Experimental Demonstration of Direct-Detection Optical Fast-OFDM using Memory Polynomials

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***Abstract*—Fast-OFDM has been used extensively in optical and wireless systems, with its advantages of simple implementation and spectral efficiency making it a good candidate for optical access networks. This work proposes a new time domain equalization method for Fast-OFDM optical access networks, which deals with ameliorating the effects of linear and nonlinear behavior of system components and optical channel. The proposed equalization technique simplifies system implementation and shows excellent results when used in conjunction with training signals designed for the purpose of minimization of least square error and hence equalization of the channel. The work reports details of the design approach and then implementation of the algorithm in an experimental test bed with an direct-detection optical link and a 10 km single mode fibre. Experimental results, obtained for transmission of 7.5 Gbit/s 4PAM signals, demonstrate error rate/transmission power advantages for the new equalization technique, relative to traditional system implementation. Results are shown for various system implementation and parameters and are based on real time signal transmission and off line receiver processing. The reported results are the first demonstration of such a system.**

***Index Terms*—Optical access networks, Fast OFDM, equalization**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a promising candidate to upgrade the data rate of optical access networks. It offers high spectral efficiency, ease of implementation using fast Fourier transform (FFT), and high system flexibility [1]. In the scenario of optical access networks, optical intensity-modulated and direct-detection OFDM (IM/DD OFDM) is a less complex and less expensive solution than coherent optical OFDM (CO-OFDM) systems [2]. The OFDM signal must be positive and real-valued for transmission over IM/DD links [3]. Therefore, a DC offset is commonly used to make the OFDM signal positive and additional subcarriers are needed for Hermitian symmetry (HS) to obtain a real signal at the output of inverse fast Fourier transform (IFFT). However, due to HS, only half of the subcarriers can be used for data modulation.

Over the past two decades, there has been a quest to improve the bandwidth efficiency of multi-carrier systems by compacting the spacing between subcarriers, using techniques such as spectrally efficient FDM (SEFDM) and Faster than Nyquist(FTN) signalling [4], with many applications in optical systems, showing substantial bandwidth saving in longhaul systems [5]. Of such techniques, Fast OFDM (F-OFDM) is a simple to implement multicarrier system, firstly proposed in [6], which has half of the subcarrier spacing of conventional OFDM, resulting in improved bandwidth efficiency. With F-OFDM, the sub-carrier multiplexing and demultiplexing can be implemented by inverse discrete cosine transform (IDCT) and DCT. Single-quadrature signals are transmitted and only real arithmetic is used which reduces processing power and implementation cost. In comparison with conventional OFDM, F-OFDM avoids the need for either HS or RF upconversion at the transmitter, the latter normally limited by in-phase/quadrature imbalance issues. Thus, DCT-based F-OFDM is highly suitable for IM/DD optical links and it has been considered an attractive multicarrier system for the deployment of cost-sensitive applications, such as optical access networks [3], [7] - [8].

To enable single-tap equalization in DCT-based F-OFDM systems symmetric prefix and suffix are usually required as guard interval (GI) and the channel impulse response (CIR) should be symmetric [9]. In [10], symmetric extension of the F-OFDM signal was proposed to avoid the need for channel symmetry. However, the net data rate will be effectively halved. For wireless F-OFDM, a pre-fitering approach was employed at the receiver to filter CIR to be symmetric [11]. Such technique, however, uses a complicated finite impulse response (FIR) filter implementation, with a symmetry constraint for its design. In [9], a hybrid implementation approach for F-OFDM using IDCT and discrete Fourier transform (DFT) was proposed to allow for single-tap equalization. However, it requires complex arithmetic and a DFT of double length in comparison to the DCT-based demodulation.

