Lattice Precoding for IM/DD POF Interconnects

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Abstract: We introduce lattice precoding (LP) as an improved version of Tomlinson–Harashima precoding (THP) for direct intensity modulation & direct detection (IM/DD) communications over plastic optical fiber (POF). We show that LP offers a significant gain greater than 5 dB over conventional methods for short-range IM/DD SI-POF systems.

OCIS codes: (060.4510) Optical communications, (060.1660) Coherent communications, (060.4080) Modulation.

1. Introduction

A short-range multimode optical communications system based on plastic optical fiber (POF) has various applications including automotive, industrial, and home optical networks. The POF system is low cost and easy to install, partly due to its large core diameter, and typically use light-emitting diodes (LEDs), not laser diodes (LDs). Most systems use step-index (SI) fiber, although graded index (GI) is also available. In automotive applications, media oriented systems transport (MOST) is a popular standard. The maximum datarate for current systems is 150 Mbps, while theoretical capacity on SI-POF can reach 5 Gbps at 50 m distance [6]. Since it was foreseen that 100 Gbps would be needed by 2020, several research projects, e.g, POF-ALL [1] and POF-PLUS [2], investigated increasing beyond 150 Mbps.

To increase datarates, the linear equalizer (LE) [3], decision feedback equalizer (DFE) [4], and maximum-likelihood sequence equalizer (MLSE) [5] have been intensively investigated. Variants of discrete multitone (DMT) have also been studied [6–9]. The DMT can reduce the equalization complexity via frequency-domain processing, and have more degrees of freedom in bit and power loading for each tones to exploit the frequency selectivity of POF channels. However, DMT has the drawbacks of non-negligible overhead due to cyclic prefix and large peak-to-average power ratio (PAPR). Higher PAPR directly degrades the system performance in IM/DD transmission because the effective signal-to-noise ratio (SNR) is inversely proportional to PAPR due to the non-negativity for the optical intensity modulator [4]. To reduce PAPR, spread DMT has been used [10, 11]. Other major approaches include carrier-less amplitude and phase (CAP) modulation [12, 13] and Tomlinson–Harashima precoding (THP) [14, 15]. Using THP, no equalization is necessary at receiver, and better performance than DFE can be achieved since no error propagation occurs. In addition, modulo operation of THP is suitable for IM/DD systems since the constellation will be self-bounded.

In this paper, we extend the THP to realize lower PAPR as well as pre-equalization by introducing lattice precoding (LP), which is also known as vector perturbation (VP) [16]. We show that LP can significantly improve the THP performance by greater than 5 dB in SI-POF channels, due to additional degrees of freedom to select better lattice points, which are modulo-invariable.

2. IM/DD POF Channels

Fig. 1 shows the optical IM/DD transmission systems. A regular M-ary pulse amplitude modulation (MPAM) is used at a baud rate of 500 MBd. We assume a resonant cavity (RC) LED at a wavelength of 650 nm, a nominal launch power of $P = -3$ dBm, a numerical aperture of 0.34, and a cutoff frequency of 150 MHz for the optical IM transmitter. We consider SI-POF with a length of $L = 25$ m and an attenuation of $\alpha = 140$ dB/km. For the DD receiver, we assume a photo diode (PD) with trans-impedance amplifier (TIA) having a noise equivalent power (NEP) of 16 pW/Hz$^{1/2}$ and a cutoff frequency of $f_{\mathrm{rx}} = 1$ GHz. System parameters are similar to [4]. We use a Gaussian filter model, which provides the lower-bound capacity [4] and is widely used in MOST [14], for SI-POF channels. The impulse response is expressed as $h(t) \propto \exp\{-(t-\tau L)^2/2\sigma^2\}$, where $\sigma = 0.132/B$ is a pulse width with $B = 1.009 \cdot L^{-0.8747}$ GHz being a channel bandwidth, $\tau = 4.97$ ns/m is a propagation delay, and L is a fiber length in meters. Note that the channel bandwidth is inversely near-proportional to the fiber length, resulting in more severe inter-symbol interference (ISI) incurred at longer distances. For a POF length of 25 m, the channel bandwidth is $B \simeq 60$ MHz, which is much lower than the baud rate, and therefore we need to deal with very high levels of ISI. To do so, we adopt LP [16], which can pre-equalize the ISI at the transmitter side (thus, no equalization is required at the receiver side), and also reduce the PAPR to improve the SNR. For IM/DD systems, the receiver SNR and PAPR are related as follows [4]:

