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A combined digital linearization and channel estimation approach for IM/DD Fast-OFDM systems

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Abstract:	A combined digital linearization and channel estimation scheme is proposed and experimentally demonstrated for short-reach intensity-modulation and direct-detection (IM/DD) optical Fast-OFDM systems. Known 2PAM-Fast-OFDM sequences are used for training a memoryless polynomial based adaptive post-distorter and for FFT-based channel estimation in IM/DD 4PAM-Fast-OFDM systems. The 2PAM signals are transmitted only over the odd SCs of the training sequences. With the combined compensation scheme, significant BER improvements are achieved for 10- and 22-km length 12.5 Gbit/s SMF links. Compared with a conventional IM/DD Fast-OFDM, the receiver sensitivity of the proposed IM/DD Fast-OFDM system is improved by about 3 dB at a bit error ratio (BER) of 10-3, after 22-km SMF transmission. In addition, the experimental results for different bias voltages and under strong filtering effects show that the proposed compensation approach can deal with some degree of MZM bias drift and can be applied for realistic wideband optical Fast-OFDM systems.
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	Roberto Llorente UPV: Universitat Politecnica de Valencia rllorent@dcom.upv.es Due to his expertise in electro-optical processing techniques and hybrid wireless-optical access networks.
	Idelfonso Monroy Eindhoven University of Technology: Technische Universiteit Eindhoven i.tafur.monroy@tue.nl Due ot his expertise in hybrid wireless-optical access networks.
	Philippos Assimakopoulos University of Kent at Canterbury: University of Kent p.asimakopoulos@kent.ac.uk Due to his knowledge of digital signal processing methods for subcarrier multiplexed systems.
Response to Reviewers:	

Manuscript Number: OFT-D-21-00352

Dear Prof. Wabnitz,

Editor-in-Chief of Optical Fiber Technology

Thank you very much for allowing the revision of our manuscript entitled

A combined digital linearization and channel estimation approach for IM/DD Fast-OFDM systems

by Luis Carlos Vieira, Shirin Hussein, Izzat Darwazeh, Chin-Pang Liu, and John Mitchell

We also would like to thank the reviewers for their time and the attention concerning the careful reading and analysis of our manuscript. Our responses to their pertinent questions and valuable comments are in the document “Responses to reviewers”.

The revised manuscript contains the highlighted changes in brown for the sake of comparison with the previous version (1st submission).

We hope that the provided answers and changes contribute to clarify the important questions pointed out in the reviewing process and to improve the quality of the paper.

Regards,

Luis C. Vieira

Corresponding Author

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Dear Reviewers,

We would like to thank you for your time and the attention concerning the careful reading and analysis of our manuscript.

We have provided changes in the manuscript as explained in our comments below. We hope that the provided answers and changes contribute to clarify the important questions pointed out in the reviewing process.

The revised manuscript contains the highlighted changes in brown for the sake of comparison with the previous version (1st submission).

Reviewer #1: This paper propose and demonstrates a combined digital linearization and channel estimation methodfor IMDD optical interconnection. 12.5Gbps over 22km SMF transmission is demonstrated experimentally using this method. The generally idea of this work is novel and solid 3-dB receiver sensitivity improvement. Here are my comments:

1, 4PAM-fast-OFDM at 12.5Gbps only occupies very limited bandwidth, which is within the channel fading bandwidth of the 10- and 22- km SMF link. How to analize the improvement of the system?

Resp.:

It seems the reviewer is referring to the fibre bandwidth and in this they are right, the signal bandwidth is small and the fibre dispersion is negligible. However, significant nonlinear distortion may arise in direct detection optical OFDM and Fast-OFDM systems due to square-law detection of photodiodes and non-ideal transfer characteristic and DC offset of MZMs.

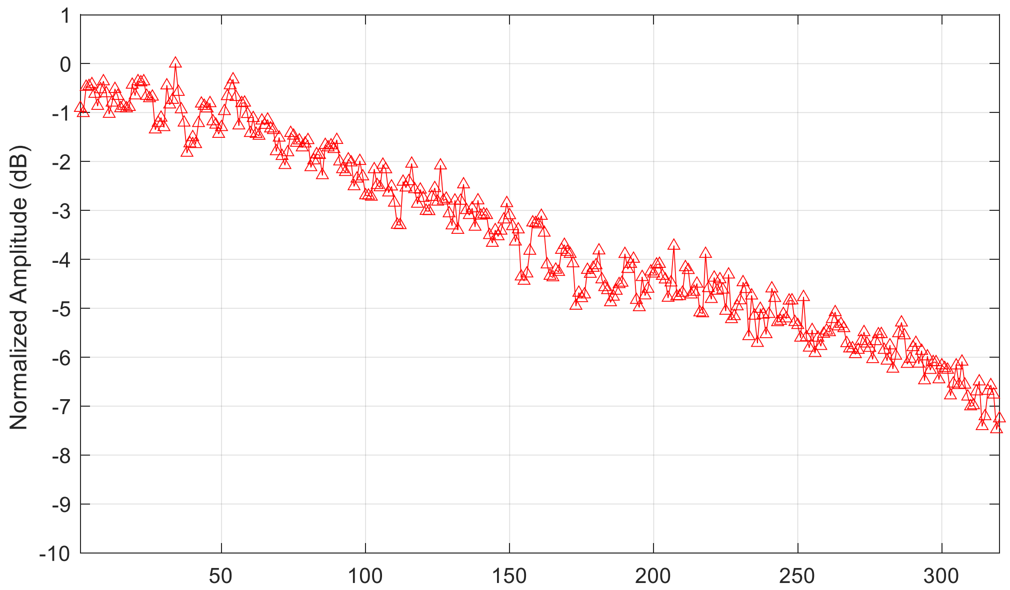
In this work, we firstly employ odd-SC-based PAM-Fast-OFDM training signals (TS) combined with memoryless polynomial based adaptive post-distortion as a nonlinearity compensation scheme. With this approach, 2PAM training symbols are modulated only on the odd SCs, with the even SCs set to zero. Thus, at the receiver side, only the odd SCs are used for frequency domain channel estimation and the intermodulation distortion falling into the even SCs is not considered, improving the channel estimation performance. The channel responses of the even SCs are estimated from the adjacent odd SCs responses. In addition, the polynomial-based post-distortion improves the system linearity by applying the inverse of the link nonlinear characteristic at the receiver side (in time domain), before the DFT-based channel estimation and equalization.

