A Spectrally Efficient Unipolar PAM Single Carrier Frequency Domain Equalization for IM/DD Systems

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Abstract—**We propose a novel hybrid pulse amplitude modulation single carrier frequency domain equalization (PAM-SC-FDE) system that outperforms similar unipolar systems in terms of bit error rate (BER), bandwidth efficiency, and peak-to-average power ratio (PAPR).**

I. Introduction

Orthogonal frequency-division multiplexing (OFDM) is becoming a good candidate for ultra-high speed optical communication systems, due to its ability to combat inter-symbol-interference (ISI) and its simple equalization structure [1]. However, OFDM signals have inherently high peak to average power ratio (PAPR), which makes it more vulnerable to the nonlinear effect of optical sources [2]. Thus, single carrier with frequency domain equalization (SC-FDE) had been proposed as an alternative to OFDM. SC-FDE is able to combat ISI with low PAPR and much lower complexity [3].

For a cost-effective implementation, as in fiber-to-the-home (FTTH) and visible light communication (VLC) systems, intensity modulation/direct detection (IM/DD) systems is preferred over coherent optical communication [5]. Here, the baseband signal modulates the intensity of the optical source. So the time-domain transmitted signal must be real and positive. Traditional SC-FDE has to be modified to make it compatible with the nature of an IM/DD system. To do so, several systems has been proposed as in [3-5]. This is achieved at the expense of bandwidth or/and complexity.

The most recently proposed IM/DD SC-FDE systems are repetition and clipping SC-FDE (RCO-SC-FDE) [4], and polar SC-FDE (P-SC-FDE) [5]. In RCO-SC-FDE, an extra fast Fourier transform/inverse fast Fourier transform (FFT/IFFT) is added to the transmitter side to generate a real signal using Hermitian symmetry, which will double the length of signal and raise system complexity. In addition RCO-SC-FDE repeats the signal twice before clipping to form unipolar signal. So, in this system only ¼ of the bandwidth is used. While in P-SC-FDE, the unipolar signal is formed by converting the complex signal from Cartesian to the polar form (amplitude and phase) and sending both parts into two consecutive blocks. Here, ½ of the bandwidth is utilized and extra complexity is added to the system.

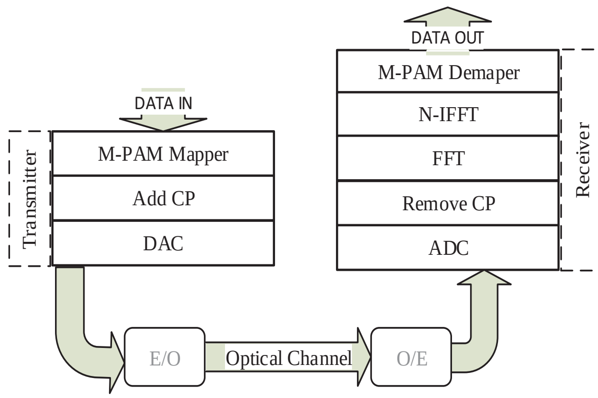

Fig. 1. Proposed PAM-SC-FDE system. (E/O: electrical-to-optical conversion, O/E: optical-to-electrical conversion).

In this paper a hybrid pulse amplitude modulation (PAM) with SC-FDE system is proposed. This system improves the bandwidth efficiency and inherently reduces the high PAPR compared to previous solutions.

II. Proposed PAM-SC-FDE system

In pulse amplitude modulation (PAM)-SC-FDE system shown in Fig. 1, the generated data sequence is mapped to a multilevel-PAM (M-PAM) constellation symbols. Then, after the addition of the cyclic prefix (CP), the signal is passed to a DAC before modulating the intensity of the optical carrier. At the receiver side, the signal is converted back to digital for further processing. Then, after CP removal, the signal is passed to the fast Fourier transform (FFT) to transfer the data from time to frequency domain for equalization. Then, an inverse fast Fourier transform (IFFT) is used to recover the time domain signal. Finally, the data is recovered after the M-PAM de-mapper.

PAM-SC-FDE unlike P-SC-FDE and RCO-SC-FDE proposes to use PAM mapper instead of quadrature amplitude modulation (QAM) mapper. PAM generates real symbols. Therefore, there is not any need to sacrifice in bandwidth or system complexity to convert the complex signal into real. On the other hand, to insure that the signal is unipolar, the output of the

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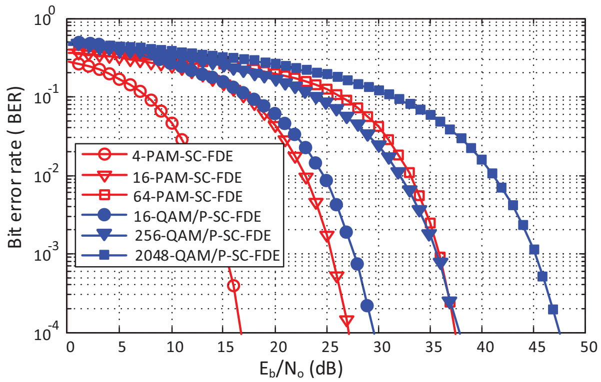

Fig. 2. BER performance of the proposed PAM-SC-FDE versus P-SC-FDE, for different constellation sizes.

