SPM and phase-noise cancellation using time-division-multiplexed and intensity-modulated pilot symbols

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Abstract: We propose a novel SPM and phase-noise cancellation scheme using pilot symbols. The pilot symbols are intensity-modulated and time-division-multiplexed with a modulated optical signal. Each pilot symbol has the same optical intensity as the multiplexed modulated symbol and therefore has the same nonlinear phase shift caused by self-phase modulation (SPM). Additionally, each pilot symbol has the same phase noise as the modulated symbol because it is generated by the same laser diode (LD). At the receiver side, self-homodyne detection is performed using the pilot symbols as absolute optical phase references. The performance of the scheme was investigated by numerical simulations of 50-km optical fiber transmission of 16-ary quadrature amplitude modulation (16QAM) signals.

Keywords: nonlinear compensation, pilot carrier, SPM, phase-noise, self-homodyne

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

Multi-level modulation schemes such as 16-ary quadrature amplitude modulation (16QAM) are taking an important role in optical fiber technologies to improve the transmission speed and the spectral efficiency. However, signal degradation due to optical nonlinear effects including self-phase modulation (SPM) is becoming a more serious problem because the signal power of a high-order multi-level modulation signal varies according to the transmitted symbols, resulting in a large peak-to-average-power ratio (PAPR). One attractive method to compensate for such nonlinear effects is digital signal processing (DSP), such as digital back propagation (DBP) and the Volterra series transfer function (VSTF), which can equalize the nonlinear distortion without using additional optical components [1, 2]. However, these nonlinear equalizers using DSP need an enormous amount of calculations, which causes serious time delays and increases the power consumption of the receiver. Phase-conjugated twin wave (PCTW) schemes are drawing attention as a new scheme that can efficiently cancel nonlinear effects without requiring heavy DSP [3]. In this scheme, a phase-conjugated lightwave is multiplexed with a
modulated optical signal by polarization multiplexing or time-division multiplexing (TDM) [4, 5]. In contrast, we have proposed and investigated a polarization-multiplexed pilot-carrier scheme that simultaneously exhibits SPM-tolerant characteristics and a phase-noise cancellation capability [6, 7, 8]. We also proposed a polarization-multiplexed and intensity-modulated pilot-carrier scheme that can completely compensate for the effect of SPM [9]. However, these schemes require polarization tracking, which increases the amount of calculations in the DSP [10]. In this study, we propose a novel pilot-signal scheme, where pilot symbols are time-division-multiplexed with a modulated optical signal [11]. At the receiver side, self-homodyne detection is performed by differential detection using a 1-symbol delay line. The error vector magnitude (EVM) performance was investigated by numerical simulations, and the results confirmed the nonlinear compensation capability. Furthermore, we also demonstrated the phase-noise cancellation capability by changing the linewidth of the light source from 100 kHz to 30 MHz.

2 Principle

Figs. 1(a) and (b) show the scheme of the proposed time-division-multiplexed and intensity-modulated pilot symbols. The lightwave from a laser diode (LD) is return-to-zero (RZ) carved and split into two branches. One is modulated as an RZ multilevel signal. The other one is intensity-modulated only so that it has the same optical intensity as the RZ signal pulse. This intensity-modulated RZ pulse train is used as the pilot symbols, which provides an absolute optical phase reference for self-homodyne detection. The modulated signal pulses and the intensity-modulated pilot symbols are time-division-multiplexed as shown in Fig. 1(a). Fig. 1(b) shows the principle of SPM and phase-noise cancellation. Each intensity-modulated pilot symbol has the same amplitude as the modulated signal.

![Diagram](image_url)  
(a) Time-division-multiplexed and intensity-modulated pilot-symbol.

![Diagram](image_url)  
(b) Compensation of nonlinear distortion and phase-noise.