We have modified the first paragraph of Section 4 as follows:

“We note that, for the signal bandwidth and the link lengths used in this work, the fiber dispersion is negligible. However, the output spectrum of the 22-km link shows strong fading between the lower and higher subcarriers, which is due to the uneven frequency response of the IM/DD link components (including the RF devices and cables). In addition, increased nonlinear distortion after the IM/DD link can be observed in the gap between the optical carrier and the data subcarriers, but it is not limited to that region.”

2, The channel response should be given.

The channel response for the 22-km length Fast OFDM link has been included in the paper as Fig. 4, with a corresponding text added to Section 4.



3, How to decide the low-frequency guard band in Fig.3?

Resp.:

The guard band between the optical carrier and the data spectrum is a way of mitigating the second-order distortion, named signal-to-signal beating interference (SSBI), in direct detection optical multicarrier systems. To avoid overlapping of the SSBI and the desired signal spectra the minimum guard band should be equal to the bandwidth of the multicarrier signal [R1]. This, however, will halve the spectral efficiency. Significant smaller guard bands were used in the reported optical OFDM [4] and Fast-OFDM [12] works. With reduced guard band, the input signal power and the bias point of optical transmitters need to be precisely controlled to avoid strong distortion levels or a distortion compensation method need to be employed.

As we stated in the paper, we used a frequency gap (guard band) of 800 MHz due to the bandwidth of the available electrical amplifiers. This guard band is significantly smaller than the Fast-OFDM signal bandwidth we used and some level of SSBI should have occured amongst the data subcarriers, with the post-distortion and odd-SC training approaches used to mitigate this deleterious effect.

The decision on the size of the guard band will depend on the level of SSBI in a specific IM/DD link and if a SSBI compensation approach is used or not. In this work, the analysis of the optical Fast-OFDM performance for different frequency gap widths is not considered. We should address this issue in future work.

We have included the following sentences in Section 3:

“The decision on the size of the guard band will depend on the level of SSBI in a specific IM/DD link and if a SSBI compensation technique is used or not. In this work, the analysis of the optical Fast-OFDM performance for different frequency gap widths is not considered.”

[R1] S. Nezamalhosseini, L. Chen, Q. Zhuge, M. Malekiha, F. Marvasti, and D. Plant, "Theoretical and experimental investigation of direct detection optical OFDM transmission using beat interference cancellation receiver," Opt. Express 21, 15237-15246 (2013).

4, At this bit rate and this distance of SMF fiber link, I think better BER should be expected. Please try to make a comparison between this 4PAM-fast-OFDM and convention PAM/NRZ.

Resp.:

We agree with the reviewer that the error rate is too high for a 22 km link, and this is mainly due to the use of non-optimum components in the experimental setup. This is not an issue for what the paper attempts to show and the absolute error rate is not a key issue but what is of interest is the improvement of BER due to the compensation technique we use.

The BER performance can also be improved by using DSP techniques, such as digital equalization. Time domain equalization methods are commonly used in conventional single-carrier PAM, e.g. the least mean squares feed-forward equalizer (LMS-FFE) [R2], unlike the frequency domain equalization used here, which is based on the one-tap channel estimation and the use of training signal.

NRZ is the simplest modulation scheme but it has low spectral efficiency. To increase the bitrate of NRZ-based optical links (e.g. 10G PON links) higher bandwidth components are needed which will increase system cost. Optical PAM-Fast-OFDM offers higher spectral efficiency than NRZ PON and simpler implementation than optical OFDM. We note that the spectral efficiency of our 4PAM-Fast-OFDM demonstrator can be further improved by reducing the guard band between the optical carrier and the signal bandwidth and with the help of our compensation approach.

We refer to the above matters in the additional sentence in the introduction, by including a new paragraph in Section 4, and by the addition of the reference [R2].

The sentence added to Introduction:

"In comparison to NRZ PONs, optical Fast-OFDM can enable much higher spectral efficiency. Thus, it can be considered a very suitable solution for cost-sensitive IM/DD systems."

The new paragraph in Section 4:

"We should point out that the reported error rates may be further reduced by using optimized components in the experimental setup. The BER performance may also be improved by using a different equalization approach with probably higher implementation complexity. In our 4PAM-Fast-OFDM scheme, the simple one-tap frequency domain equalization is adopted. In single-carrier PAM, for example, time-domain equalization approaches are commonly employed [R2]. However, they usually require many equalizer taps."

[R2] R. V. Der Linden, N. C. Tran, E. Tangdiongga and A. M. J. Koonen, "Increasing flexibility and capacity in real PON deployments by using 2/4/8-PAM formats," in IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 1, pp. A1-A8, Jan. 2017.

5, Fig.2 can be improved, with differently lines for optical path and electrical path.

Resp: Fig. 2 has been changed accordingly.

Reviewer #2: This paper proposes and demonstrates a combined digital linearization and channel estimation approach for IM/DD based Fast-OFDM systems. The experimental results show the receiver sensitivity of the proposed IM/DD Fast-OFDM system is improved by about 3 dB compared to previous approach. This paper is well organized and well written. I have no further comment about the quality of this paper and suggest this paper to be accepted for publication.

