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Low complexity MIMO method based on matrix transformation for few-mode multi-core optical transmission system

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ABSTRACT

This paper proposes and demonstrates a low complexity multiple-input multiple-output (MIMO) equalization digital signal processing (DSP) method for the few mode multi-core (FMMC) fiber optical transmission system. The MIMO equalization algorithm offers adaptive equalization taps according to the degree of crosstalk in cores or modes, which eliminates the interference among different modes and cores in space division multiplexing (SDM) transmission system. Compared with traditional MIMO method, the proposed scheme has increased the convergence rate by 4 times and reduced the number of finite impulse response (FIR) filters by 55% when the numbers of mode and core are three.

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1. Introduction

Demand on huge optical transmission capacity has been increasing rapidly due to the tremendous growth of Internet services such as 4k video, on-line game and remote medicine [1,2]. Recently, high capacity hero experiments and theoretical model strongly suggest that all the dimensions which we already employed in the transmission link have been exhausted [3,4]. Fiber loss, nonlinearities and optical instrument bandwidth have been forced to transmission limitation. We must consider novel multiplexing schemes, for instance, space division multiplexing (SDM) [5,6]. Various SDM transmission experiments have been demonstrated. For example, a dense space division multiplexed transmission over 12 cores $\times$ 3 modes few mode multi-core (FMMC) fiber has been proposed in [7], and 305 Tb/s transmission capacity employing 19-SDM, 100 wavelength division multiplexing polarized QPSK signals has been demonstrated in [8].

Among these SDM schemes, the FMMC optical transmission system is most promising [9–11], in which the number of spatial channels per fiber has been further increased to achieve higher capacity. One of the main challenges in realizing FMMC optical transmission system is the interference among the modes and cores. The inevitable coupling and differential mode delay require the usage of multiple-input multiple-output (MIMO) algorithm to equalize the signals at the receiver. The complexity and memory length of the algorithm increase with the coupling of cores/modes and delay difference between the fastest and slowest mode of the fiber. For a conventional MIMO equalization, the same number of taps with maximum channel coefficients is required to achieve reasonable performance [12]. Hence the computational complexity of MIMO equalization increases significantly for larger number of cores and modes. Generally, the crosstalk is strong among modes and weak among cores, which allows us to adopt adaptive approach to reduce the scale of MIMO equalization.

In this paper, we propose a novel MIMO equalization method based on matrix transformation (MT) for the FMMC optical transmission system. The MT based MIMO method can realize the equalization for modes and cores by matrix partition and tap adjustment. Compared with the traditional method, the proposed method precisely equalizes the mode dispersion and core coupling with lower complexity. The mean squared error (MSE) and bit error rate (BER) are also investigated in the demonstration.

2. Principle

Fig. 1 illustrates the principle of the proposed method. In FMMC fiber, differential mode delay and crosstalk caused by mode or core coupling are two major reasons which arouse signal deterioration.

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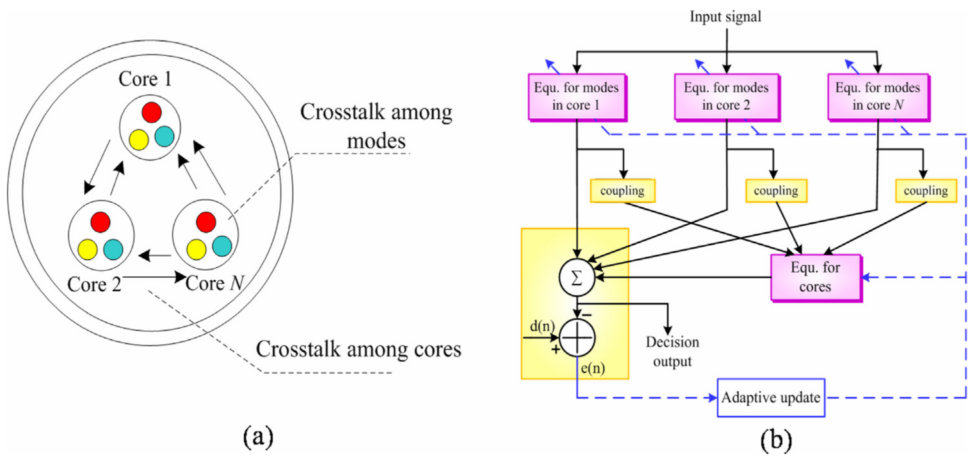

Fig. 1. (a) Few mode multi-core fiber model; (b) diagram of MIMO equalization method based on matrix transformation (Equ.: equalization).