In this paper, we propose and demonstrate a memory polynomial (MP) based time domain equalization approach for direct-detection optical DCT-based F-OFDM systems. The performance of the proposed scheme is compared against that of a IDCT/DFT F-OFDM system [9]. The MP model is a simplification of the more general Volterra series model and has the advantage of capturing memory effects while keeping the number of coefficients low [12]. Using the MP based equalizer, both channel linear and nonlinear distortions, coming e.g. from a RF amplifier or an optical transmitter, can be reduced. In addition, the MP equalizer can be trained in an offline manner and, although the MP is a nonlinear model, its coefficients can be obtained using a simple linear least-squares (LS) identification algorithm. To improve the equalization performance, we also propose applying a de-noising approach to the received training signals used for the estimation of the equalizer coefficients. Excellent performance results are obtained with the combined de-noising and MP equalization scheme. To the best of the authors' knowledge, this work is the first experimental demonstration of the proposed nonlinear equalization technique for IM/DD optical F-OFDM systems.

II. Signal Model and Equalization Approach

A. Fast OFDM Signal

For a F-OFDM system with N subcarriers, the k^{th} subcarrier is modulated by the real-valued input s(k). The expression of generating discrete time samples for a F-OFDM symbol using IDCT is given by:

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

where $n = \{0, 1, 2, ..., N-1\}$ is the index of time samples in a F-OFDM symbol, and $\epsilon(k) = \sqrt{0.5}$ for $k = 0$ and 1 for $k = 1, ..., N-1$.

B. MP-based Equalization

In Fig. 1, a block diagram of the MP-based nonlinear equalization scheme for IM/DD F-OFDM links is shown. In the MP equalizer training block, the inverse of the link nonlinearity and channel response are modelled based on a linear LS fitting algorithm and using the received and the known reference training signals (TSs). The LS algorithm minimizes the error between the reference TS and the modelled signal. After the training phase, the coefficients of the actual MP equalizer are updated. The equalized signal y_{eq} is then serial-to-parallel converted and sent to the DCT-based demodulation stage. The MP equalization training can be performed in an offline manner, with the equalizer updating interval depending on the specific characteristics of the IM/DD link.

The MP-based equalizer model is given by

$$y_{eq}(n) = \sum_{k=1}^{K} \sum_{q=0}^{Q} a_{kq} y(n-q) |y(n-q)|^{k-1} \tag{2}$$

where $y(n-q)$ is the received signal delayed by q sample periods, K is the nonlinearity order, Q is the memory length, and a_{kq} are the model coefficients. In this work, we use only odd-order nonlinear terms in the MP model, for reduced complexity. We tested the system performance with a full order (even and odd) MP structure and did not find any significant BER improvement.

By doing preliminary tests with the MP equalization scheme, we noted that if the received TS is highly corrupted by the IM/DD link noise the equalization performance degrades. To improve MP modelling accuracy we employ a simple de-noising approach to the received TSs before they are processed by the LS training algorithm. In this work, the de-noising technique is implemented using a set of two reference TSs, which are repeated transmitted over the optical F-OFDM link. Then, the received and transmitted TSs are time aligned and the received TSs are averaged over the number of transmissions. We note that, as the averaging is applied just to the TSs and the MP equalizer training can be done offline, the link data rate will practically not be affected.

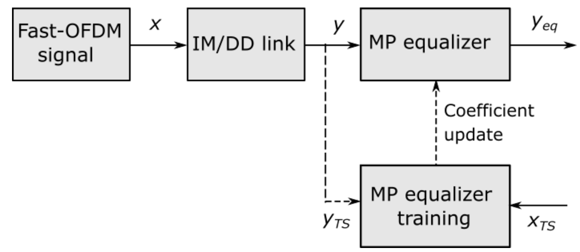

Fig. 1: The MP equalization approach.