Resp: We thank the reviewer for their comments which recognize the contribution of our work.

Highlights

- A combined nonlinearity compensation and channel estimation scheme is proposed for optical Fast-OFDM.
- 2PAM training symbols are modulated on odd Fast-OFDM subcarriers.
- 3-dB receiver sensitivity improvement (BER = 10^{-3}) for a 22-km SMF link is reported.
- The compensation approach can deal with some degree of MZM bias drift.

A Combined Digital Linearization and Channel Estimation Approach for IM/DD Fast-OFDM Systems

Luis Carlos Vieira [a, b], Shirin Hussein [a], Izzat Darwazeh [a], Chin-Pang Liu [a], and John Mitchell [a]

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***Abstract*—A combined digital linearization and channel estimation scheme is proposed and experimentally demonstrated for short-reach intensity-modulation and direct-detection (IM/DD) optical Fast-OFDM systems. Known 2PAM-Fast-OFDM sequences are used for training a memoryless polynomial based adaptive post-distorter and for FFT-based channel estimation in IM/DD 4PAM-Fast-OFDM systems. The 2PAM signals are transmitted only over the odd SCs of the training sequences. With the combined compensation scheme, significant BER improvements are achieved for 10- and 22-km length 12.5 Gbit/s SMF links. Compared with a conventional IM/DD Fast-OFDM, the receiver sensitivity of the proposed IM/DD Fast-OFDM system is improved by about 3 dB at a bit error ratio (BER) of 10-3, after 22-km SMF transmission. In addition, the experimental results for different bias voltages and under strong filtering effects show that the proposed compensation approach can deal with some degree of MZM bias drift and can be applied for realistic wideband optical Fast-OFDM systems.**

***Index Terms*—Fast-OFDM, IM/DD systems, post-distortion, channel estimation.**

1. INTRODUCTION

Optical orthogonal frequency division multiplexing (OOFDM) has been considered a candidate to upgrade the data-rate of short-reach fiber-optic networks, such as passive optical networks (PONs) [1]-[3]. OOFDM advantageously offers high spectral efficiency and significant system flexibility, and enables the use of single-tap frequency-domain equalizers. Optical intensity-modulated and direct-detection OFDM (IM/DD-OFDM) is less complex and more suitable for cost-efficient deployment of optical access networks compared to coherent optical OFDM (CO-OFDM) systems [1], [4]. The OFDM signal must be real-valued and positive for transmission over IM/DD links [5]. Thus, additional subcarriers are needed for Hermitian symmetry, at the transmitter side, to obtain a real signal at the output of inverse fast Fourier transform (IFFT) and only half of the subcarriers can be used for data modulation.

Fast-OFDM has also been proposed for application in IM/DD optical systems [5]-[12]. With Fast-OFDM, simple single-quadrature modulation formats are used and only half of the subcarrier spacing of conventional OFDM is required, allowing to double the number of effectively-modulated subcarriers within the same bandwidth [13]-[15]. Fast-OFDM may be implemented by inverse discrete cosine transform (IDCT) and DCT, see e.g. [8] and [10], or by IDCT/FFT as proposed in [11] and experimentally demonstrated in [7]. With the latter implementation approach, simple single-tap equalization can be employed. Compared to conventional OFDM, the Fast-OFDM technique does not require Hermitian symmetry at the transmitter side of IM/DD systems, as the IDCT directly generates real-valued signals. Due to the use of real operations, Fast-OFDM offers reduced complexity [5]. In comparison to NRZ PONs, optical Fast-OFDM can enable much higher spectral efficiency. Thus, it can be considered a very suitable solution for cost-sensitive IM/DD systems.

Fast OFDM and OFDM signals are sensitive to the IM/DD system nonlinearity due to usually high peak-to-average power ratio (PAPR). In Mach–Zehnder modulator (MZM)-based IM/DD DC-offset optical Fast-OFDM systems, the MZM is commonly biased at the quadrature point for best linearity [12]. Even at this bias, however, the high peaks of a Fast-OFDM signal may reach the nonlinear region of the MZM characteristic. In addition, MZMs suffer from the bias-drift problem, i.e. slow changes in the optimum bias point [16]. Thus, some adaptive linearization and/or PAPR reduction technique might be needed to reduce the signal's nonlinear distortion.

Adaptive digital predistortion and post-distortion approaches have been proposed for linearization of optical communication systems, with polynomial-based models commonly used [17]-[21]. Memory polynomials are able to compensate for system dynamic nonlinearity and generally perform better than memoryless polynomials [19], [22]. However, memory polynomials require a higher number of model coefficients. The EVM performances of both memory and memoryless polynomial based digital predistortion for OFDM radio-over-fiber (RoF) links were compared in [19], with similar results reported for some of the experimental cases. However, the bandwidth of the OFDM signal was just 18 MHz and the memory effects were not very significant. In [23], a memoryless polynomial based nonlinear equalizer was employed for a phosphorescent white LED-based 375-MHz visible light communication (VLC) link, with bit error ratio (BER) results lower than 3.8 x 10^{-3} reported. No good results were obtained for higher modulation bandwidths, such as 450 and 525 MHz. Unlike post-distortion, predistortion requires an additional feedback link for model identification, and the nonlinearity of the feedback link itself will degrade the predistortion performance [18]. Thus, post-distortion can be considered a simpler solution, especially if it is based on memoryless polynomials.

