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Improving channel capacity by nonlinearity compensation and noise suppression in high-speed multi-span optical transmission systems

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ABSTRACT

In this paper, the channel capacity of 40 Gb/s multi-span nonlinear optical transmission systems with nonlinearity compensation and self-adapting Wiener filtering is studied by use of Finite State Machine (FSM) approach. The comparison of channel capacity of the system with differential phase shift keying (DPSK) and on–off keying (OOK) modulation is also investigated. The channel capacity increases monotonically with the input power for transmission systems with simultaneous compensation of dispersion and nonlinearity, which performs as well as linear system. DPSK shows a much better performance and the channel capacity has an improvement of at least 48 percent over that OOK modulation. A further reduction of the amplified spontaneous emission (ASE) noise accumulation is obtained by Wiener filtering, which improves the channel capacity considerably when the input peak power is less than 3 mW.

1. Introduction

In optical fiber transmission systems, the combined effect of amplified spontaneous emission (ASE) noise, chromatic dispersion and Kerr nonlinearities such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM) limits the system performance and channel capacity seriously. Since the dispersion has been managed with dispersion compensating fibers (DCF) and other reliable solution, Kerr effect is the main limitations to the signal's transmission in high-bit-rate transmission systems [1]. In order to solve this problem, several techniques have been proposed in the literature, generally making use of optical phase Conjugation (OPC) technique [1–3] along the transmission line, or reducing the fiber nonlinear effects with optimized dispersion maps [4,5] and scaled translational symmetry (STS) [6,7], and thus yielding to the realization of nonlinearity compensation. Meanwhile, Wiener filtering as a practicable method is also used to reduce nonlinear phase noise caused by the interaction of ASE noise with fiber nonlinearity [8]. The channel capacity is the figure of merit used to assess the transmission performance. Determining the achievable transmission rates of information across noisy channels has been one of the central pursuits in information theory since Shannon invented the subject in 1948 [9]. Over the last decade, the evaluation of the ultimate capacity of the optical channel has emerged as a topic of great interest to the optical fiber transmission systems [10–13], and estimations of the 'fiber capacity' that include fiber nonlinearity have relied on a variety of assumptions such as weak nonlinearity [10], low dispersion [11] or heuristic [12] and information rates [13] approaches. However, in the above studies, no connections are made to nonlinearity compensation, modulation and self-adapting filtering.

In this paper, improving the channel capacity of transmission systems with simultaneous compensation of dispersion and nonlinearity and noise suppression is studied using Finite State Machine (FSM) approach [13]. The channel capacity of the systems with non-return-to-zero differential phase shift keying (NRZ-DPSK) and NRZ-on-off keying (OOK) modulation is also investigated. The results manifested that NRZ-DPSK modulation shows a much higher channel capacity, which has an improvement of at least 48 percent over that of NRZ-OOK. Meanwhile, the study found that the channel capacity of the transmission systems with simultaneous compensation of dispersion and nonlinearity increase monotonically with the input power and performs as well as linear systems due to well suppression of the nonlinear effects. Moreover, it is found that the ASE noise accumulation is the principal limiting factor for channel capacity at lower power levels. The channel capacity is improved considerably after reducing the ASE noise by self-adapting filtering when the input peak power is less than 3 mW.

2. Calculation of achievable information rates

A channel's output alphabet and input alphabet are respectively $y = (y_1, \ldots, y_n)$ with $y_i \in Y$ and $x = (x_1, \ldots, x_n)$ with $x_i \in X$. We consider

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the situation where the input is a binary sequence $X = \{0, 1\}$. The channel is completely defined by X, Y and the conditional probability function $P(Y|X)$. In here, the optical transmission channel is modeled as an inter-symbol interference (ISI) channel. The achievable information rates (ARIs) is calculated by FSM approach, this approach is described by the input alphabet X, output alphabet Y, and by finite states S. It is assumed that m previous and m next bits influence the observed bit x_i, and the state $S = \{x_{i-m}, \ldots, x_{i-1}, x_i, x_{i+1}, \ldots, x_{i+m}\}$ is determined by the $2m+1$ input bits [14].

The channel capacity C is defined as the maximization of mutual information $I(X,Y)$ over all possible input distributions $p(x)$ [13].

$$C = \max_{p(x)} I(X, Y) \tag{1}$$

The mutual information is defined as:

$$I(X, Y) = H(Y) - H\left(\frac{Y}{X}\right) \tag{2}$$

where $H(U) = -E(\log_2 P(U))$, U is a random variable.

We calculate the information rate in the case of independent and uniformly distributed (i.u.d.) channel input source (commonly considered in practice). Using this source for calculation the achievable information rate is a lower bound for the channel capacity.