III. Experimental Setup

The experimental setup of the proposed IM/DD F-OFDM transmission system with MP-based time domain equalization is shown in Fig. 2. The F-OFDM signal is generated in MATLAB as following described. Initially, the input data sequence is encoded into 4PAM symbols and, after serial-to-parallel conversion, processed by the IDCT block, which is set with 512 subcarries. Then, a zero-pad (ZP) with length of 32 is added as guard interval and the resulting F-OFDM signal is parallel-to-serial (P/S) converted. In this work, the number of active subcarries is 192, with the remaining ones set to zero. A frequency gap (null subcarriers) of 780 MHz is inserted between the optical carrier and the data subcarriers due to the bandwidth of the available electrical amplifiers. This gap helps to avoid strong signal-to-signal beating interference (SSBI) due to the square-law of the direct-detection receiver. The signal bandwidth is around 1.87 GHz and the total bandwidth (with the frequency gap) is around 2.65 GHz. The TSs used for the MP equalizer training are generated using 2PAM instead of 4PAM modulation. A set of 2 TSs and 480 data symbols are sequentially generated in MATLAB to form one F-OFDM frame. The corresponding F-OFDM signal is uploaded to the arbitrary waveform generator (AWG), which is set with a DAC sampling rate of 10 GS/s. Considering the 4PAM modulation and signal structure used, the total data rate (excluding guard interval) is 2 x 10G x 192/512 = 7.5 Gbit/s. From the AWG output, the signal is 6-GHz low-pass filtered and fed to an electrical amplifier which then drives a LiNbO3 MZM-based optical transmitter. The MZM has a DC Vpi of around 3.5 V and a RF Vpi of 5.5 V (@ 1 GHz) and it is biased near the quadrature point. In this experimental setup, a 1550-nm laser with output power of 11 mW is used as optical source and the optical F-OFDM signal is transmitted over a 10-km length SMF link, with attenuation coefficient ≤ 0.2 dB/km and dispersion coefficient ≤ 18 ps/(nm.km), and directly detected by a 50-GHz PIN photodiode. To control the level of received optical power (ROP), a variable optical attenuator (VOA) is used. The photodetected signal is then fed to the digital storage

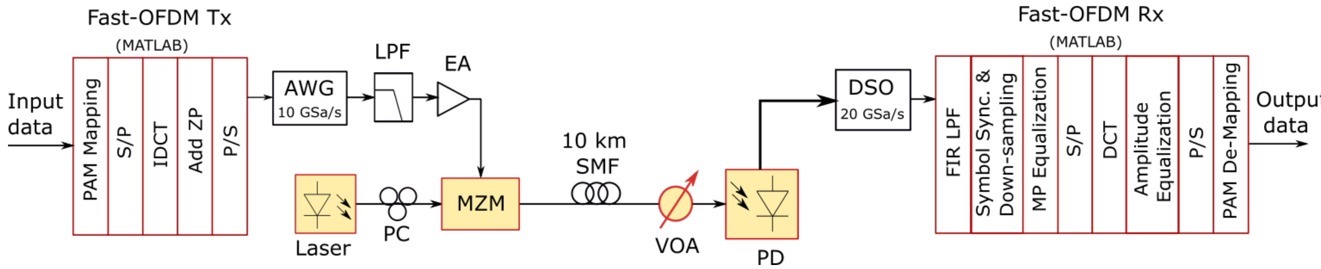

Fig. 2: Experimental setup of the MP-based optical F-OFDM direct-detection system.

oscilloscope (DSO), which has an ADC sample rate of 20 GS/s.

The received digital signal is offline processed in MATLAB, and the receiver DSP blocks are shown in Fig 2. Firstly, a low-pass FIR filter with 20 taps and a cutoff frequency of 3.1 GHz is employed to improve SNR. Then, symbol syncronization is performed to identify the start of each F-OFDM frame and the signal is downsampled at a ratio of 2:1. After that, the MP equalization is applied. The MP coefficients are previously obtained using the training approach as explained in Section 2. The time domain equalized signal is then serial-to-parallel converted and demodulated using the DCT block followed by an amplitude equalization per subcarrier. At the end, the resulting signal is parallel-to-serial converted and PAM decoded.

IV. Experiment Results

In Fig. 3, the received spectra after the 10-km IM/DD 4PAM-F-OFDM link with and without the MP equalization approach are illustrated. In Fig. 3a, it can be seen the filtering effect in the unequalized output signal, which comes from the combined frequency response of the eletro-optic components. The spectrum in Fig. 3b shows the improvement in the frequency response due to the MP-based equalization scheme. The equalized results were obtained for Q = 10, K = 3, and with two received TSs averaged by 10 times.