In this paper, we propose and experimentally demonstrate a combined memoryless polynomial based adaptive post-distortion (in time domain) and frequency-domain channel estimation scheme for short-reach IM/DD PAM-Fast-OFDM links. In [4], binary phase-shift keying (BPSK) training signals modulating the odd subcarriers (SCs) of OFDM were used to reduce the effect of signal-to-signal beating interference (SSBI) and improve the accuracy of one-tap frequency-domain channel estimation. Here, we propose using known 2PAM-Fast-OFDM training sequences (TSs) for both post-distortion training and channel estimation applied to 4PAM-Fast-OFDM links, with the 2PAM signals transmitted over the odd SCs of the TSs. The even SCs of the TSs are set to zero, and their channel estimation are obtained at the receiver side by averaging the adjacent odd SCs' channel responses. Another key feature of the proposed compensation scheme is that, in addition to the data-SC post-distortion, the 2PAM-based TSs are post-distorted before being sent to the frequency-domain demodulator, enhancing the channel estimation performance. We note that 2PAM signals are more robust to noise interference than 4PAM [24]. According to our knowledge, this work is the first demonstration of the combined compensation scheme for IM/DD 4PAM-Fast-OFDM systems, with excellent BER results achieved for 10- and 22-km length 12.5 Gbit/s links. In addition, this is the first application of the memoryless polynomial model for a 3.1-GHz bandwidth signal.

2. Signal Model and Compensation Approach

A. Fast-OFDM System

Considering a Fast-OFDM system with N subcarriers, the k-th subcarrier is modulated by the real-valued input s(k) and the discrete time signal x(n) is obtained by IDCT

$$x(n) = \sqrt{\frac{2}{N}} + \sum_{k=0}^{N-1} \varepsilon(k) s(k) cos\left[\frac{\pi(2n+1)k}{2N}\right] \tag{1}$$

where n = {0,1,2, …, N – 1}, and $\varepsilon(k) = \sqrt{0.5}$ for k = 0 and 1 for k = 1, …, N – 1. In this work, zero-padding (ZP) is adopted as guard interval to avoid inter-symbol interference. At the receiver side, a length-2N FFT demodulation approach [11] is applied, enabling the use of frequency-domain single-tap equalizers.

B. Digital Linearization and Channel Estimation

A block diagram of the digital linearization scheme for IM/DD Fast-OFDM links is shown in Fig. 1. In this work, a third-order polynomial function is used as post-distorter model. The received and the known reference TSs are inserted in reverse order in the post-distorter training block so that the inverse of the link nonlinear characteristic is modelled using a linear least-squares (LS)-based fitting algorithm. After the training phase, the polynomial coefficients of the actual post-distorter, inserted after the IM/DD link (in baseband), are updated. The post-distorted signal y_{pos} is then sent to the frequency-domain processing stages. We note that the post-distortion training approach can be performed in an offline manner, with the post-distorter updating interval depending on specific IM/DD link characteristics.

In the diagram shown in Fig. 1, the post-distorter output $y_{pos}(n)$ is given by

$$y_{pos}(n) = \sum_{k=0}^{K} a_k y(n)^k \tag{2}$$

where $y(n)$ is the received signal (in baseband), a_k are the model coefficients, and K is the polynomial order. In this work, K is set to 3, and the model coefficients are obtained using the 2PAM-over-odd-SC Fast-OFDM received and known TSs (y_{TS} and x_{TS} in Fig. 1) and the linear LS fitting method, provided by the "polyfit" function in MATLAB.

After the post-distortion is completed, the signal samples are serial-to-parallel converted and fed into a FFT module for demodulation. After the FFT, the channel estimation is realized for the data-carrying subcarriers based on the received and known TSs. Firstly, the channel responses of the odd subcarriers are estimated as

$$H(k_{odd}) = \frac{y_{TS}(k_{odd})}{x_{TS}(k_{odd})} \tag{3}$$

where $y_{TS}(k_{odd})$ and $x_{TS}(k_{odd})$ are the k_{odd}-th frequency component of the received TS and the known reference TS, respectively. Subsequently, the channel response of each even subcarrier is obtained by averaging the channel responses of the adjacent odd subcarriers. Finally, the actual channel response used for the equalization of a Fast-OFDM frame is estimated by averaging over all TSs within the frame.

In the proposed compensation scheme, the received TSs are post-distorted before being sent to the FFT-based demodulator, which improves the channel estimation/equalization performances. Thus, we can say that our memoryless polynomial based post-distortion has also a dynamic compensation effect on the system performance.

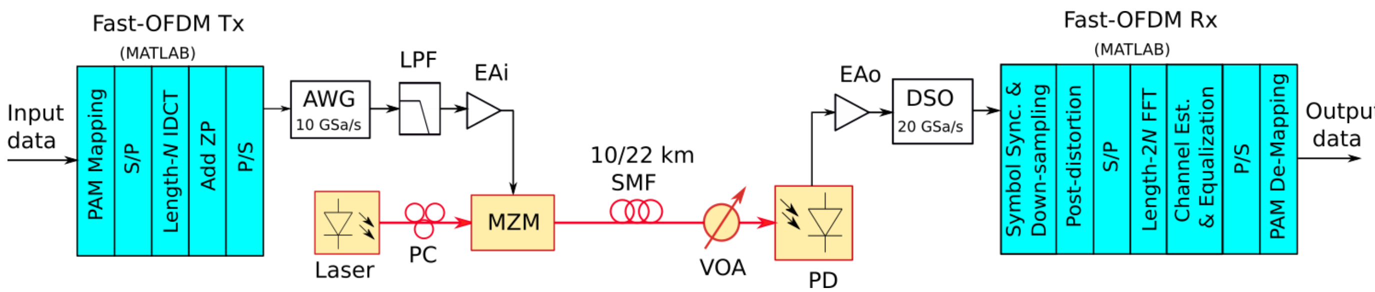

Fig. 2 - Experimental setup of the IM/DD Fast-OFDM system.