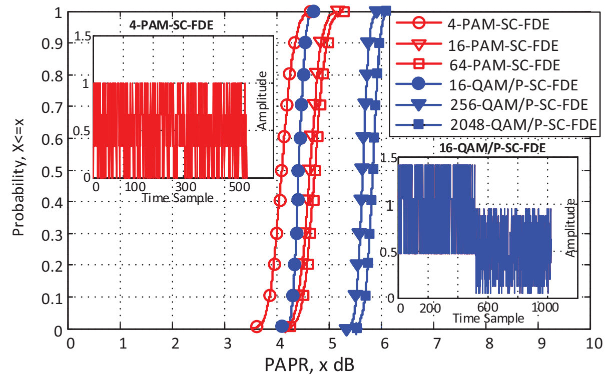

Fig. 3. Cumulative distribution function of the PAPR of the proposed PAM-SC-FDE versus P-SC-FDE, for different constellation sizes.

PAM, which is bipolar, is shifted to the zero level. PAM-SC-FDE utilizes the whole bandwidth as no extra redundant data is add to signal, and the length of the transmitted signal has the same as the signal length at the output of the mapper. In addition, in PAM-SC-FDE small constellation sizes could be used to achieve the same bit rate as in P-SC-FDE. The effective bit rate Rb of both systems (PAM-SCFDE and P-SC-FE) in terms of baud rate Rs is thus given by,

$$R_b\,|_{\text{PAM-SC-FDE}} = \log_2(M) \times R_s\,, \quad (1)$$

$$R_b\,|_{\text{P-SC-FDE}} = \log_2(M) \times R_s/2. \quad (2)$$

The system complexity of PAM-SC-FDE is minimum compared to the previously mentioned systems because of its simple implementation (no extra processing is added to the system compared to original SC-FDE). In terms of PAPR, the signal at the output of the mapper is not modified or further processed as in P-SC-FDE. Therefore, PAM-SC-FDE has fixed envelope transmitted time signal that has lower PAPR compared to other systems, as illustrated in Fig 3.

III. System Performance

The proposed system is evaluated via simulations over an additive white Gaussian noise (AWGN) channel, and then the bit error rate (BER) performance is compared to the recently proposed P-SC-FDE for different modulation orders. The data sequence is generated from a random binary sequence generator with 512 IFFT/FFT size. Perfect synchronization between transmitter and receiver and ideal ADC/DAC are assumed.

The BER performance of PAM-SC-FDE versus P-SC-FDE is shown in Fig 2. For fair comparison between both systems, 4 (2 bits), 16 (4 bits), and 64 (6 bits) PAM in PAM-SC-FDE are compared with 16 (4 bits), 256 (8 bits), and 2048 (12 bits) QAM in P-SC-FDE. This is because the effective bit rate of the proposed system is twice the bit rate of P-SC-FDE. The BER performance of the proposed system is better than P-SC-FDE for the same effective bit rate for all constellation sizes, i.e., for BER = 10-3 and 1.25 Gbaud PAM-SC-FDE gives 13 dB gain in performance compared to P-SC-FDE for 2.5 Gb/s bit rate, and 10 dB for 5 Gb/s and 9 dB for 7.5 Gb/s. This gain in performance is due to the small constellation sizes used to achieve the same bit rat as P-SC-FDE. On the other hand, the simplicity of PAM-SC-FDE and the fixed envelop of the signal waveform (Fig. 3) will lead to a reduction in the PAPR as shown by the cumulative distribution function (CDF) plots in Fig. 3. Indeed PAM-SC-FDE offers, e.g. about 0.5 dB for 4-PAM/16-QAM, reduction in PAPR compared to P-SC-FDE for the same effective bit rate. This reduction becomes higher as the constellation size gets higher.

IV. Conclusion

A new approach that increases bandwidth efficiency and minimizes complexity in optical IM/DD SC-FDE is proposed in this paper. This approach proposes a simple solution to get uinpolar SC-FDE signal suitable for optical communication. This system shows that the BER performance is better than the recently proposed P-SC-FDE. While in terms of complexity and bandwidth efficiency, the proposed system surpasses P-SC-FDE by using simple system implementation and 100% saved bandwidth. In addition, the PAPR is inherently reduced. Therefore, this gives this system an advantage over conventional SC-FDE IM/DD systems.

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