According to Shannon–McMillan–Breiman theorem [15].

$$\lim_{n\to\infty} -\frac{1}{n}\log_2 P\left(Y_1^n\right) = E(\log_2 P(Y)) \tag{3}$$

where Y_1^n denote $\{Y_1, Y_2, \ldots, Y_n\}$. Therefore, the information rate (1) can be estimated from a long sequence Y_1^n by calculating $\log_2 P(Y_1^n)$. Using Eqs. (3) and (2), the following expression is obtained [14].

$$I(Y;X) = \lim_{n\to\infty} \frac{1}{n}\left[\sum_{t=1}^{n} \log_2 P(y_t|s) - \sum_{t=1}^{n} \log_2 P\left(y_t|y_1^{t-1}\right)\right] \tag{4}$$

The $P(y_t|y_1^{t-1})$ can be estimated by the Bahl–Cocke–Jelinek–Raviv (BCJR) algorithm [16].

$$\log_2 P\left(y_1^t\right) = \sum_{i=1}^{t} \log_2 P\left(y_i|y_1^{i-1}\right) \tag{5}$$

$$P(y_t|y_1^{t-1}) = \sum_{s,s'} \alpha_{t-1}(s) P(y_t|s) P_{s,s'} \tag{6}$$

The probability $\alpha_t(s)$ of the states at instance t is calculated by

$$\alpha_t(s) = \frac{\sum_{s} \alpha_{t-1}(s') P(y_t|s) P_{s,s'}}{\sum_{s,s'} \alpha_{t-1}(s') P(y_t|s) P_{s,s'}} \tag{7}$$

where $P_{s,s'}$ is the probability of transition from previous state S to current state S', which is 1/2 for two possible transitions, and 0 otherwise. The conditional probability $P(y_t|s)$ depends on the physical properties of the channel and can be determined by collected histograms with commercially available VPItransmissionMaker [17]. The BCJR algorithm is a maximum a posteriori probability decoding algorithm that can be used for any kind of FSM-driven sequence [18].

The FSM approach is applicable to any transmission system and allows the usage of the achievable information rate as a figure of merit for a long-haul transmission system, which also can be used to cancel the inter-symbol interference in the receiver [13]. To investigate "one-for-many" scaled translation symmetry (STS) scheme and Wiener filtering effectiveness for nonlinearity compensation, we reduce our attention to the receiver for eliminating the inter-symbol interference, let $m = 0$.

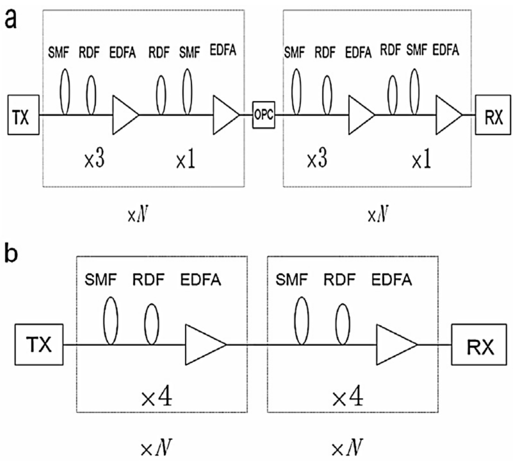

Fig. 1. (a) Sketch map of "one-for-three" STS span with dispersion and nonlinearity simultaneous compensation transmission system. (b) Sketch map of only dispersion compensation transmission system.

3. System model description

Two models of the 40 Gb/s fiber transmission system are shown in Fig. 1(a) and (b), respectively, where TX and RX represent transmitter and receiver. The three modulation formats are considered and share the same channel but with different transmitter (TX) and receiver setups in both systems. For return-to-zero (RZ), the transmitter consists of a pseudorandom bit sequence (PRBS) generator and a Gaussian pulse modulator. NRZ-OOK transmitter consists of a continuous wave laser, a PRBS generator, a NRZ modulator and an amplitude modulator (AM). NRZ-DPSK has a similar transmitter setup as NRZ-OOK, except with an additional differential precoder. Each of the modulator's output is a bit sequence length of 2^{14} with 16 samples per bit. The receiver (RX) is composed of a demodulator with three different demodulation formats and a sampler followed by a decision circuit.

Fig. 1(a) shows the "one-for-three" STS transmission system with OPC. Excellent dispersion and nonlinearity compensations are achieved simultaneously in this system [10], where an OPC is placed in the middle and a loop recirculating N times on each side of OPC. Each loop consists of three SMF + RDF spans, each consisting of 40 km SMF 40 km reverse dispersion fiber (RDF) +16 dB erbium-doped fiber amplifier (EDFA), and one RDF + SMF span consisting of 40 km RDF 40 km SMF +16 dB EDFA. The EDFA has a noise figure of 5 dB. Meanwhile, we have also simulated two comparative systems to see how effective "one-for-three" STS system is for nonlinearity compensation. One of the comparative systems has neither OPC in the middle nor "one-for-three", which is the distributed dispersion compensation (DC) transmission system, as shown in Fig. 1(b). Another comparative system is a linear Shannon system, where the nonlinear refractive index is zero. Meanwhile, to investigate the effectiveness of filtering to improve channel capacity, based on our previous work [8], Wiener filtering was added at the end of such "one-for-three" STS transmission systems with OPC and distributed DC transmission systems, respectively. The Fiber parameter values are given in Table 1.

4. Numerical result and discussions

Series of numerical simulations were carried out on a commercial transmission simulator (VPItransmissionMaker WDM version 6.0), where the combined effect of Kerr nonlinearities, ASE noise and dispersion is considered. Then, $P(y_t|s)$ can be derived from the collected histograms. The algorithm to calculate the achievable information rate is described in Section II. In the case of binary