Trellis Shaping-based Sequence Selection for Inter-datacenter Single-Span Links

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Abstract: We propose trellis shaping technique to implement sequence selection for fiber nonlinearity mitigation in inter-datacenter single-span link. A gain in AIR of 0.2 bits/4D-symbol compared with MB shaping is achieved experimentally over a five-channel 80-km fiber link.

1. Introduction

Single-span links covering distances of 80-120 km at high data rates have become increasingly popular due to the growing demand for inter-data-center networks in the future [1]. To further improve the data rate, probabilistic amplitude shaping (PAS) techniques have been utilized by adjusting the probability distribution of transmitted signal amplitudes. The benefits of PAS techniques in the linear regime have been extensively studied using various shaping schemes [2]. Recently, research has shifted towards shaping architectures that can mitigate fiber nonlinearity by considering the effects of both linear and nonlinear noise in the fiber link.

Several techniques have been proposed to reduce the fiber nonlinear noise after PAS techniques, such as Huffman-coded sphere shaping [3], generalized Maxwell-Boltzman-based constant composition distribution matching (GMB-CCDM) [4], enumerative sphere shaping [5] and sequence selection scheme [6]. Among these techniques, sequence selection scheme can provide best performance by selecting ”good sequences” for transmission. The implementation of sequence selection bases on bit scrambling have been demonstrated in simulation to provide a nonlinear shaping gain of 0.24 bits/s/Hz. However, the scheme assumes the random-selection bit sequence is fixed and known to the receiver, which is less practical in the realistic transmission systems.

In this paper, we propose to use trellis shaping [7] to select the good sequences for fiber transmission. The selected bit sequences are the codeword of the given convolutional code, which are not necessarily known at the receiver side, providing a more practical way to map information bits on good sequences. We also conduct an experiment in a five-channel wavelength division multiplexing (WDM) transmission system over 80-km standard single-mode fiber (SSMF) employing dual-polarization 64-ary quadrature amplitude modulation (DP-64QAM) at 60 GBaud. A gain in achievable information rate (AIR) of 0.2 bits/4D-symbol compared with ideal MB distribution at spectral efficiency of 10 bits/4D-symbol is achieved.

2. Principle of Trellis Shaping for Fiber Nonlinearity Mitigation

The encoder and decoder principle of trellis shaping based on sign-bit scheme is shown in Fig. 1(a). The convolutional code $\mathbb{C}$ has a code rate of 1/2 with 1×2 generator matrix of $\mathbf{G}$. $\mathbf{H}^T$ and $(\mathbf{H^{-1}})^T$ represent the 2×1 parity check matrix and the corresponding 1×2 left inverse matrix of the convolutional code $\mathbb{C}$. We consider a uniform distributed modulation format with n bits per symbol, which contains $(n-1)$ least significant bits (LSBs) and 1 most significant bit (MSB). The encoder process is described in Fig. 1(a). The MSB sequence b is encoded by a 1-input, 2-output encoder, which is represented by matrix $(\mathbf{H^{-1}})^T$. Then the sign-bit sequence is a sequence of binary 2-tuples, given by $\mathbf{x} = \mathbf{b}(\mathbf{H^{-1}})^T$. Next, a Viterbi decoder is performed to find the sign-bit sequence z in the coset $\mathbb{C}\oplus\mathbf{x}$, which satisfy certain metric. It is noted that the the MSB sequence b is unchanged when the output sequence x is modulo-2 added to any valid codeword y in $\mathbb{C}$. The decoder process is also shown in Fig. 1(a), where the received sequence r is also separated into LSB and MSB sequences. The LSB sequence is first demodulated. The MSB sequence is then passed through a 2-input,1-output matrix $\mathbf{H}^T$ to obtain the MSB.

Fig. 1(b) show the constellation mapping of the sign-bit trellis shaping scheme based on 64QAM format. It is noted that the MSB sequence is used to select the quadrant based on the 2-tuples binary structure. The LSB sequence is encoded based on Gray mapping scheme in one quadrant to maximize the generalized mutual information (GMI), as shown in Fig. 1(c). It is noted that the decoding message of LSB sequence can be used to decode the MSB sequence, which is similar as the multi-level coding/multi-stage decoding (MLC/MLD) scheme.

The concept heart of the trellis shaping is that a metric can be designed to optimize the transmission performance under certain channel conditions. In this paper, we evaluate the metric in two ways. The first one is to transmit the candidate sequences along the fiber link and then calculate the GMI as the metric, which we call “fiber model”. The second one is to use the perturbation model to describe the fiber link and then evaluate the GMI of the candidate sequences based on the calculated perturbation terms and coefficients.

