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Orthogonal Matching Pursuit based Sparse Nonlinear Equalization for 40-Gb/s/wavelength Long-Reach PON

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Abstract: We propose to use an orthogonal matching pursuit based sparse nonlinear equalization (OMP-SNE) for 40-Gbit/s OFDM-IM-DD long-reach PON over 60-km SSMF. Compared with conventional NE, the number of coefficients utilizing OMP-SNE is reduced by 63%.

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1. Introduction

As the rapid growth in data consumption by broadband access subscribers, the bandwidth bottleneck gradually shifts to the metro and the last-mile traffic [1]. Intensity modulation and direct detection (IM-DD) based orthogonal frequency-division multiplexing (OFDM) long-reach passive optical network (PON) has been considered as one of the promising candidates to economically built the low-cost, high-capacity and wide-coverage access networks [2-4]. In order to compensate the nonlinear distortions resulting from electro-optic modulation, fiber nonlinearity, etc., as well as improve the system power budget and performance, the Volterra series based nonlinear equalization (NE) has been introduced to the OFDM-IM-DD long-reach PONs [3,4]. However, in the conventional Volterra series based time-domain NE algorithms, the number of coefficients grows exponentially with the memory length, which leads to high complexity (i.e., proportional to the number of coefficients) and thus increase the system cost and power consumption [3,4]. Since the coefficient distribution in NE reveals sparsity [5,6], it is feasible to use a time-domain sparse nonlinear equalization (SNE) with much lower complexity. In this paper, an orthogonal matching pursuit based SNE (OMP-SNE) is proposed to use and experimentally demonstrated for compensating the nonlinear distortions in the OFDM-IM-DD LR-PONs with high optical power launched to the fiber.

2. Orthogonal Matching Pursuit based Sparse Nonlinear Equalization

In the truncated 3rd-order Volterra series based NE [3,4], the n^{th} sample of the output equalized signal is given by

$$y(n)=\sum_{k_1=0}^{N-1} h_1(k_1)r(n-k_1)+\sum_{k_1=0}^{N-1}\sum_{k_2=k_1}^{N-1} h_2(k_1,k_2)r(n-k_1)r(n-k_2)+\sum_{k_1=0}^{N-1} h_3(k_1)r^3(n-k_1) \quad (1)$$

where $r(n-k_i)$ is the $(n\text{-}k_i)^{th}$ sample of the received signal corrupted by nonlinear distortion, $h_b(k_1,k_2,...k_b)$ is coefficients of the b^{th}-order term, and N is the memory length. Consider M-point training sequence $y(n)$ is transmitted with $n=0,1,\cdots,M-1$ before data transmission in each frame, the received training sequence $r(n)$ after NE based on Eq. (1) can be written in a matrix form as

$$\mathbf{y}=[y(0),y(1),\cdots,y(M-1)]^T=\mathbf{Ah} \quad (2)$$

where $\mathbf{A}$ and $\mathbf{h}$ are $M\times L$ measurement matrix and $L\times 1$ coefficient vector ($L=(N^2+5N)/2$) of the nonlinear equalizer, respectively, defining as $\mathbf{A}=[\boldsymbol{\alpha}_1,\boldsymbol{\alpha}_2,\cdots,\boldsymbol{\alpha}_L]$ and $\mathbf{h}=[h_1(0),h_1(1),\cdots,h_1(N-1),h_2(0,0),h_2(1,1),\cdots,h_2(N-1,N-1),$ $h_2(0,1),h_2(1,2),\cdots,h_2(N-2,N-1),\cdots,h_2(0,N-1),h_3(0),h_3(1),\cdots,h_3(N-1)]^T$. Since the important coefficients of NE are sparse [5,6], here the OMP algorithm [6,7] is performed for coefficient estimation of the nonlinear equalizer with P nonzero coefficients before SNE. The OMP-SNE algorithm for coefficient estimation and SNE is summarized as following: 1) Initialize the residual $\mathbf{b}_0=\mathbf{y}$, the index set $\boldsymbol{\Lambda}_0=\phi$, the matrix of chosen atoms $\mathbf{S}_0=\phi$, and the iteration counter p = 1. 2) Find the index $k_p=\arg\max_l\left|\boldsymbol{\alpha}_l^H\mathbf{b}_{p-1}\right|, l=1,2,\cdots,L, l\notin\boldsymbol{\Lambda}_{p-1}$. 3) Augment the index set $\boldsymbol{\Lambda}_p=\boldsymbol{\Lambda}_{p-1}\cup k_p$ and the matrix of chosen atoms $\mathbf{S}_p=[\mathbf{S}_{p-1},\boldsymbol{\alpha}_{k_p}]$. 4) Solve the least squares (LS) problem $\hat{\mathbf{h}}_p=(\mathbf{S}_p^H\mathbf{S}_p)^{-1}\mathbf{S}_p^H\mathbf{y}$ and update the new residual $\mathbf{b}_p=\mathbf{y}-\mathbf{S}_p\hat{\mathbf{h}}_p$. 5) Increment p, and return to Step 2 if $p<P$. 6) After obtaining the optimal index set $\boldsymbol{\Lambda}=\boldsymbol{\Lambda}_P$ and the coefficients of P-sparse nonlinear equalizer $\hat{\mathbf{h}}(\boldsymbol{\Lambda})=\hat{\mathbf{h}}_P$ using OMP algorithm with training sequence, the received data can be equalized by the P-sparse nonlinear equalizer $\mathbf{y}=\mathbf{A}\hat{\mathbf{h}}(\boldsymbol{\Lambda})$ with much fewer coefficients.