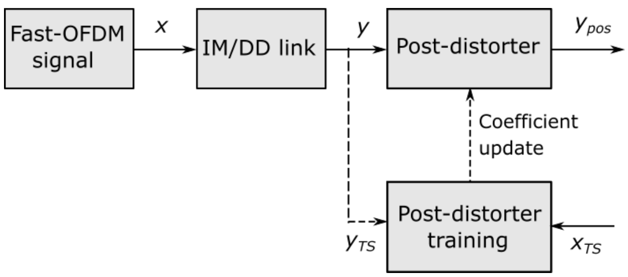

Fig. 1. The digital linearization approach.

3. Experimental Setup

The experimental setup of the proposed IM/DD Fast-OFDM system is shown in Fig. 2. The input bit stream is encoded into 4PAM symbols for data transmission. The training sequence (TS), for both post-distortion training and frequency-domain channel estimation (CE), is generated using 2PAM modulation. After serial-to-parallel conversion, both 2PAM/4PAM signals are processed by the IDCT block. Then, the ZP is added and the Fast-OFDM signal is parallel-to-serial (P/S) converted.

In this work, the Fast-OFDM signal (generated in MATLAB) is set with 320 data subcarriers and IDCT size of 512. A frequency gap of 800 MHz is inserted between the optical carrier and the data subcarriers due to the bandwidth of the available electrical amplifiers, and to avoid strong SSBI due to the square-law detector [4]. The decision on the size of the guard band will depend on the level of SSBI in a specific IM/DD link and if a SSBI compensation technique is used or not. In this work, the analysis of the optical Fast-OFDM performance for different frequency gap widths is not considered. The total bandwidth (including the frequency gap) is 3.9 GHz. The ZP length is set to 16. Here, a Fast-OFDM frame consists of either 2 or 4 TSs and 492 data symbols. The generated Fast-OFDM signal is uploaded to the arbitrary waveform generator (AWG), with a DAC sampling rate of 10 GS/s. As 4PAM modulation format is used, the data rate (excluding guard interval) is 2 x 10G x 320/512 = 12.5 Gbit/s. After the AWG, a low-pass filter (LPF) with 3-dB bandwidth of 6 GHz is used to remove unwanted higher frequency components. The filtered signal is fed into an electrical amplifier (EAi) to drive a LiNbO3 MZM, which has a DC Vpi of around 3.5 V and a RF Vpi of 5.5 V (@ 1 GHz). The MZM is biased at the optimal point for intensity modulation (near the quadrature point), unless otherwise stated. As optical source, a 1550-nm laser with output power of 11 mW is used. After the MZM, the optical Fast-OFDM signal is transmitted over short-reach SMF links, with attenuation coefficient ≤0.2 dB/km and dispersion coefficient ≤18 ps/(nm.km). At the receiver end, a variable optical attenuator (VOA) is used to control the received optical power (ROP). The received optical signal is directly detected by a 50-GHz PIN photodiode, with the electrical signal pre-amplified by an 8-GHz bandwidth low noise amplifier (EAo) and sampled by the digital storage oscilloscope (DSO) with an ADC sample rate of 20 GS/s for offline processing.

The receiver DSP blocks for the offline Fast-OFDM demodulation with post-distortion are shown in Fig. 2. The received signal is downsampled at a ratio of 2:1 and a symbol synchronization algorithm is employed to identify the start of each Fast-OFDM symbol. Then, after the initial post-distortion training phase, the data symbols and received TSs are post-distorted, serial-to-parallel converted, and processed by the FFT block. In this work, the Fast-OFDM signal is demodulated based on the length-2N FFT approach [11]. The frequency-domain CE and equalization are executed as explained in Section 2. The resulting equalized signal is parallel-to-serial converted and PAM decoded.

4. Experiment Results and Discussion

The spectra at the input/output of a 22-km IM/DD link for the 4PAM-Fast-OFDM signal, without the combined compensation scheme, are illustrated in Fig. 3. We note that, for the signal bandwidth and the link lengths used in this work, the fiber dispersion is negligible. However, the output spectrum of the 22-km link shows strong fading between the lower and higher subcarriers, which is due to the uneven frequency response of the IM/DD link components (including the RF devices and cables). In addition, increased nonlinear distortion after the IM/DD link can be observed in the gap between the optical carrier and the data subcarriers, but it is not limited to that region. These spectra were acquired without any time averaging or equalization set in the DSO. In Fig. 4, the channel response versus SC index, obtained by the channel estimation block (see Fig. 2), is shown. The maximum power fading on the SCs is about 7.5 dB, which is in agreement with the in-band fading measured at the 22-km Fast-OFDM link output (Fig 3b).

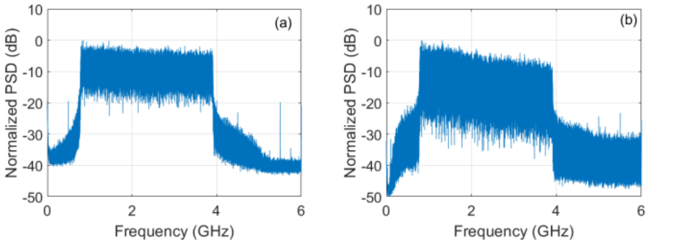

Fig. 3. Measured electrical spectra of the 4PAM-Fast-OFDM signal: (a) AWG output; (b) IM/DD link output (EAo output), without digital compensation.

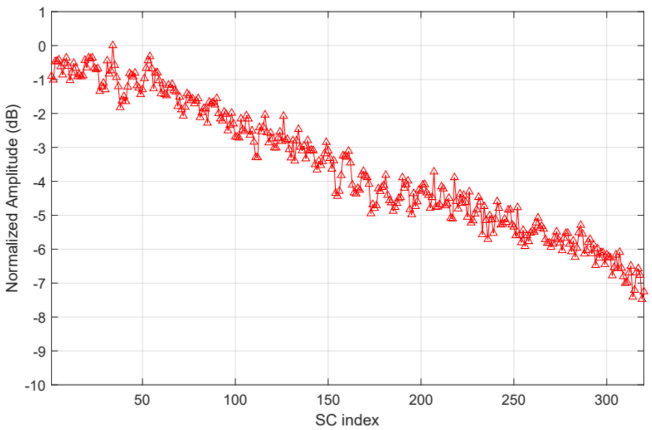

Fig. 4. Estimated channel response for the 22-km IM/DD Fast-OFDM link.