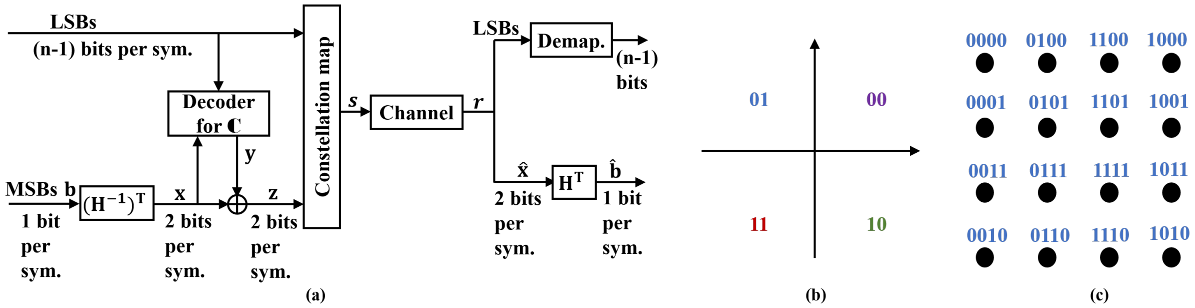

Fig. 1. (a) Sign bit shaping scheme using the rate-1/2 convolutional code ℂ, constellation mapping for 64QAM (b) MSB and (c) LSB.

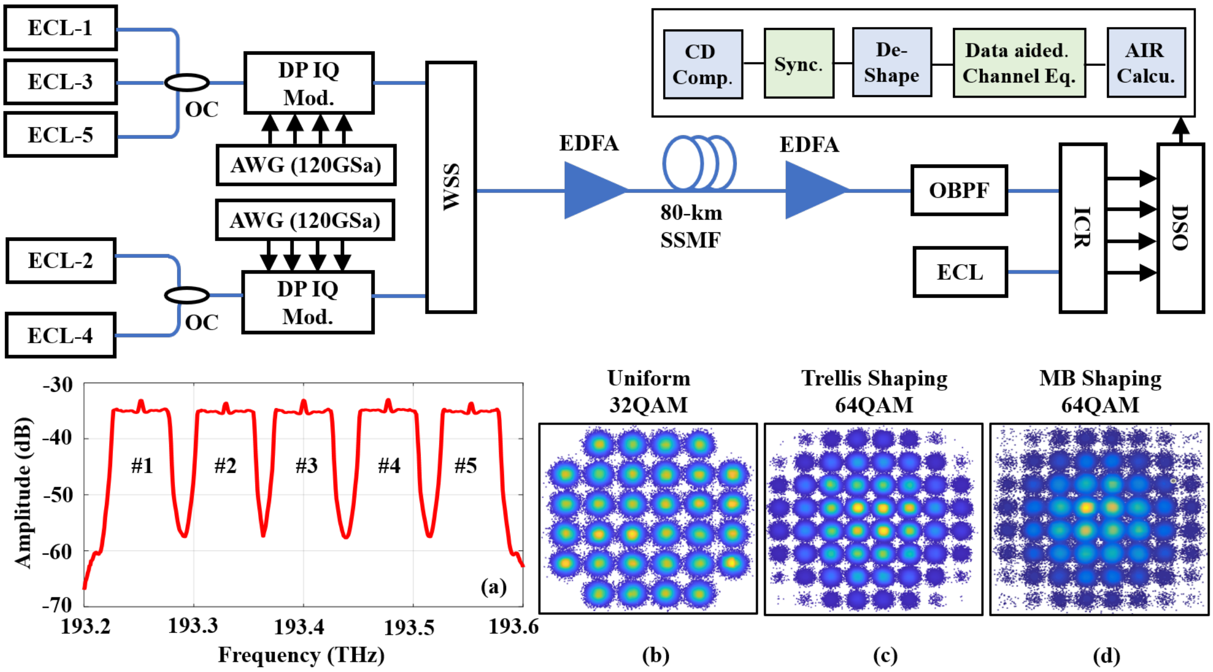

Fig. 2. Experimental setup of 45GBaud DP-64QAM transmission system. Insets: (a) Signal spectrum, (b) Uniform constellation, (c) Trellis shaping constellation, (d) MB shaping constellation.

3. Experimental Setup

We conduct an experiment to evaluate the effectiveness of the proposed sequence selection scheme, as shown in Fig. 2. A 60 Gbaud 64QAM signal waveform is generated offline, with pulse-shaping roll-off factor of 0.01. The digital signal is then up-sampled and loaded to an arbitrary waveform generator (AWG, Keysight 8194A) operating at 120 GSa/s to achieve digital-to-analog conversion. The four analog signals are launched to a dual-polarization optical IQ modulator to achieve electrical-to-optical conversion via five external cavity lasers (ECLs) spacing at 75 GHz. The five channel optical signals are separated into two groups and then combined by a wavelength selective switch (WSS). The optical spectrum of the five-channel optical signal is also shown in Fig. 2(a). An erbium-doped fiber amplifier (EDFA) is used to control the power of the optical signal, which is then launched into the fiber link and transmitted over 80-km SSMF. After fiber transmission, the optical signal is first amplified by another EDFA and the central channel is selected by an optical bandpass filter (OBPF). The filtered optical signal is then detected by a standard integrated coherent receiver (ICR) to achieve the optical-to-electrical conversion. The electrical signal is finally digitized by a 50 GHz digital storage oscilloscope (DSO, Keysight Infiniium UXR) operating at 256 GSa/s for further offline DSP.

