signals are combined together and transmitted to the receiver side through the single mode fiber link. In the receiver, the directly detected spectrally overlaid electrical signal is firstly digitalized and then processed off-line using SIC based digital signal processing (DSP) algorithms, whose flow chart is depicted in Fig. 1(b).

For an intensity modulated and directly detected (IM/DD) signal on the i^{th} branch, the received electrical signal can be expressed as:

$$I_i = \frac{1}{2} R H_i P_i \left[1 - \sin\left(\frac{\pi}{V_\pi} x_i\right)\right] + n_i \qquad (1)$$

where R, P_i and V_π are responsivity of the PD, the optical power of the i^{th} branch and the half-wave voltage of the MZM, respectively. H_i is channel response of i^{th} signal, x_i is the i^{th} OFDM baseband driving signal, and n_i is the additive noise of i^{th} branch. After optical power multiplexing, the resultant photocurrent is $I = \sum_{i=1}^{n} I_i$. With small signal approximation and direct current (DC) removing, it can be further simplified as $I = m \sum_{i=1}^{n} H_i P_i x_i + n$, where m is a constant. As the idea of our scheme is to utilize optical power division multiplexing in terms of using the same frequency band, the multiplexed optical signals should have different power levels. Without loss of generality, we assume that the power levels (P_i) are arranged in descending order, namely $P_1 > P_2 > \cdots > P_n$.

Then at the SIC receiver, the detected mixed signal is firstly resampled before frame synchronization, and then demodulated and decoded one by one according to the descending order of power levels using SIC algorithm, with the help of training symbol based channel estimation. The SIC process mainly consists of three steps: (1) estimate the channel response and demodulate the stronger signal x_i while treating all the other signals $x_{i+1} \cdots x_n$ as interference noise; (2) re-modulate the estimated signal $\hat{x}_i$ and multiply it by the channel response H_i before subtracting the product from the received signal I and then decode the weaker signal x_{i+1}; (3) go on with the aforementioned steps until all the signals are decoded. Following the SIC demodulation, the signal to interference plus noise ratio (SINR) of the i^{th} signal is

$$SINR_i = \frac{|H_i P_i x_i|^2}{\sum_{k=i+1}^{n} |H_k P_k x_k|^2 + n}, i = 1, \ldots, n-1 \qquad (2)$$

From equation (2), we can conclude that SIC algorithm suppresses interference from stronger (earlier decoded) signals for relatively weaker (yet to be demodulated) signals. So even the signals with the lowest power can be correctly recovered if ideal channel estimation is possible.

As a proof of concept, in this work, we demonstrate a parallel transmission of two spectrally overlaid QPSK modulated DDO-OFDM signals over 50 km SMF using only one laser and one PD. The simulation platform is based on joint Matlab and VPI^{TM} using the system configuration shown in Fig. 1(a).

3. SIMULATION RESULT

In our simulation, two sets of spectrally overlaid independent real-valued baseband QPSK-OFDM signals are generated offline using Matlab and then sent to a digital-to-analog converter (DAC) operated at a sampling rate of 10 Gs/s. After going through a 5-GHz low-pass filter (LPF) and linear amplification, the baseband OFDM signals are fed to drive the MZMs. After that, the intensity modulated optical signals can be combined using optical power division multiplexing with various optical power division ratios (OPDR) (defined as $\mathrm{OPDR} = 10\log_{10}\frac{P_1}{P_2}$, in dB unit). The baseband QPSK-OFDM parameters and the specially designed frame structure are the same as in [6]. The resultant net data rate for each QPSK-OFDM is 8.3-Gb/s.

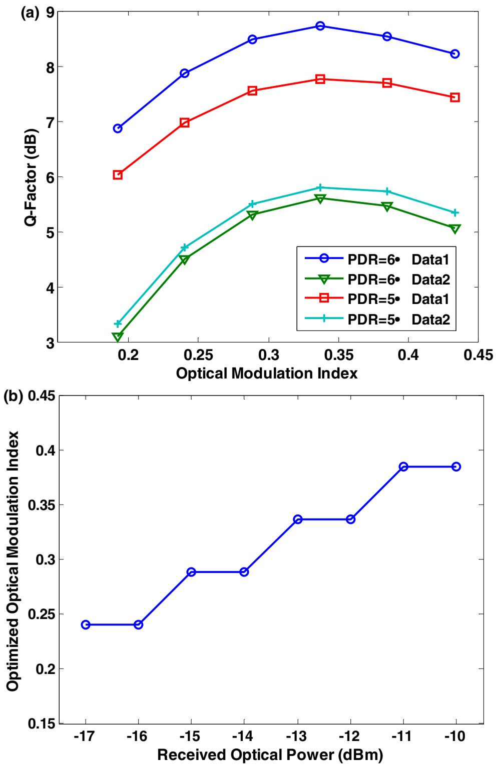

Fig. 2: Optimization of optical modulation index. (a) with fixed ROP=-15 dBm, (b) with fixed OPDR=5 dB.