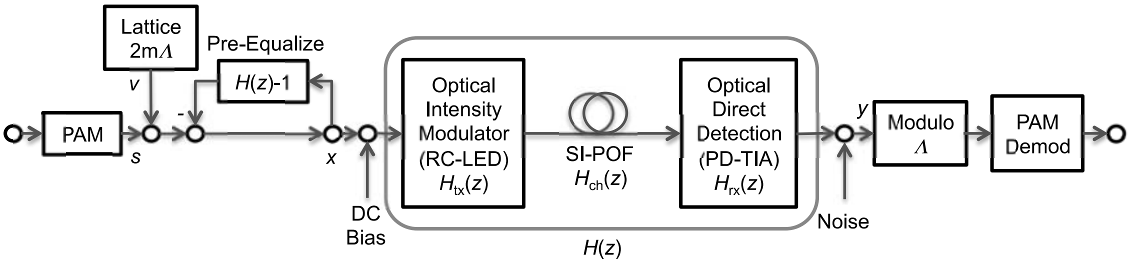

Fig. 1: Optical IM/DD short-range transmission systems with LP.

$\mathsf{SNR} = \alpha^2 P^2/(\mathsf{PAPR}\cdot\mathsf{NEP}^2\cdot f_{\text{rx}})$. When PAPR is 9 dB, the SNR is about 43 dB for the system parameters listed above. In consequence, any PAPR reduction directly provides an SNR gain.

3. Lattice Precoding (Vector Perturbation) for Joint Pre-Equalization and PAPR Reduction

In Fig. 1, a schematic of LP [16] (which is an extended version of THP [15]) is illustrated. At the transmitter, PAM-modulated symbols s are pre-equalized by a feedback filter of $H(z)-1$ so that the output of the channel $H(z)$ will be ISI-free. The main drawback of such zero-forcing pre-equalization lies in the fact that the channel input symbols x can have a very large amplitude (and thus energy inefficient) because of the channel frequency selectivity. To restrict the amplitude of pre-equalized symbols x, THP uses modulo operators at both transmitter and receiver. The transmitter modulo operator causes symbol amplitudes to be bounded within $-\Lambda$ and Λ before the channel input. The modulo operator at the transmitter is equivalent to the addition of unique lattice symbols $v \in 2m\Lambda$ (m is an integer) into the PAM symbols s. At the receiver, the noisy channel output y is fed into the receiver modulo operator (without any equalization), which can auto-cancel any lattice points added at the transmitter, and then to a standard demodulator. For THP, the lattice point (or, corresponding integer value m) is uniquely determined such that the pre-equalized symbols x are Λ-bounded. However, it should be noted that any other lattice points are invariant after the receiver modulo operator. In other words, there are infinite degrees of freedom to choose the lattice perturbation vector v in LP, in comparison to the conventional THP. This additional degree of freedom for LP can give us a great opportunity refining the channel input x to be in favor of the system, for example, minimizing PAPR. To achieve low PAPR without sacrificing energy efficiency, we first look for 32 lattice survivors having the smallest ℓ_2 norm, and select the best one having the lowest PAPR among the survivors.

4. Simulation Results

Fig. 2 shows the empirical complementary cumulative distribution function (CCDF) of PAPR for 16PAM for the different equalizers. ”Pre-LE” refers to the case where the LE is implemented fully at the transmitter (with no equalization at the receiver) and “Post-LE” refers to the case where the LE is implemented fully at the receiver (with no equalization at the transmitter). It is seen that the proposed LP can reduce the PAPR by 0.3 dB compared to the conventional THP at an outage of 10%. Here, we use $\Lambda = 1.8$ for lattice points. Note that DMT has a large PAPR due to the Gaussianity of summed multitones according to the central limit theorem. In contrast, the PAPR of the post-LE employed at the receiver side is 4 dB lower than the pre-equalization LP method. Although this low PAPR leads to a significant gain in receiver SNR, the bit-error rate (BER) performance is degraded, as discussed below.

Figs. 3, 4, and 5 show BER performance of DMT, post-LE, pre-LE, THP, and LP for 8, 16, and 64PAMs, respectively. Although post-LE had an excellent PAPR characteristic at the transmitter, the required post equalization caused major noise enhancement and its BER performance became comparable to that of pre-LE. It is verified from these figures that the proposed LP performs the best with a significant advantage by greater than 5 dB among other schemes including post-LE, pre-LE, THP, and DMT. Note that we did not use non-uniform bit/power loading for DMT. Correspondingly, the worst frequency channel component contributes to such a poor BER performance. In addition, an additional SNR penalty is incurred by its large PAPR, as shown in Fig. 2.

