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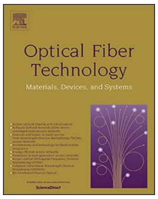

Regular Articles

Channel estimation in few mode fiber mode division multiplexing transmission system

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ABSTRACT

It is abundantly clear that obtaining the channel state information (CSI) is of great importance for the equalization and detection in coherence receivers. However, to the best of the authors' knowledge, in most of the existing literatures, CSI is assumed to be perfectly known at the receiver. So far, few literature discusses the effects of imperfect CSI on MDM system performance caused by channel estimation. Motivated by that, in this paper, the channel estimation in few mode fiber (FMF) mode division multiplexing (MDM) system is investigated, in which two classical channel estimation methods, i.e., least square (LS) method and minimum mean square error (MMSE) method, are discussed with the assumption of the spatially white noise lumped at the receiver side of MDM system. Both the capacity and BER performance of MDM system affected by mode-dependent gain or loss (MDL) with different channel estimation errors have been studied. Simulation results show that the capacity and BER performance can be further deteriorated in MDM system by the channel estimation, and an 1e-3 variance of channel estimation error is acceptable in MDM system with 0–6 dB MDL values.

1. Introduction

Owing to the merit of its dielectric nature and huge information-carrying capacity, fiber based optic communication is considered as one appealing solution in the future communication system [1]. Single-mode fibers (SMF) transmission system is gradually approaching its Shannon bound and has fewer space to explore. Additionally, the drawbacks of strict requirement and complexity in alignment and packaging further makes it less attractive nowadays [2]. From the viewpoint of information theory, multimode optical fiber (MMF) can provide extra degrees of freedom (DOFs) and therefore greatly increase the information capacity. Nevertheless, due to the effects of modal dispersion, the fundamental bandwidth limitation severely limits the achievable data rates in current MMF transmission systems. Recently, space division multiplexing (SDM), using multicore fiber (MCF) or few-mode fiber (FMF) has been proposed as a promising alternative to the future optical communication system [3]. FMF has the advantages of higher data rate, power efficiency and nonlinearity tolerance in comparison with SMF. On the other hand, compared with MMF supporting over a huge number of modes which makes it extremely challenging to process, FMF only supports the propagation of few orthogonal spatial modes, which has the potential of providing high mode selectivity and low attenuation, sharply reducing the system processing complexity [4]. Therefore, the FMF based mode division multiplexing (MDM) system has attracted considerable interests recently.

By using the orthogonal spatial and polarization modes of FMF to transmit independent parallel data streams, SDM system or MDM system can be considered as multiple input multiple output (MIMO) channels, and thus significantly improves system channel capacity [5–7]. However, apart from those advantages, there still exist several open issues and challenges needed to be addressed.

Currently the FMF-based MDM systems mainly suffer from significant mode-dependent loss (MDL) and large differential mode group delay (DMGD). MDL originates from inline components: optical amplifiers, couplers, multiplexers, as well as from non-unitary crosstalk in the fiber and at fiber splices and connectors. Due to the imperfections in optical components, the modes in MDM system experience differential gains or losses, which causes SNR disparities and a loss of the orthogonality of the modes [8,9]. The differential mode group delay (DMGD) is mainly caused because the multiple spatial modes supported by FMF have different group velocities (GD). DMGD, together with the crosstalk, can result in spatial or temporal inter-symbol interference (ISI) [10]. Different from the MD effect does not fundamentally degrade the system performance but only affecting the receiver complexity, MDL is a fundamentally channel capacity limited factor [11]. Recently, it was demonstrated that, MIMO digital signal processing techniques offer potential solutions in compensating DMGD and mitigating the impairments caused by MDL in MDM systems with coherent detection

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[12–22]. Specifically, by employing the MIMO equalization, the chromatic dispersion (CD) and mode dispersion (MD) can be well compensated [12], and the frequency-domain equalization (FDE) technique was demonstrated to have more superior performance than the time-domain equalization (TDE) technique in terms of computational complexity [13,14], which accelerates the research of proposing lower complexity, faster adaption frequency MIMO equalizers [15,16]. As for the MDL, advanced MIMO signal processing techniques including space time coding [17–19], maximum likehood detection [20] or near ML detection [21] have been proposed. A detailed summary for DMGD and MDL mitigation methods in MDM transmission has been reviewed in [22].

Among the existing literatures on MDM system, to the best of our knowledge, most of them assume that perfect channel state information (CSI) is known at the receiver in MDM system [19–21], however, this assumption is not realistic in practice because the CSI achieved by channel estimation at the receiver can never be perfect with limited pilot symbols [23,24]. Besides, although recently channel estimation technique was introduced in the MIMO DSP coherent receiver in [16–18], for example, in [16] a CAZAC code based channel estimation was employed in 6 × 6 MIMO FDE equalizer, they did not discuss much about the detailed process or its related effects. Inspired by that, in this paper, channel estimation process in MDM system is discussed and effects of MDL on the MDM system in the presence of channel estimation are quantified. Two classical channel estimation methods, i.e., least square (LS) method and minimum mean square error (MMSE) method are studied with the assumption of spatially while noise lumped at the receiver side of the MDM system. The capacity performance and the BER performance affected by the MDL have been investigated with different channel estimation error. Simulation results show that both the capacity and BER performance can be further degraded with channel estimation.

