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Abstract

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Reach Extension with Lattice Precoding for Optical PAM Transmission in Data Center Networks

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Abstract *We apply an improved version of Tomlinson–Harashima precoding (THP), called lattice precoding (LP), to intensity modulation & direct detection (IM/DD) in short-reach optical fiber communications for data center network (DCN). We show that LP offers a significant gain greater than 6 dB over conventional methods and reach expansion by up to 21%.*

Introduction

There have been an increasing interest on the reach extension of low-cost 400-Gb/s optical interconnects, such as 8×56 Gb/s 4-ary pulse-amplitude modulation (4PAM) standardized in IEEE 802.3bs, for the data center network (DCN) applications. For such broadband intensity modulation & direct detection (IM/DD) transmission, we shall deal with bandwidth limitation due to the fiber chromatic dispersion (CD).

Various investigations on anti-CD techniques have been presented to date for short-reach IM/DD systems[1]. For receiver (Rx) side, these include feed-forward (FF) linear equalizer (LE)[2], Volterra-series equalizers[3,4], maximum likelihood sequence estimation (MLSE)[5–8], and neural network equalizers[9,10]. For transmitter (Tx) side, discrete multitone (DMT)[11–13], carrier-less amplitude & phase (CAP) modulation[14,15], and Tomlinson–Harashima precoding (THP)[16] were investigated. The authors introduced an improved version of THP, called lattice precoding (LP)[17] or vector perturbation (VP), for plastic optical fiber (POF).

In this paper, we investigate the benefit of LP in DCN networks to evaluate the anti-CD performance in standard single mode fiber (SSMF) instead of POF. We show that LP can significantly improve the THP performance by greater than 2 dB in DCN channels, due to additional degrees of freedom to select better lattice points, which are modulo-invariant. It is also shown that the LP can extend the reach by up to 21%.

IM/DD PAM Transmission

We consider a regular M-ary PAM transmission at a baud rate of 30 GBd. We assume a laser diode (LD) at a wavelength of $\lambda = 1550.3$ nm, a launch power of $P = 6.3$ dBm, and a cutoff frequency of $f_{\rm tx} = 40$ GHz for the optical Lithium-Niobate (LN) modulator. We use SSMF with an attenuation of $\alpha = 0.2$ dB/km and a CD parameter of $D = 16$ ps^2/km. For the Rx, 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 $f_{\rm rx} = 32$ GHz. For simplicity, we assume that the transfer function of LN modulator and PD detector can be modeled by a first-order low-pass filter as $H_{\rm tx}(f) = (1 + \jmath f/f_{\rm tx})^{-1}$, where f is a frequency and $\jmath = \sqrt{-1}$ is an imaginary unit. Both Tx and Rx use root-raised-cosine (RRC) pulse shaping filter $H_{\rm rrc}(z)$, with a role-off factor of 10%.

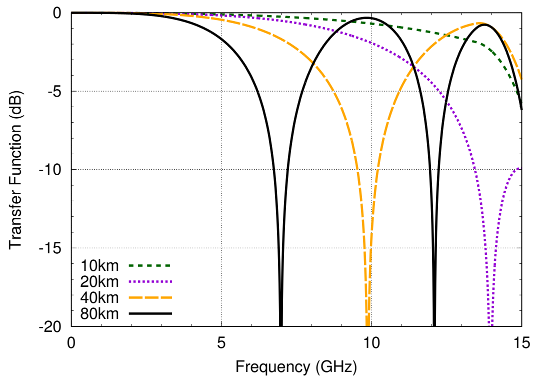

Fig. 1: Transfer function $|H(f)|$ of 30 GBd IM/DD transmission for SSMF lengths of $L \in \{10, 20, 40, 80\}$ km.

