Optics Communications 428 (2018) 169–175

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Semi-analytic modeling of FWM noise in QAM Nyquist-WDM system with phase-conjugated twin waves

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ARTICLE INFO

Keywords:
Nyquist-WDM
QAM
Four-wave mixing
Phase-conjugated twin waves

ABSTRACT

Nonlinear models previously reported for coherent optical fiber transmission have been used to explain the mechanism of nonlinear noise squeezing by phase-conjugated twin waves (PCTW) scheme, but the reduction of four-wave-mixing (FWM) noise by the nonlinearity mitigation method cannot be directly derived from these models for a quasi-symmetric dispersion map, especially when the effect of walk-off between channels is included. Semi-analytic models based on a statistical method are derived herein order to quantify the reduction of FWM noise for quadrature amplitude modulation (QAM) PCTW Nyquist-WDM systems. Our models derived here show that the variance of non-degenerate FWM noise is irrelevant to the number of signal points within a QAM constellation diagram, as is different from the degenerate FWM case. Numerical results by using our models show that even though the effect of walk-off is included, the PCTW scheme is still greatly effective to reduce the impact of FWM noise for a quasi-symmetric map. The performances of central channel for two cases of 16QAM PCTW Nyquist-WDM systems with same total spectral bandwidth and spectral efficiency, 16-channel 32-Gbaud/ch and 32-channel 16-Gbaud/ch, are numerically compared by using our models

1. Introduction

Nyquist wavelength-division multiplexing (Nyquist-WDM) systems, based on the use of optical pulses with an almost rectangular frequency spectrum and bandwidth ideally equal to the Baud-rate, have been proposed to achieve high spectral efficiency (SE) of optical fiber communication and some experiments for such system have been demonstrated [1,2]. Optical nonlinear impairments must be mitigated in order to improve performance of long-haul and high-capacity optical fiber communication systems [3]. Many techniques have been proposed for the mitigation [4–7]. Among them, a model-centric nonlinear equalizer for coherent systems based on a 2D discrete-time model of physical impairments in long-haul time and wavelength channel systems using inverse Volterra theory has been introduced [6,7]. A digital backpropagation (DBP) method has also drawn much attention for its ability to compensate for signal-to-signal nonlinear interactions without altering the transmission link, which uses the knowledge of the physical channel and inverts it digitally and can be applied at the receiver, or at the transmitter with pre-distortion [8]. For WDM systems, it is very difficult to implement because high bandwidth for the coherent receiver is demanded and accurate DBP requires a substantial increase in digital signal processing (DSP) complexity, proportional to the number of spans. Fiber nonlinear impairments can also be effectively mitigated using optical phase conjugator (OPC) [9]. However, inserting an OPC into the links significantly reduces the flexibility of the optical network. breakthrough fiber nonlinearity compensation technique called phase-conjugated twin waves (PCTW) has been proposed recently by X. Liu et al. [10–12]. In the PCTW scheme, the signal complex waveform and its phase-conjugate copy are simultaneously transmitted in x- and y polarization states to achieve nonlinear noise cancellation at the receiver through coherent superposition of the two copies. The suppressive effects of PCTW technique on fiber nonlinearities depend on the symmetry of dispersion map. When the symmetry is satisfied completely, the nonlinear effects can be greatly reduced.

When channel spacing becomes narrow and channel number is large for WDM system, four-wave-mixing (FWM) effect is dramatically elevated, potentially leading to severe impair of system performance. FWM tones acts as noise due to the randomness of bit-sequences in all channels [13]. It is mandatory for WDM system designer to evaluate various nonlinear impairments in order to obtain good performance of system [14]. A finite-bandwidth noise theory was introduced to calculate the variance of degenerate and non-degenerate FWM noise for single span WDM transmission with on–off-keying (OOK) format [15]. For multi-span dispersion-managed (DM) transmission, the calculation

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https://doi.org/10.1016/j.optcom.2018.07.049
Received 9 May 2018; Received in revised form 14 July 2018; Accepted 16 July 2018
Available online 18 July 2018
0030-4018/

model was further developed in [16]. The dependence of FWM light on randomly changing polarization states along fiber was analyzed in [17,18]. For some high-level modulation formats such as differential quadrature-phase-shift keying (DQPSK) and 8-level phase-shift keying (D8PSK), semi-analytic models of FWM noise are given also in [19,20].

To the best of our knowledge, so far, no calculation model of FWM noise has been presented for QAM format, and although nonlinear models previously reported for coherent optical fiber transmission based on the first-order perturbation approach have been used to explain the mechanism of nonlinear noise squeezing by PCTW scheme for a symmetric dispersion map, the extent of reduction of FWM noise by the nonlinearity mitigation method cannot be derived from these previous models for a quasi-symmetric dispersion map, especially when the effect of walk-off between channels is included. In this paper, we statistically analyze the variances of degenerate and non-degenerate FWM noises for QAM PCTW Nyquist-WDM system. The variance of non-degenerate FWM noise is validated from our models to be irrelevant to the number of signal points within a QAM constellation diagram, as is different from the degenerate FWM case. By using our model, the performances of central channel for two cases of 16QAM PCTW Nyquist-WDM systems with same total spectral bandwidth and spectral efficiency, 16-channel 32-Gbaud/chand 32-channel 16-Gbaud/ch, are numerically given. The FWM noise is validated to be still greatly reduced by the PCTW scheme even if the channel spacing is relatively small.

The remainder of this paper is organized as follows. In Section 2, QAM Nyquist-WDM transmission with PCTW is described. In Section 3, expression of 16QAM optical signal is given. In Section 4, degenerate FWM models for single-span transmission with PCTW and without PCTW are given. In Section 5, non-degenerate FWM Models for single-span transmission with PCTW and without PCTW are given. In Section 6, performance degradation due to FWM Noise with and without PCTW is expressed. In Section 7, numerical results and discussions are given. In Section 8, simulation method used to validate our semi-analytical model is given. We summarize our conclusion in Section 9.