In Fig. 5, the BER results versus ROP for both the proposed and conventional optical 4PAM-Fast-OFDM systems are shown. These results are obtained using 2 and 4 TSs and for the 22-km IM/DD link. In the post-distorter model of (2), K is set to 3. The conventional 4PAM-Fast-OFDM is implemented without post-distortion and based on 2PAM-block-CE. The BER performance of the 4PAM-Fast-OFDM with the proposed compensation scheme is significantly better than that obtained for the conventional Fast-OFDM link, for the 2- and 4-TS cases. For example, for the 2-TS case at a BER of 10^{-3}, the required ROPs are about −7.8 and −10.8 dBm for the conventional and proposed IM/DD 4PAM-Fast-OFDM systems, respectively. At the ROP of −4.8 dBm, BER improvements of two orders of magnitude are achieved with the combined compensation approach in comparison to the conventional Fast-OFDM system. From Fig. 5, it can also be seen that the BER results are enhanced by increasing the TS length from 2 to 4, as expected.

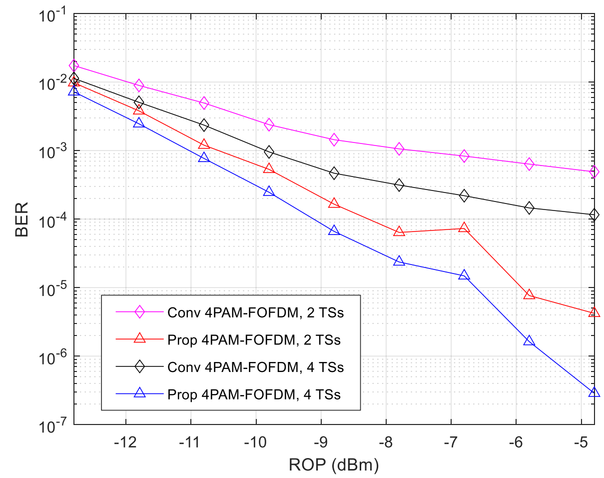

Fig. 5. BER performances versus ROP for the conventional and proposed IM/DD 4PAM-Fast-OFDM systems, for 22-km SMF.

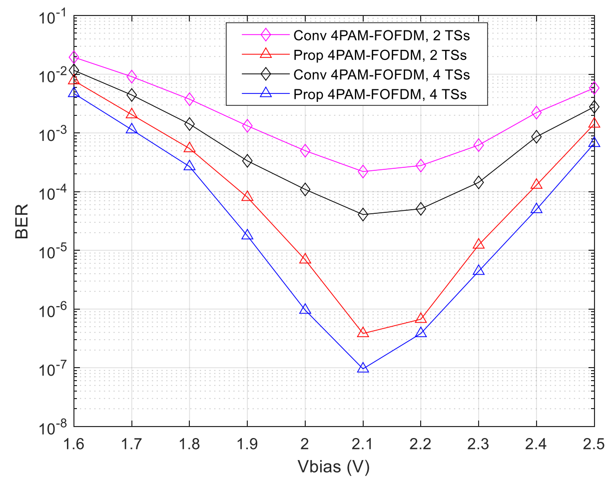

Fig. 6. BER performances versus MZM bias voltage for the conventional and proposed IM/DD 4PAM-Fast-OFDM systems, for 10-km SMF.

In MZM-based IM/DD systems, the MZM bias point determines the ratio of the optical carrier to sideband powers and this has significant impact on both the system performance and spectral efficiency [25]. In addition, the optimum MZM bias point may drift due to intrinsic reasons, related to the flow of electrical charge in the device structure, and due to changes in environmental conditions (such as temperature and humidity) [16]. Thus, it is important to demonstrate the proposed Fast-OFDM scheme for the MZM operating at non-optimum bias points. In Fig. 6, the performances of the conventional and the proposed IM/DD 4PAM-Fast-OFDM systems for different MZM bias voltages, and for 2 and 4 TSs, are compared. The length of the optical link is 10 km. The experimental results clearly show the enhancement in the system performance with the proposed compensation scheme, with BER improvements of more than two orders of magnitude achieved at the bias point of 2.1 V. The BER results for the proposed Fast-OFDM system operating within the bias range of 1.9 to 2.4 V and of 1.9 to 2.3 V for the 2-TS and 4-TS cases, respectively, are below the minimum BERs of 2.2 x 10^{-4} and 4 x 10^{-5} (at 2.1V bias) obtained for the conventional Fast-OFDM and for the corresponding TS cases. This shows that the proposed compensation approach can give improved performance for IM/DD Fast-OFDM systems even if the MZM deviates (up to a certain level) from the optimum operating point.

In Fig. 7, the 4PAM received signal constellations after the 10-km IM/DD link and obtained for 2 TSs are presented. It can clearly be seen the improvement in the signal constellation when the combined compensation scheme is applied to the optical Fast-OFDM link.

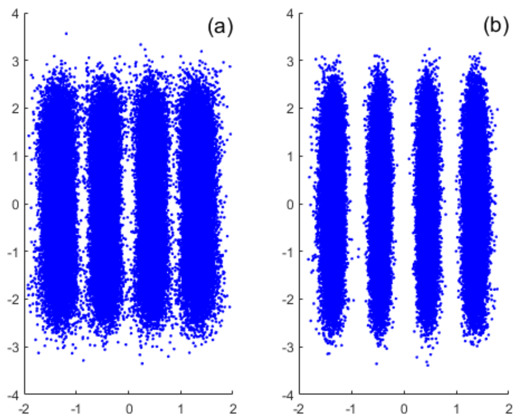

Fig. 7. 4PAM received signal constellations after 10-km IM/DD link and for 2 TSs: (a) conventional Fast-OFDM (b) proposed Fast-OFDM.