Fig. 1. Principle of time-division-multiplexed and intensity-modulated pilot symbols.
As a result, the optical phases of the two RZ pulses are identically rotated by SPM, keeping the mutual relative phase angle between them. Furthermore, this relative phase angle does not fluctuate due to the phase-noise of the LD, because the pilot symbol has the same phase-noise as the modulated signal. On the receiver side, self-homodyne is performed by differential detection using a 1-symbol delay line. The influence of SPM and phase noise is compensated for because the pilot symbol has phase noise and nonlinear phase-shift identical to those of the modulated signal. The amplitude of the received signal after the self-homodyne varies according to the square of the intensity of the RZ signals. However, the influence can be cancelled by DSP. Additionally, the differential detection generates unwanted signal pulses caused by self-homodyne with neighboring signal pulses. This influence is also eliminated by DSP.

3 System setup

The performance of the proposed method was evaluated by numerical simulation. Fig. 2 shows a 50-km 16QAM signal transmission system using the time-division-multiplexed and intensity-modulated pilot symbols and self-homodyne detection. The lightwave from an LD was RZ carved into a 10GHz pulse train with a 40% duty cycle. The generated RZ pulses were split into two branches. One was modulated by 10-GSymbol/s 16QAM with PRBS 211-1 data, whereas the other branch was intensity-modulated so that the two branches had the same optical intensity. The modulated RZ pulses and the intensity-modulated pilot-symbols were time-division-multiplexed using a 50 ps delay line and transmitted by a standard single mode fiber (SSMF) and a dispersion compensation fiber (DCF) having a total length of 50 km, thus cancelling the total chromatic dispersion. The dispersions of the SSMF and the DCF were 16.75 ps/nm/km and −77 ps/nm/km, respectively. The transmission through the optical fibers was numerically calculated using the well-known split-step Fourier method. The input power to the optical fiber was adjusted from 0 to 10 dBm. On the receiver side, self-homodyne detection was performed using two 50 ps delay lines for in-phase (I) and quadrature (Q) signal components. Using the same transmission system, we also performed conventional homodyne detection without the pilot symbols for comparison. Here, we assumed an ideal local oscillator with an optical power of 10 dBm, which was ideally synchronized to the optical signal. The noise figure of the Er-doped fiber amplifiers
(EDFAs) was 3 dB. The linewidth of the LD was varied between 100 kHz and 30 MHz in order to confirm the phase-noise cancellation capability. The signal quality was evaluated by EVM.

4 Results and discussion

Fig. 3(a) shows the constellation of the received signal using conventional homodyne detection without pilot symbols in a back-to-back (BtB) condition. Fig. 3(b) shows the constellation of the homodyne detection after the transmission with an input optical power of 10 dBm. The received optical power was −15 dBm. The linewidth of the LD was 100 kHz. The 16QAM signal was seriously distorted by SPM. However, when we employed the detection using the intensity-modulated pilot symbols, the EVM performance was dramatically improved by the SPM cancellation capability of the proposed scheme, as shown in Fig. 3(c). Figs. 3(d)

Fig. 3. Results of numerical simulations.
and (e) show EVM characteristics versus received optical power of the conventional homodyne scheme and the proposed self-homodyne scheme, respectively. Here, the received optical power includes those of both the modulated signal and the pilot symbols. In the case of conventional homodyne, when we increased the input power to 10 dBm, EVM was degraded to 35% or worse due to the waveform distortion caused by SPM. In the case of the proposed self-homodyne, however, the EVM penalty was only less than 3%, even when we increased the input power from 0 dBm to 10 dBm. Furthermore, even when we used an LD with a linewidth of as large as 30 MHz, the same compensation performance was observed, as shown in Fig. 3(f). We plotted the EVM performance of the 16QAM signals versus the linewidth of the LD in Fig. 3(g). However, we could not observe any significant degradation of the performance even at a linewidth of 30 MHz.

5 Conclusions

A novel intensity-modulated pilot-symbol scheme was proposed. Numerical simulations showed the SPM compensation characteristics of the proposed scheme. The results also verified the phase-noise cancellation capability of the scheme, which will be necessary to realize future ultra-multi-level QAM transmission technology [12].