In the presence of CD, the transfer function of fiber channels can be expressed for IM/DD systems as follows[16]: $H_{\rm ch}(f) = \cos\big(L(2\pi f)^2\beta_2/2\big)$, where L is a fiber length and $\beta_2 = -D\lambda^2/2\pi c_0$ is a CD coefficient (c_0 is the speed of light). Fig. 1 illustrates the transfer function $|H(z)|$ of the IM/DD systems, where $H(z)$ includes all linear impacts through LN modulator $H_{\rm tx}(z)$, SSMF channel $H_{\rm ch}(z)$, and PD $H_{\rm rx}(z)$ as well as RRC pulse shaping $H_{\rm rrc}(z)$. Note that the channel bandwidth $B_{\rm w}$ (until the first fading occurs such that $|H_{\rm ch}(B_{\rm w})| = 0$) is inversely proportional to the fiber length L, resulting in more severe intersymbol interference (ISI) at longer distances. For $L = 80$ km, the channel bandwidth will be $B_{\rm w} \simeq 6.98$ GHz, which is much lower than the

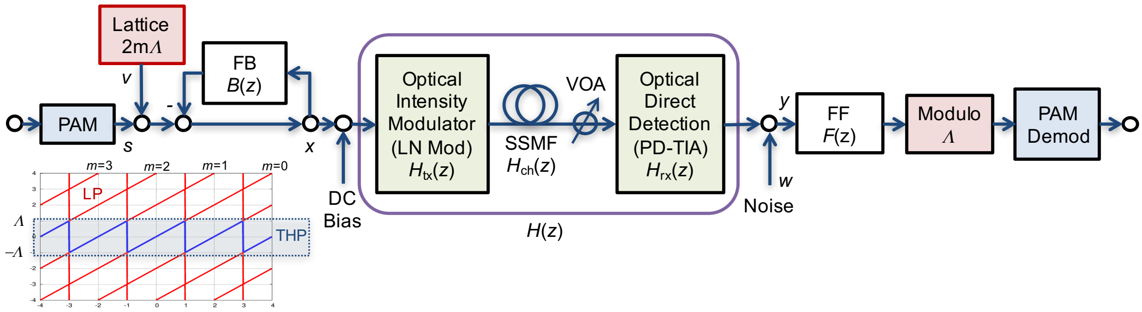

Fig. 2: Optical IM/DD short-reach transmission systems with LP, which allows more degrees of freedom than THP.

baud rate of 30 GBd, and therefore we need to deal with very high levels of ISI. To do so, we adopt LP[17], which can pre-equalize the ISI at the Tx side (thus, no complicated equalization such as MLSE is required at the Rx side).

Lattice Precoding (Vector Perturbation)

In Fig. 2, a schematic of LP[17] (which is an extended version of THP[16]) is illustrated. At the Tx, PAM-modulated symbols s are pre-equalized by a feedback (FB) filter of $B(z)$ so that the receiving signals through the channel $H(z)$ and FF filter $F(z)$ will be ISI-free. The pre-equalized signal x and channel output y are expressed as $x(z) = (1 + B(z))^{-1}s(z)$ and $y(z) = H(z)x(z) + w(z)$ in z-transform, where w is an effective noise. When we use $B(z) = H(z) - 1$, we can realize ISI-less environment even without the FF filter $F(z)$, so that the Rx complexity can be minimized. However, such zero-forcing pre-equalization does not perform best in general. The optimal FB and FF filters are derived via minimum mean-square error (MMSE) criterion[16]. Even with MMSE, one remarkable drawback of such pre-equalizations lies in the fact that the channel input symbols x can have a very large amplitude (and thus energy inefficient) because of the inverse nature of frequency selective channels caused by CD.

To restrict the amplitude of pre-equalized symbols x, THP uses modulo operators at both Tx and Rx. The Tx modulo operator limits symbol amplitudes as $|x| \leq \Lambda$ before the channel input. It is well-known that the modulo operator at the Tx is equivalent to the addition of lattice symbols $v \in 2m\Lambda$ (m is an integer) into the PAM symbols s, as shown in Fig. 2. At the Rx, the noisy channel output y is fed into FF filter followed by the Rx modulo operator, which can auto-cancel any lattice points v added at the Tx, and then to a standard PAM demodulator.