The performance of the proposed 4PAM-Fast-OFDM system is also compared against that of a post-distorted 16QAM-OFDM system. The BER results are shown in Fig. 8, for the 22-km IM/DD link and 4 TSs. The 16QAM-OFDM signal is generated with same total bit rate and occupied bandwidth of the 4PAM-Fast-OFDM. BPSK training signals are used for OFDM channel estimation. For most of the measured results, similar BERs are obtained with the proposed 4PAM-Fast-OFDM and the post-distorted 16QAM-OFDM. At the higher ROP levels, the proposed system outperforms the OFDM system.

We should point out that the reported error rates may be further reduced by using optimized components in the experimental setup. The BER performance may also be improved by using a different equalization approach with probably higher implementation complexity. In our 4PAM-Fast-OFDM scheme, the simple one-tap frequency domain equalization is adopted. In single-carrier PAM, for example, time-domain equalization approaches are commonly employed [26]. However, they usually require many equalizer taps.

The promising results reported in this work show that the proposed compensation scheme can be used to improve the performance of short-reach IM/DD Fast-OFDM systems. However, for long fiber links, with significant chromatic dispersion, digital linearization based on models with memory are usually required, e.g., using Volterra equalizers [27].

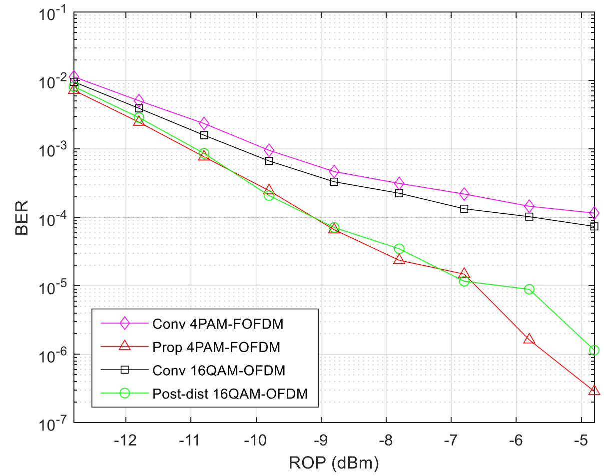

Fig. 8. BER performances versus ROP for the conventional and proposed IM/DD 4PAM-Fast-OFDM systems in comparison with conventional and post-distorted IM/DD 16QAM-OFDM. SMF length of 22 km, 4 TSs.

5. CONCLUSION

We have proposed and experimentally demonstrated, for the first time, a memoryless polynomial based adaptive post-distortion combined with frequency-domain channel estimation scheme for a 3.1-GHz bandwidth 4PAM-Fast-OFDM signal at 12.5 Gbit/s over 10- and 22-km IM/DD links. With this compensation scheme, known 2PAM-over-odd-SC Fast-OFDM TSs are employed for both post-distortion training and FFT-based channel estimation. The results show that the proposed IM/DD Fast-OFDM system can achieve about 3-dB receiver sensitivity improvement at a BER of 10^{-3} for a 22-km SMF and using 2 TSs, in comparison to the conventional Fast-OFDM system. In addition, the good performance results obtained for IM/DD links operating at different bias voltages and under strong filtering effects show that the proposed compensation scheme can deal with some degree of MZM bias drift and can be applied for realistic wideband optical Fast-OFDM systems. As future work, the extension of application of the proposed scheme should be further investigated.

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REFERENCES

[1] M. Chen et al., "Experimental Demonstration of an IFFT/FFT Size Efficient DFT-Spread OFDM for Short Reach Optical Transmission Systems," in Journal of Lightwave Technology, vol. 34, no. 9, pp. 2100-2105, 1 May1, 2016.
[2] Han Ji, Bangjiang Lin, Xuan Tang, Junxiang Xu, "Triple-layer hybrid optical OFDM scheme for passive optical network," Optics Communications, Volume 466, 2020, 125622.
[3] C. Zhang, W. Zhang, X. He, C. Chen, H. Zhang and K. Qiu, "Physically Secured Optical OFDM-PON by Employing Chaotic Pseudorandom RF Subcarriers," in IEEE Photonics Journal, vol. 9, no. 5, pp. 1-8, Oct. 2017.
[4] M. Chen, J. He, Q. Fan, Z. Dong and L. Chen, "Experimental Demonstration of Real-Time High-Level QAM-Encoded Direct-Detection Optical OFDM Systems," in Journal of Lightwave Technology, vol. 33, no. 22, pp. 4632-4639, 15 Nov.15, 2015.

[5] J. Zhou et al., "FOFDM Based on Discrete Cosine Transform for Intensity-Modulated and Direct-Detected Systems," in Journal of Lightwave Technology, vol. 34, no. 16, pp. 3717-3725, 15 Aug.15, 2016.

[6] E. Giacoumidis, S. K. Ibrahim, J. Zhao, J. M. Tang, A. D. Ellis and I. Tomkos, "Experimental and Theoretical Investigations of Intensity-Modulation and Direct-Detection Optical Fast-OFDM Over MMF-Links," in IEEE Photonics Technology Letters, vol. 24, no. 1, pp. 52-54, Jan.1, 2012.

[7] X. Ouyang, H. Zhang, Y. Chen, S. Alam, M. N. Petrovich, F. Poletti, D. J. Richardson, F. C. G. Gunning, and J. Zhao, "Experimental demonstration of improved equalization algorithm for IM/DD fast OFDM," IEEE Photonics Technology Letters, vol. 27, no. 16, pp. 1780–1783, 2015.