2. QAM Nyquist-WDM transmission with PCTW

Nyquist-WDM systems with rectangular spectrum and sinc-like pulse shape in time of each channel allow channel spacing equal to Baud-rate while avoiding both crosstalk between adjacent channels and inter-symbol interference. In the proposed PCTW scheme, which co-propagate a signal with its phase-conjugated mirror image along the optical fiber link can mitigate both intra- and inter-channel nonlinearities. Specifically speaking, the electric field in the Y polarization E_Y is the phase-conjugate of that in the X polarization E_X (=E), where the electric field E carries the data D. The waveform distortion caused by fiber nonlinearity can be described as the perturbation of E and E^* by δ and $-\delta^*$. At the receiver, the original waveform can be recovered by superimposing $E_X+\delta$ and $(E_X-\delta)^*$. When δ is imaginary-valued, the nonlinear signal distortions can be well canceled. Not only the symmetry of dispersion map but also the walk-off between channels will determine whether the value of δ is imaginary when inter-channel nonlinearities are included. In order to simplify our model, the polarization states of optical signals in all channels are assumed to be maintained along fiber link.

Advanced modulation formats such as M-ary QAM encode a data signal in amplitude and phase of the optical electric field. The resulting complex amplitude of this field is described by points in a complex constellation plane. Fig. 2 shows the normalized constellation points for a 16QAM signal and the outermost point's level within each dimension L_M serves for the normalization.

In this paper, the FWM noise is discussed for our system based on two assumptions for simplicity. One of them is that the polarization states are unvaried along fiber link and polarization mode dispersion (PMD) has no effects on the evolution of signal pulses. Polarization mode coupling (PMC) has been also ignored for simplicity. The other is that, except for fiber loss, the FWM lights generated at different distances have not been influenced by dispersion and fiber nonlinearities in transmission, as has been done in [13].

In this paper, the expressions of the variances of degenerate and non-degenerate FWM noises are given only for single-span transmission. These expressions can be easily extended to the multi-span case in a similar way as described in [19]. Semi-analytic models of FWM noise in QAM Nyquist-WDM system with PCTW are exhaustively discussed here. As a comparison, the case without PCTW is given also. Different from the PCTW scheme where the signal complex waveform and its phase-conjugate copy are, respectively, transmitted in x- and y polarization states, there is not any wave transmitting in y polarization state for the case without PCTW.

3. Expression of 16QAM optical signal

When the randomness of symbol sequence is taken into account, the electrical field of phase-conjugated twin waves along a birefringent fiber for 16QAM can be expressed as

$$E_{x,y} = A_{x,y} \exp\{-j[\omega t - kz - \theta]\} + \text{C.C}, \tag{1}$$

where A_ζ ($\zeta = x$ or y) is the slowly varying envelope of the electric field corresponding to ζ principal axis, C.C. denotes complex conjugate, θ is the initial phase, $A_y = (A_x)^*$, and

$$A_x = \sum_{n=-\infty}^{\infty} \left[L_M U_n f(t', z)\right], \tag{2}$$

where $L_M = \sqrt{P_{\max}}$, $P_{\max}$ is the maximum peak power of all possible launched optical pulse in each polarization state when the randomness of symbol sequence is taken into account and $P_{\max}$ are assumed to be same for all channels. U_n is the nth normalized 16QAM symbol, $f(t', z)$ is a pulse shape function normalized by the initial peak amplitude of launched pulse is mainly determined by the effects of fiber loss, dispersion and fiber nonlinearities, mainly including self-phase modulation (SPM) and cross-phase modulation (XPM). t' is the time of the nth symbol of selected channel relative to reference channel, $t' = t + nT - z/V - \tau$, T is symbol period, V and τ is relative group speed and initial time delay, n is an integer indicating the nth symbol in symbol sequence. Taking into account the randomness of symbol sequence, we can obtain

$$U_n = \left[\frac{\sqrt{2}}{2}(c_n + jd_n)\exp\left(-j\frac{\pi}{4}\right)\right]\sum_{\zeta=1}^{4}\varepsilon_n^{(\zeta)}, \tag{3}$$

where

$$\varepsilon_n^{(1)} = \frac{1}{4}(1+a_n)(1+b_n)\sqrt{2}\exp\left(j\frac{\pi}{4}\right), \tag{4}$$

$$\varepsilon_n^{(2)} = \frac{1}{4}(1-a_n)(1+b_n)\frac{\sqrt{10}}{3}\exp\left[j\arctan\left(\frac{1}{3}\right)\right], \tag{5}$$

$$\varepsilon_n^{(3)} = \frac{1}{4}(1+a_n)(1-b_n)\frac{\sqrt{10}}{3}\exp\left[j\arctan(3)\right], \tag{6}$$

$$\varepsilon_n^{(4)} = \frac{1}{4}(1-a_n)(1-b_n)\frac{\sqrt{2}}{3}\exp\left(j\frac{\pi}{4}\right), \tag{7}$$

where $a_n = \pm 1, b_n = \pm 1, c_n = \pm 1, d_n = \pm 1$. For launched Nyquist pulse shaped signal, the function of $f(t', z)$ is expressed as

$$f(t', z=0) = \sin c\left(\frac{t'}{T}\right)\frac{\cos(\pi\zeta t'/T)}{1-(2\zeta t'/T)^2}, \tag{8}$$

where ζ is a roll-off factor.

4. Degenerate FWM model for single-span transmission

No optical amplifier is used at the end of optical fiber link for the single-span transmission discussed in Sections 4 and 5.