For THP, the lattice point (or, its integer m) is uniquely determined such that the pre-equalized symbols x are Λ-bounded: $|x| \leq \Lambda$. However, notice that any other lattice points are invariant after the Rx 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 flexibility for LP can give us a great opportunity refining the channel input x to be in favor of the system, for example, minimizing peak-to-average power ratio (PAPR)[17] or maximizing the energy efficiency. We use sphere detection with 32 survivors to search for the best lattice points having the smallest ℓ_2 norm: $\min_{\boldsymbol{m}\in\mathbb{Z}^N} \|(\boldsymbol{I} + \boldsymbol{B})^{-1}(\boldsymbol{s} + 2\Lambda\boldsymbol{m})\|_2^2$, where $\boldsymbol{I}$, $\boldsymbol{B}$, $\boldsymbol{s}$, and $\boldsymbol{m}$ are identity matrix, matrix representation of FB filter $B(z)$, the PAM sequence, and the lattice integers, respectively, for a block length of N symbols. Note that this paper assumes sufficient back-off of 12 dB for LN modulator bias so that high linearity for IM can hold irrespective of PAPR. Hence, we consider only ℓ_2 norm minimization unlike the previous work[17], which minimizes joint ℓ_2 and ℓ_∞ norms.

Simulation Results

We assume hard-decision forward error correction (FEC) codes based on Reed–Solomon, whose required pre-FEC bit-error rate (BER) is 10^{-3} or 2×10^{-2} for an overhead of 7% and 20%, respectively. For performance evaluation, we consider system margin of an optical signal-to-noise ratio (OSNR) to achieve the target pre-FEC BER. For simplicity, we do not consider hardware impairments such as linewidth, jitters, nonlinearity, quantization noise, etc. for LD, LN demodulator, and PD. We use $\Lambda = 1.8$ for lattice points.

Fig. 3 shows the BER performance as a function of OSNR relative to the system budget at a launch power of $P = 6.3$ dBm, for 4PAM transmission over an SSMF length of $L = 60$ km. Note that a region requiring OSNR higher than the system budget is an infeasible zone for reliable transmission. For example, the conventional LE has no margin at a 7% FEC limit, whereas 3.4 dB margin is achieved by LP. Higher FEC overhead allows

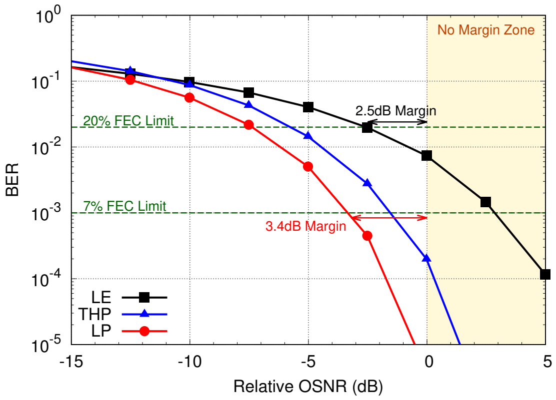

Fig. 3: BER vs. OSNR relative to system budget for 4PAM in $L = 60$ km.

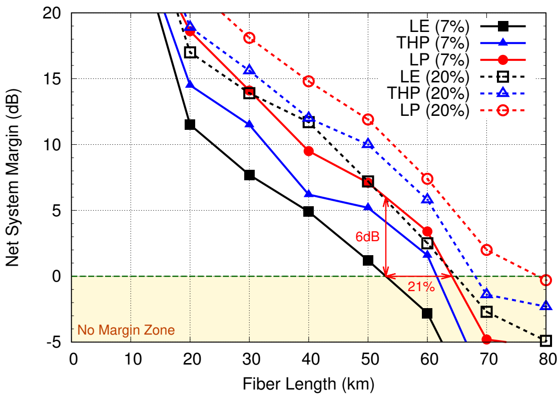

Fig. 4: Net system margin vs. fiber length L for 4PAM.

higher system margin; e.g., LE will achieve 2.5 dB margin with 20% FEC. One can see that THP offers higher margin than LE, and more importantly LP achieves further improvement.

In Fig. 4, we plot the net system margin as a function of the fiber distance L. It is observed that the system margin is nearly proportional to the fiber distance for $L \geq 15$ km, around which the frequency fading causes stronger ISI[16] because the bandwidth B_w becomes less than the baud rate as shown in Fig. 1. Within the system power budget, the conventional LE may be able to reach up to 53 km, whereas the LP can expand the reach by 21% due to the improved margin by approximately 6 dB.

Conclusions

We proposed to use an extended version of THP, called LP, to improve the BER performance for short-range IM/DD PAM transmissions over SSMF channels for DCN communications. LP can pre-equalize the ISI at the Tx side, and improve the energy efficiency compared to THP. It was verified that a significant gain of greater than 6 dB is achievable in comparison to LE, leading to a 21% reach extension from 53 km to 64 km.

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