In order to evaluate the transmission performance of the parallel DDO-OFDM system with optical power division multiplexing and SIC, we firstly optimize the optical modulation index (OMI, defined as $\mathrm{OMI} = \frac{\pi V_{rms}}{V_\pi}$, $V_{rms}$is the root-mean-square (RMS) amplitude of the electrical OFDM signal to drive the MZM) in optical back-to-back (OB2B) case. During the OMI optimization, the phase difference between the two OFDM branches is set to zero and the two OMIs are assumed to be identical. From the results shown in Fig. 2, with fixed received optical power (ROP=-15dBm), the optimal OMI is independent of the OPDR, while it increases slightly with the ROP when the OPDR is fixed at 5dB. With the optimized OMI, we then investigate the influence of OPDR on the BER performance of the two OFDM signals. As shown in Fig. 3, the optimized OPDR

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to minimize the BER of weaker signal (Data2) is found to be around 5 dB, in which scenario two superposed QPSK signals will become exactly 16QAM. If OPDR>5 dB, there is a trade-off between performances of the two optical power multiplexed signals. One can change the OPDR and adjust the performance of stronger signal according to its quality of service (QoS) requirement.

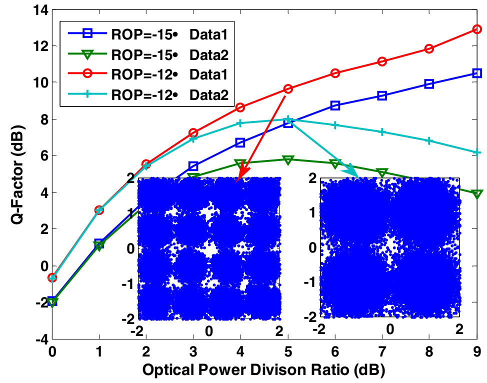

Fig. 3: Relationship between Q-factor and the OPDR, the insets are corresponding constellation diagrams

With the optimal OPDR and optimized OMI, then we can measure the BER performance vs different ROPs both in OB2B and SMF links and the results are summarized in Fig.4. As expected, regardless of the dispersion induced power penalty, the BER for the weaker signal is worse than the stronger one, nevertheless, soft-decision (SD) FEC coding can be applied to the weaker signal to ensure error-free transmission so that the system data rate can be doubled.

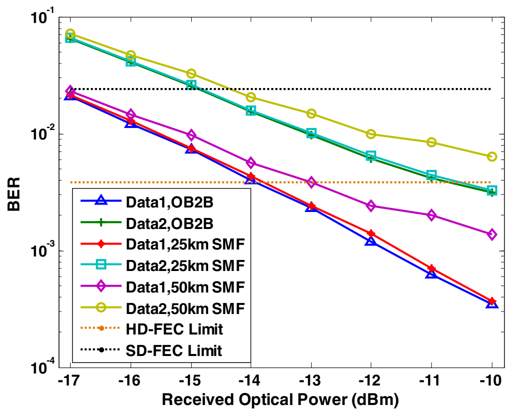

Fig. 4: BER of optical power division multiplexed QPSK-OFDM signals in OB2B and SMF links.

Finally, for practical use consideration, we study the impact of phase difference between the two overlaid signals on the transmission performance by tuning the phase shifter on the second branch in Fig. 1(a). The result in Fig. 5 shows that at fixed received ROP=-14 dBm, the phase difference induced OB2B transmission performance distinction can be negligible within the range from 0 to 60 degree. To solve significant phase mismatch problems, phase pre-distortion can also be used as in [5].

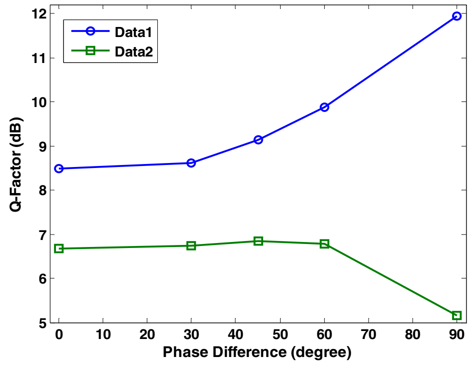

Fig. 5: The influence of phase difference on Q-factor.

4. CONCLUSIONS

We have proposed and demonstrated a spectrally overlaid optical power division multiplexing scheme for DDO-OFDM transmission using an SIC receiver. With optimized OMI, the OPDR can be adjusted to satisfy the QoS requirement of each signal. If enhanced FEC coding is applied to the lower-power tributary, system spectral efficiency can be nearly doubled along the transmission of 50-km SMF. Moreover, the transmission performance of the optical power multiplexed DDO-OFDM signal is insensitive to phase difference, which paves the way for its application in short-range optical communication systems like uplink scenario of passive optical networks (PON).

5. ACKNOWLEDGMENTS

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