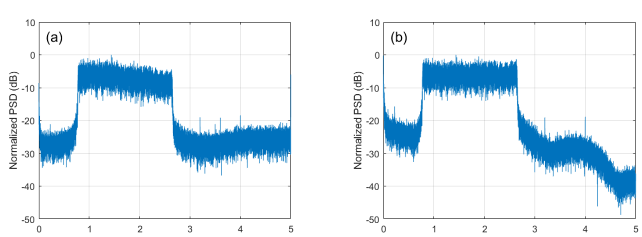

Fig. 3: Spectra of the received 4PAM-F-OFDM signal at a ROP of -5.3 dBm: (a) without and (b) with MP equalization, Q = 10, K = 3.

In Fig.4 the BER performances of the MP-equalized optical F-OFDM link are presented, considering different time-averaging factors applied to the received TSs used for the MP equalizer training. In the MP equalizer model of (2), K and Q are set to 3 and 10, respectively. From these results, it can clear be seen the BER improvement with increasing the time-averaging of the TSs. For example, at a BER of 10^{-3}, by averaging 10x the TSs the receiver sensitivity is improved by around 1.5 dB in comparison with the case without averaging. For the following BER results, the TS averaging of 10 times is adopted.

We now investigate the F-OFDM system performance with different memory lengths (Q) set in the MP model of (2), with the BER results for Q = 5, 10, and 15 shown in Fig. 5. The model nonlinearity order K is set to 3. The performance for a DFT-based optical F-OFDM system, using zero-forcing frequency-domain equalization, is also included. The same transmitted F-OFDM signal is used to obtain the BER results for both the DCT- and DFT-demodulation cases. Also, the same FIR filter parameters are used for both cases. It can be seen that the proposed F-OFDM system outperforms the DFT-based system for all measured cases. The best performances are achieved for Q = 10 and 15. For a simpler equalizer implementation, a MP model with Q = 5 could be used, with a small penalty in system performance in comparison with Q = 10.

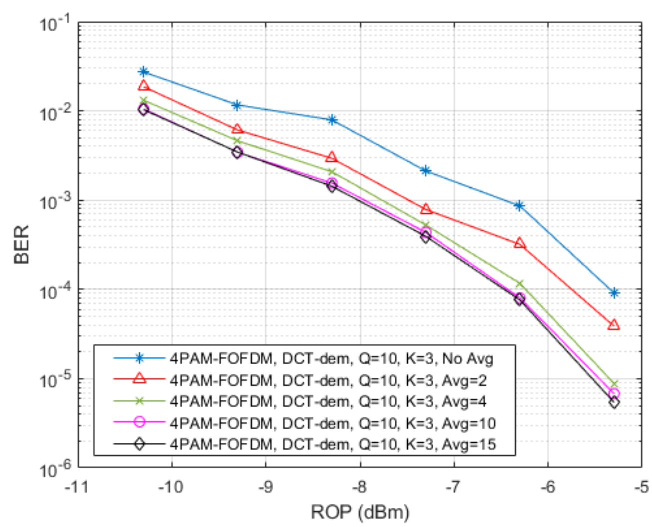

Fig. 4: BER performances with different training signal time-averaging factors.

The BER results of the proposed equalization approach for different nonlinearity orders K in the MP model are shown in Fig. 6. The MP equalizer is set with Q = 10. The results for the DCT-based receiver with a linear equalizer (K = 1), and for the DFT-based demodulation system are also included for comparison. The BER performances of the DCT-based F-