The outline of the paper is organized as follows. Section 2 briefly describes the MDM system model. Section 3 introduces the training based channel estimation in MDM system. The capacity of MDM system with channel estimation is analyzed in Section 4. Numerical results are provided in Section 5 and Section 6 concludes the paper.

2. System model

The MDM system model has been thoroughly investigated in previous works [7,8,10,11,25]. They can be mainly divided into two kinds, one is the MDM system model with lumped noise as in [10,11,25], in which the spatially white noise is assumed to be lumped at the receiver. The other is the MDM system model with distributed amplified spontaneous emission (ASE) noise as described in [7,8], in which the distributed ASE noise generated at each amplification stage accounts for the dominant noise in the optical link and is subject to the MDL at each segment. The differences between these two models are in the ways of MDL influencing the system performance. In this paper, for simplicity, the MDM system model proposed in [10] is adopted, which provides a nice statistical representation of MDL through equivalence to the eigenvalue distribution of a zero-trace Gaussian unitary ensemble. A single polarization per spatial mode is considered to solely focus on the primary impairments from MDL and the non-linear effects are neglected.

2.1. MDM system model

In this section, a MDM system concatenated by numerous short sections is considered, as described in [10]. Assuming M orthogonal propagating modes are activated in the FMF, the overall $M \times M$ propagation matrix can be expressed as follows:

$$\mathbf{H}_{M\times M} = \prod_{k=1}^{K} \mathbf{M}_k = \prod_{k=1}^{K} \mathbf{U}_k\mathbf{V}_k\boldsymbol{\Lambda}_k^H = \prod_{k=1}^{K} \mathbf{U}_k diag\,[\lambda_1 \ \cdots \ \lambda_N]\boldsymbol{\Lambda}_k^H \tag{1}$$

The $\mathbf{V}_k$ and $\mathbf{U}_k$, are frequency-independent random unitary matrices representing mode coupling in the kth section. The diagonal matrix $\boldsymbol{\Lambda}_k$ represents modal propagation matrix including both MDL and modal dispersion in the kth section. Its diagonal elements can be expressed by $\lambda_{i=1\cdots N}^{(k)} = \exp(g_i^{(k)}/2 - jw\tau_i^{(k)})$, in which $g_i^{(k)}, i = 1 \ldots N$ are the uncoupled modal gains measured in log power gain units (or dB). They satisfy $g_1^{(k)} + \cdots + g_N^{(k)} = 0$ and have root-mean-square (rms) value σ_g. Generally, in the strong coupling regime when $K > > 1$ it is determined by the rms accumulated MDL $\xi = \sqrt{K}\sigma_g$. $\tau_i^{(k)}, i = 1 \cdots N$ are the uncoupled modal group delays, satisfing $\tau_1^{(k)} + \cdots + \tau_N^{(k)} = 0$ and have rms value σ_g. According to [10], the standard deviation (STD) of over modal gains in dB is determined by $\sigma_{MDL} = \xi\sqrt{1 + \xi^2/12}$.

2.2. MDM MIMO transmission system

The FMF based MDM system over parallel coupled transmission paths can always be molded as a general MIMO system. Without of loss generality, denote the $M \times M$ dimensional channel matrix concatenated by numerous short sections between the transmitter and the receiver as $\mathbf{H}$, then the received symbols is an $M \times 1$ vector $\mathbf{y}$ written by:

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{2}$$

where $\mathbf{s}$ is the transmitted symbol vector with $\mathbf{Q} = E\{\mathbf{s}\mathbf{s}^H\} = P_d/M \cdot \mathbf{I}_M$. $\mathbf{n}$ is a $M \times 1$ noise vector at the receiver with the variance σ_n^2. Assume the total transmit power is P_d, then the average receiver signal to noise ratio (SNR) can be defined as $\rho_d = P_d/\sigma_n^2$.

2.3. Discussion on different noise loading

In the following, effects of two different noise loading models on the capacity performance of MDM system are discussed. For the first case, i.e., the spatially white noise is lumped at the receiver, as illustrated in Fig. 1 below, the noise $\mathbf{n} \sim CN(\mathbf{0}, \sigma_n^2\mathbf{I}_M)$ is assumed to be additive white Gaussian noise (AWGN) with its entries are independent and identically distributed (i.i.d.) zero-mean circularly symmetric complex Gaussian (ZMCSCG).

In this case, the channel capacity can be expressed as:

$$C = \log_2\left[\det\left(\mathbf{I} + \frac{\rho_d}{N}\mathbf{H}\mathbf{H}^H\right)\right] \tag{3}$$

For the MDM system model that the distributed ASE noise is assumed to be loaded at each inline amplifier, the system model can be described as Fig. 2 below.

The corresponding expression can be written by:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \sum_{j=1}^{K-1} \mathbf{M}_K \cdots \mathbf{M}_{j+1}\mathbf{n}_j + \mathbf{n}_K \tag{4}$$

Due to the effects of the distributed MDL, the equivalent noise is polarized and its coherency matrix $\mathbf{Q}$ is not proportional to the identity as the case of lumped AWGN. Then the coherency matrix $\mathbf{Q}$ can be written as follows:

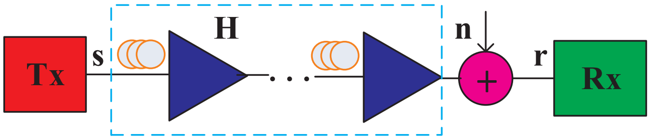

Fig. 1. The optic link of lumped noise model.