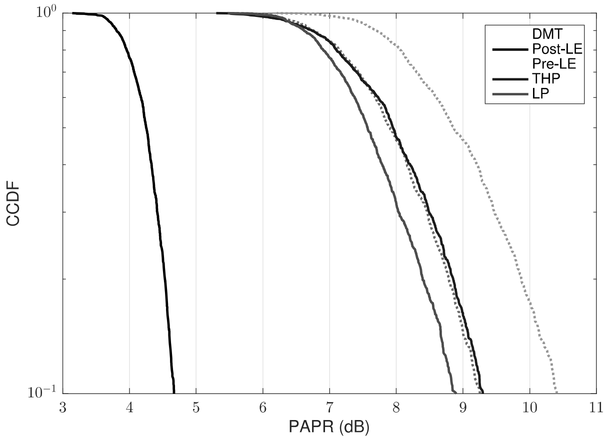

Fig. 2: PAPR performance for 16PAM.

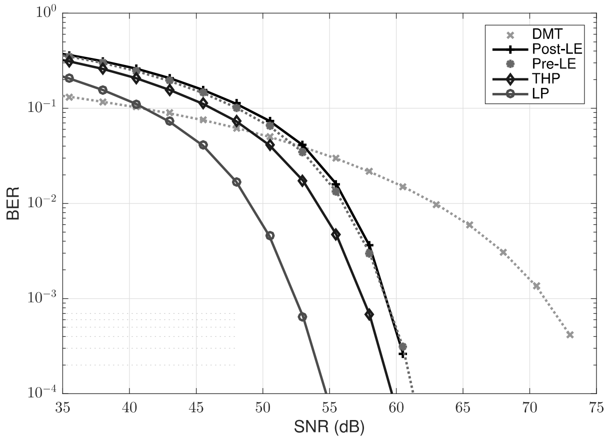

Fig. 4: BER performance for 16PAM.

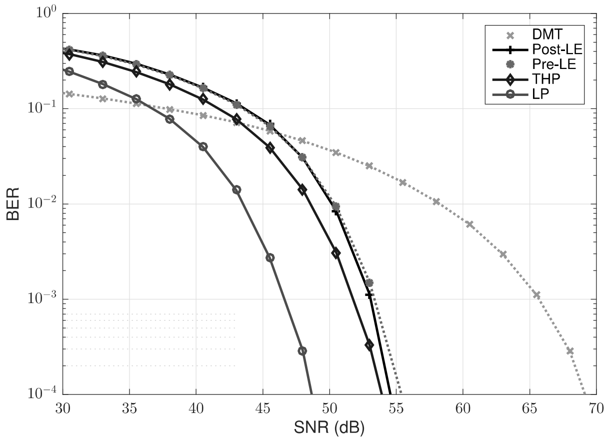

Fig. 3: BER performance for 8PAM.

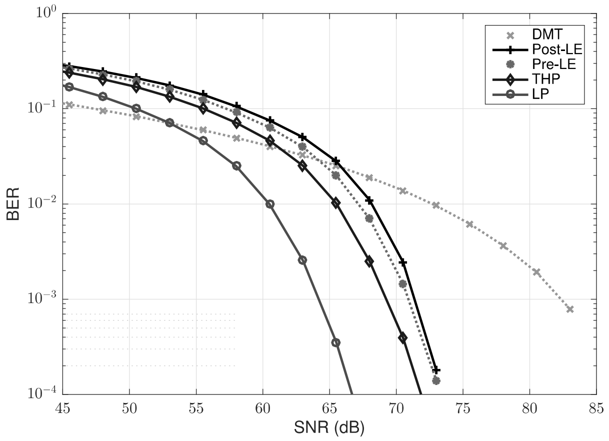

Fig. 5: BER performance for 64PAM.

5. Conclusions

We proposed to use a generalized version of THP, called LP or VP, to improve the BER performance for short-range IM/DD transmissions over SI-POF channels, where severe ISI occurs. LP can pre-equalize the ISI at the transmitter side, and improve the performance of THP by reducing the PAPR at the same time. It was verified that a significant gain of greater than 5 dB is achievable in comparison to LE, THP, and DMT, at an SI-POF distance of 25 m.

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