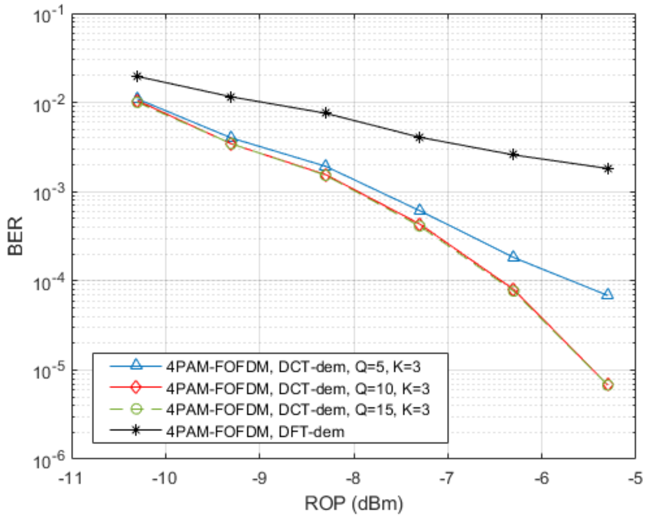

Fig. 5: BER performances different MP memory lengths.

OFDM system with the MP equalizer are significantly better than those for the DCT receiver with linear equalizer and for the DFT receiver case. At the higher ROP levels, the best results are achieved with the MP nonlinearity order K of 5 and, at the lower ROPs, the best performance is for $K = 3$. Generally, a MP model with lower K is desirable for reduced implementation complexity. For the case of $K = 7$, the BER performance of the MP equalizer is slightly degraded at lower ROPs. This is because the noise at the system output can bias the coefficient estimates of a MP model and this problem is magnified as the nonlinear order K increases [13].

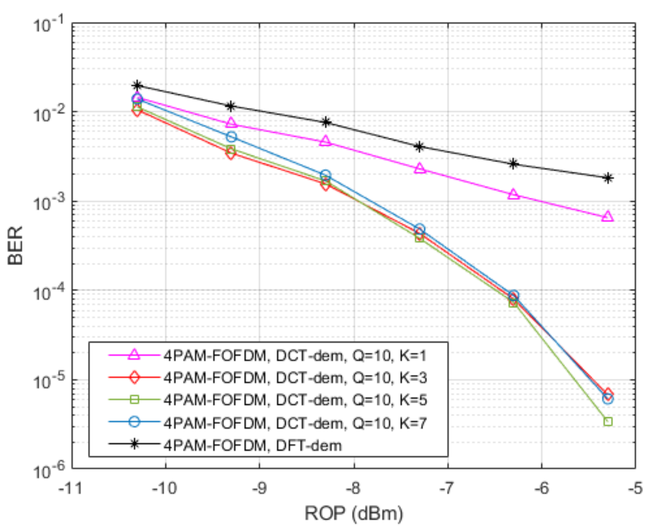

Fig. 6: BER performances for different K orders; K=1 is a linear equalizer.

V. Conclusion

A new design of optical access network links, based on Fast-OFDM and new equalization technique, is proposed. The key contribution of the work is in the design of equalizers that ameliorate the linear and nonlinear distortions of the optical link, based on using memory polynomials and training signals. The equalizers are easy to construct and can be trained off-line, with the advantage of simple implementation that captures memory effects while keeping the number of coefficients low. The paper describes the implementation of an equalizer and its application in an experimental optical link. Demonstration of 4PAM signals modulating a laser using an external MZM and transmitting signals over a 10km SMF link show advantages over previously reported techniques. The experimental system transmits 7.5 Gbit/s over a bandwidth of 2.65 GHz, which includes a guard-band of 780 MHz, giving a spectral efficiency of just over 2.8 bits/s/Hz. The Fast-OFDM was generated using an IDCT algorithm with 512 subcarriers and only 192 of these were active. The signal was physically generated using an AWG, with a sampling rate of 10 Gsamples/s resulting in the 7.5 Gbit/s signal. Detailed measurements of off-line processed data showed that the new system not only has the advantage of reduced bandwidth (relative to OFDM system) but also a bit error advantage. De-noising of training signal, using averaging in a noisy receiver environment, showed significant BER advantages of using the nonlinear equalization technique even with a small number of coefficients and simple filter construction. We believe that the use of such equalizers in conjunction with Fast-OFDM will pave the way to simple and cost effective optical access networks, to satisfy the growing demands of high rate and high quality data.

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