The signal crosstalk exists in both modes and cores (as shown in Fig. 1(a)), where the crosstalk among modes is stronger than that among cores. In order to eliminate the crosstalk, MIMO equalization method is needed at the receiver, which can estimate the channel response matrix for compensation. If we assume that there are M spatial-mode channels and N cores, an $(M\times N)^2$ MIMO algorithm is required for traditional method, which results in a potentially high computational complexity and latency. Therefore, we propose a MIMO DSP equalizer based on MT and the flow diagram of the equalization is shown in Fig. 1(b). It reduces the MIMO matrix scale and offers adaptive equalization taps according to the degree of crosstalk among cores or modes, which decreases the complexity of MIMO algorithm. The original $(M\times N)^2$ MIMO matrix is partitioned into N small mode matrices with order of M^2 and one core matrix with order of N^2. The mode matrices are used to compensate the signal damage caused by mode multiplexing and coupling in the core, and the core matrix is used to compensate the signal deterioration from interaction between cores. The input signal is firstly split into tributaries and then sent into N parallel blocks for mode equalization in different cores. The inversed channel filter weights would converge to an optimum solution after iteration process. Next, the compensated signals of the N parallel blocks are coupled for equalization of cores. Gradient constraint condition is applied to enforce an accurate calculation of convolution during estimation. At the error block, the tap length and filter weights can be adaptively updated according to the error function. The convergence rate can be reduced by the adaptive update of filter weights, which is realized by adjusting the step size during estimation. In the scheme, constant module algorithm (CMA) is adopted for MIMO equalization. The step size $\sigma(n)$ can be expressed as

$$\sigma(n)=\begin{cases}\alpha\dfrac{|e(n)|^2}{\beta^2}\exp\dfrac{-e(n)^2}{2\beta^2}, & \left|e(n)\right|<\beta\\ \alpha/\beta\exp(-1/2), & |e(n)|\ge\beta\end{cases}\qquad(1)$$

here α, β are two constant parameters and $e(n)$ is the error function, which is represented by

$$e(n)=y'(n)\left(1-|y'(n)|^2\right)\qquad(2)$$

where $y'(n)$ is the output of MIMO equalization. In our following analysis, we have α=0.004 and β=0.9. It can keep a big step size when the error function is large while maintain a small step size when the error function is small. The update of the filter weights can be expressed as

$$W_{n+1}=W_n+\sigma(n)e(n)Y(n)\qquad(3)$$

where W_n is the filter weights after nth iteration and $Y(n)$ the received signal. The adaptive update can maintain a fast convergence rate while ensuring more accurate estimation.

3. Demonstration and results

The system setup is shown in Fig. 2, where we adopt three modes and three cores to demonstrate the proposed method. Each core supports three lowest-order linearly-polarized modes (LP_{01}, LP_{11a} and LP_{11b}), which are predicted to have the lowest propagation losses. At the transmitter, total nine QPSK modulated sequences are generated and separated into three sub-streams, which are sent into the three cores respectively. The QPSK symbols are created using pseudo-random bit stream with a length of 2^{15}. The transmitter consists of a continuous wave laser with a 100 kHz line-width at 1551.92 nm and an I/Q-modulator. Three 7 GBaud QPSK signals are combined and coupled into one core by a mode multiplexer (Mux). The driven voltage of the electric signal is set to be 3.4 V, which is slightly lower than the V_π of the I/Q-modulator. After mode multiplexing, the three optical signals are injected into three cores of the FMMC fiber through the fan-in device. The individual cores of the fiber have a 13.1 µm diameter at a core pitch of 42 µm. The air-hole diameter is 9.4 µm with air-hole pitch of 13.3 µm. After 50 km FMMC fiber transmission, the signals are fed into three mode de-multiplexers (DeMux) through fan-out device. The respective outputs from mode DeMux are guided into the multi-mode coherent receiver for detection. After analog to digital conversion, the nine digital symbols streams are equalized by our proposed MT-based MIMO method. The flow of digital signal processing stages is as follows: 1) sampling; 2) dispersion compensation and time recovery; 3) MT-based MIMO equalization; 4) phase offset removing.

Fig. 3 shows the required finite impulse response (FIR) filter number with different mode numbers and core numbers, where the BER is set to be 1×10^{-3}. Because the traditional equalization needs to adopt maximum MIMO ports and considers the worst coupling situation, there are much redundant equalization and the number of FIR filters is large. For FMMC system with M spatial modes and N cores, the MIMO equalizer needs FIR filter number of $(M\times N)^2$ with traditional method [13]. However, our proposed method can reduce the number to $M^2\times N+N^2$, which can realize MIMO DSP process with smaller scale. Compared with the traditional equalization, our proposed method can reduce the number of FIR filters by 55% when the numbers of mode and core are three.

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