The offline DSP is also shown in Fig. 2. In the experimental demonstration, chromatic dispersion (CD) compensation is first performed, followed by time/frequency synchronization. After pulse deshaping, the signal is resampled to 2 samples per symbol. Next, real-value decision-directed least-mean square (DD-LMS) channel equalization is performed in fully data-aided mode. Finally, the AIR is calculated over approximately 1×10^7 symbols. MB shaping with block length of 1000 and uniform signaling are also investigated. For fair comparison, the MB distribution of $[0.5372, 0.322, 0.115, 0.0249]$ and 32QAM format are applied, resulting in a spectral efficiency of 5 bits/s/Hz, which is the same as trellis shaping 64QAM signal. Constellation diagrams for uniform signaling, MB shaping and trellis shaping in back-to-back condition are shown in the insets (b)–(d) of Fig. 2.

The number of selected sequence is set to 128 in the experimental demonstration, corresponding to the number of candidate sequence y in Fig. 1. The fiber model is computed via split-step Fourier method with parameters of attenuation α = 0.2 dB/km, CD coefficient D = 17.0 ps/nm/km and nonlinear coefficient γ = 1.3 1/W/km. The recovered sequence with largest AIR is chosen to transmit in the experimental test bed. The perturbation model [8], however, is obtained by first transmitting uniformly 32QAM signal over the fiber link and then computing the nonlinear perturbation coefficients $C_{m,n}$ based on the perturbation term $\Delta u_{x/y}$ as:

$$\Delta u_{x/y} = \sum_{m,n} \left(H_n H^*_{m+n} H_m + V_n V^*_{m+n} H_m \right) C_{m,n}, \tag{1}$$

where H_m and V_m are the symbol sequences for the x- and y-polarization. Finally, the perturbation model is used to choose the good sequence for fiber transmission in the experimental demonstration.

4. Results and Discussion

The effective signal-to-noise ratio (SNR) versus power per channel is shown in Fig. 3(a). It is observed that trellis shaping has the highest effective SNR, which is 1.1 dB higher than MB shaping 64QAM at the corresponding optimal launch power. It is noted that the optimal launch power of trellis shaping is 1 dB larger than MB shaping 64QAM indicating better fiber nonlinearity tolerance. Taking AIR for consideration, it can be seen in Fig. 3(b) that at the optimal launch power of 10 dBm, trellis shaping 64QAM provides 0.20 bit/4D-sym AIR gains over MB shaping 64QAM. The performance of fiber model is a little better than that of perturbation model. Next, Fig. 3(c) shows the effect of number of tested sequences. It is shown that 256 tested sequences are sufficient for trellis shaping scheme to provide the optimal performance in two models.

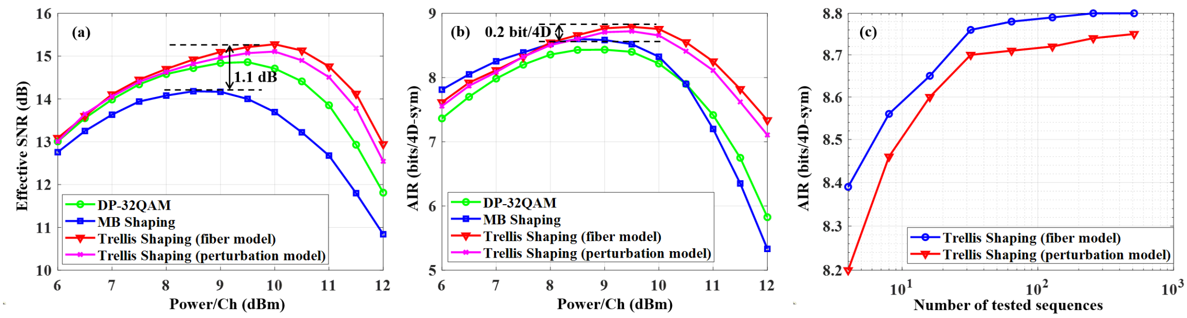

Fig. 3. Performance versus launch power for 80-km SSMF link: (a) Effective SNR in dB, (b) AIR in bits/4D, and (c) AIR versus number of tested sequences.

5. Conclusion

We propose trellis shaping-based implementation of sequence selection in the inter-data-center single-span fiber transmission link without knowing the candidate sequence at the receiver side. The experimental results indicate the proposed scheme can provide 0.2 bit/4D-sym gain over MB shaping, indicating trellis shaping can effectively select the good sequence in the fiber transmission systems.

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