3. Experimental Setup and Results

The experiment setup of the OFDM-IM-DD transmission system based on the proposed OMP-SNE is shown in Fig. 1. The main parameters of the OFDM modulation include 20-point cyclic prefix (CP) and 1024-point inverse fast Fourier transform (IFFT) with effective payload and their complex conjugates encoded at the 2nd to 191st and 1024th to 835th subcarriers, respectively. After hard clipping, the electrical signal is then loaded into an arbitrary waveform generator (AWG) operating at a sample rate of 54-GSa/s to generate the electrical signal with a bandwidth of around 10-GHz. For each transmission, 10 OFDM symbols are used for coefficients estimation before 460 effective symbols. Then the amplified electrical signal is utilized to modulate optical light from a DFB laser at wavelength of 1550.12 nm with coherence control through a 10G-class Mach-Zehnder modulator (MZM), followed by an erbium doped fiber amplifier (EDFA) to enable the launch power of 18-dBm. After 60-km standard single-mode fiber (SSMF) transmission without in-line amplifier and pre-amplifier, an optical receiver consisting of an optical band-pass filter, a variable optical attenuator (VOA) and a photo detector (PD) is used to detect the optical signal. The detected signal is then digitized and stored by a real time oscilloscope (OSC) operating at a sampling rate of 100GSa/s. Finally, off-line DSPs including OMP-SNE and OFDM demodulation are performed.

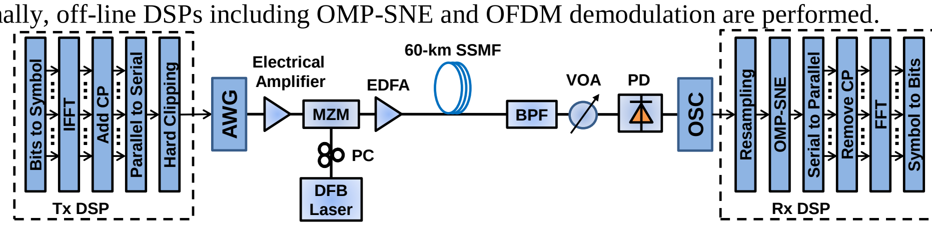

Fig. 2 Experimental setup and DSP block diagram.

The average SNRs at different memory length *N* of the conventional LS-NE [4] after 60-km SSMF transmission are shown in Fig. 3(a). One can see that the SNR of LS-NE improves as the memory length *N* increases and then reaches a saturation value of 20.3 dB at a memory length of 11, which is 3.7 dB higher than that of without NE. The average SNRs at different sparsity level *P* of OMP-SNE with the memory length of 11 are shown at Fig. 3(b). Compared with LS-NE with the memory length of 11, similar average SNR can be achieved for OMP-SNE with the sparsity level of 32, which reduces the number of coefficients by a factor of as much as 63.6% and thus significantly reduces the complexity. The distribution of estimated coefficients by OMP algorithm at the sparsity level of 32 is also shown in Fig. 3(c). Fig. 3(d) shows the measured BER versus received optical power (ROP) using different equalization methods for 40-Gbit/s transmission over 60 km SSMF. To optimize the BER performance, Chow's adaptive bit and power loading algorithm is applied. It can be seen that 7% hard-decision FEC limit of 3.8×10^{-3} can be achieved at the ROP of -9.5 dBm by utilizing the OMP-SNE or LS-NE, resulting in total 27.5 dB loss budget for single wavelength with 18-dBm optical launched power to the fiber.

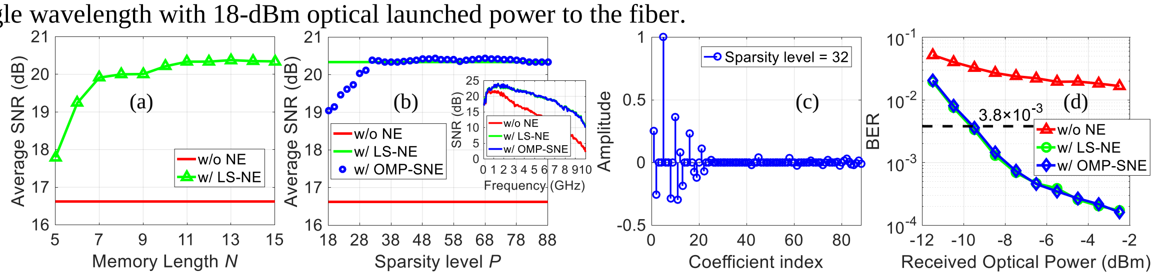

Fig. 3 (a) Average SNR versus the memory length *N* for LS-NE and (b) sparsity level *P* for OMP-SNE after 60-km SSMF transmission (inset: probed SNR curve inside the signal bandwidth at a ROP of -2.5dBm); (c) estimated coefficients by OMP algorithm at a sparsity level of 32; (d) measured BER versus ROP for 40-Gbit/s transmission over 60 km SSMF.

4. Conclusion

In this paper, we have proposed to use and experimentally demonstrated an OMP-SNE for LR-PONs. For a 40-Gbit/s OFDM-IM-DD transmission system over 60-km SSMF, the OMP-SNE has achieved similar performance and reduced the number of coefficients by a factor of as much as 63.6% compared to conventional LS-NE at a memory length of 11.

Acknowledgements

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