[8] Zhihua Zhou, Jing He, Jie Ma, Yaoqiang Xiao, Yun Cheng, "Adaptive modulation scheme for DML-based IM/DD FOFDM systems using overlap frequency-domain equalization," Optical Fiber Technology, Volume 48, Pages 213-217, 2019.

[9] L. Zhao, J. He, Z. Zhou, R. Deng and L. Chen, "The Research of Optical Fast OFDM Based on Channel Estimation Algorithm," in IEEE Photonics Journal, vol. 8, no. 3, pp. 1-5, June 2016.

[10] E. Giacoumidis, S. K. Ibrahim, J. Zhao, J. M. Tang, I. Tomkos and A. D. Ellis, "Experimental demonstration of cost-effective intensity-modulation and direct-detection optical Fast-OFDM over 40km SMF transmission," OFC/NFOEC, Los Angeles, CA, 2012.

[11] X. Ouyang and J. Zhao, "Single-tap equalization for fast OFDM signals under generic linear channels," IEEE Communications Letters, vol. 18, no. 8, pp. 1319-1322, 2014.

[12] Z. Zhou, J. He, J. Ma and M. Chen, "Experimental Demonstration of an SFO-Robustness Scheme with Fast OFDM for IMDD Passive Optical Network Systems," in Journal of Lightwave Technology, vol. 38, no. 20, pp. 5608-5616, 15 Oct.15, 2020.

[13] M. Rodrigues and I. Darwazeh, "Fast OFDM: A proposal for doubling the data rate of ofdm schemes," in Proc. IEEE/IEE Int. Conf. Telecommun., 06 2002.

[14] J. Zhao and A. D. Ellis, "A novel optical fast OFDM with reduced channel spacing equal to half of the symbol rate per carrier," 2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference, 2010, pp. 1-3.

[15] F. Cruz-Roldán, W. A. Martins, P. S. R. Diniz and M. Moonen, "Achievable Data Rate of DCT-Based Multicarrier Modulation Systems," in IEEE Transactions on Wireless Communications, vol. 18, no. 3, pp. 1739-1749, March 2019.

[16] J. P. Salvestrini, L. Guilbert, M. Fontana, M. Abarkan and S. Gille, "Analysis and Control of the DC Drift in LiNbO3-Based Mach–Zehnder Modulators," in Journal of Lightwave Technology, vol. 29, no. 10, pp. 1522-1534, May15, 2011.

[17] H. Qian, S. J. Yao, S. Z. Cai and T. Zhou, "Adaptive Postdistortion for Nonlinear LEDs in Visible Light Communications," in IEEE Photonics Journal, vol. 6, no. 4, pp. 1-8, Aug. 2014.

[18] C. Mateo, J. Clemente, P. Garcia-Ducar, P. L. Carro, J. de Mingo and I. Salinas, "Digital predistortion of a full-duplex Radio-over-Fiber mobile fronthaul link with feedback loop," 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, 2017.

[19] L. C. Vieira and N. J. Gomes, "Experimental demonstration of digital predistortion for orthogonal frequency-division multiplexing-radio over fibre links near laser resonance," IET Optoelectronics, vol. 9, no. 6, pp. 310–316, 2015.

[20] M. U. Hadi, P. A. Traverso, G. Tartarini, O. Venard, G. Baudoin and J. Polleux, "Digital Predistortion for Linearity Improvement of VCSEL-SSMF-Based Radio-Over-Fiber Links," in IEEE Microwave and Wireless Components Letters, vol. 29, no. 2, pp. 155-157, Feb. 2019.

[21] A. Hekkala et al., "Predistortion of Radio Over Fiber Links: Algorithms, Implementation, and Measurements," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 59, no. 3, pp. 664-672, March 2012.

[22] Lei Ding et al., "A robust digital baseband predistorter constructed using memory polynomials," in IEEE Transactions on Communications, vol. 52, no. 1, pp. 159-165, Jan. 2004.

[23] Yingjun Zhou, Yiran Wei, Fangchen Hu, Jian Hu, Yiheng Zhao, Jianli Zhang, Fengyi Jiang, and Nan Chi, "Comparison of nonlinear equalizers for high-speed visible light communication utilizing silicon substrate phosphorescent white LED," Opt. Express 28, 2302-2316, 2020.

[24] Khaliq Muhammad Shoaib, Cantono Mattia, Straullu Stefano and Curri Vittorio, "Performance Assessment of Short-Reach Multi-Level PAM Transmission Exploiting LMS Equalization," IET Optoelectronics, vol. 11, no. 4, pp. 134 - 140, 2017.

[25] O. Omomukuyo, M. P. Thakur and J. E. Mitchell, "Experimental demonstration of the impact of MZM non-linearity on direct-detection optical OFDM," 2012 IEEE Wireless Communications and Networking Conference (WCNC), 2012, pp. 3753-3757.

[26] R. V. Der Linden, N. C. Tran, E. Tangdiongga and A. M. J. Koonen, "Increasing flexibility and capacity in real PON deployments by using 2/4/8-PAM formats," in IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 1, pp. A1-A8, Jan. 2017.

[27] Q. Hu, K. Schuh, M. Chagnon, F. Buchali, S. T. Le and H. Bülow, "50 Gb/s PAM-4 Transmission Over 80-km SSMF Without Dispersion Compensation," 2018 European Conference on Optical Communication (ECOC), Rome, Italy, 2018.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT authorship contribution statement

Luis Carlos Vieira: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Writing - review & editing.

Shirin Hussein: Investigation

Izzat Darwazeh: Supervision, Writing - review & editing.

Chin-Pang Liu: Resources

John Mitchell: Writing - review & editing.