The final publication is available at

https://doi.org/10.1364/SPPCOM.2017.SpM2F.2

Additional Information

MIMO Equalization for Two-Mode Division Multiplexing over Standard SMF at 850 nm

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Abstract: Multiple-input multiple-output (MIMO) receivers are proposed to cope with the signal distortion caused by modal coupling, induced by (de)multiplexers, and modal dispersion in mode-division multiplexing systems over single-mode fiber (SSMF) at 850 nm.

OCIS codes: (060.2330) Fiber optics communications; (060.4230) Multiplexing; (250.4745) Optical processing devices.

1. Introduction

Nowadays, Mode Division Multiplexing (MDM) has become a promising technique to overcome the capacity limit of optical links. Many proposals of MDM have been presented to increase capacity in long-haul transmissions using few-mode fiber and in short-reach links using multi-mode fiber. The use of standard 9/125 µm single-mode fiber (SSMF) at the 850 nm window has been proposed as a low-cost solution to improve the link reach provided by MMF [1]. At 850 nm only 2 linear polarized modes, LP_{01} and LP_{11}, propagate in SSMF, which makes this interface suitable to double the capacity by means of a 2×2 MDM (see Fig. 1). Nevertheless, the main disadvantage comes from the difference between the group velocities that causes a high differential mode delay (DMD) of around 2 ns/km.

When implementing the MDM system, the most critical elements are the mode multiplexer (MX) and demultiplexer (DMX). Several proposals of MX/DMX for SSMF at 850 nm, based on fiber couplers, have been published and the theoretical results present high performance in selecting/rejecting the propagated modes with low losses and broadband operation [2-3]. In view of those results, multiple-input multiple-output (MIMO) processing appears to be unnecessary. However, there exists some factors that can degrade the performance of the MX/DMX as relaxed fabrication tolerances, detuning of the optical source and the non-ideal behavior of other devices required to implement MDM as mode converters or mode filters [2][4].

In this work, we propose MIMO receiver schemes based on the decision feedback equalizer (DFE) to cope both with the modal coupling induced by MX/DMX and the high modal dispersion of the SSMF at 850 nm.
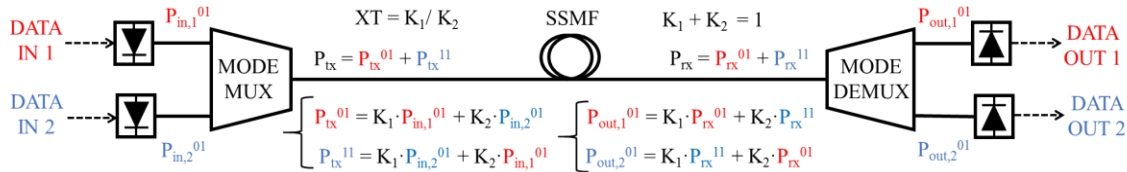

Fig. 1. Optical MDM link over SSMF at 850 nm, and equations relating power transfer between the signals caused by MX/DMX.

2. MIMO DFE receivers: definitions

The equalizers used in this work are based on a T/2 fractionally-spaced minimum mean square error (MMSE) DFE. The DFE equalization exhibits low-complexity but offering low error detection probability for dispersive mediums. A single-input single-output (SISO) DFE is composed by a feed-forward filter (FWF) of $K_w + 1$ coefficients that operates on the received signal sampled at half the symbol rate, and a feed-back filter (FBF) of K_b coefficients working at baud-rate on previous detected symbols, see Fig. 2a. The ability to cancel part of the inter-symbol interference (ISI) by means of FBF prevents from excessive noise enhancing over the equalized symbols. The MIMO-DFE receiver operates on the N_{RX} received signals to estimate the N_{TX} transmitted data streams. It consists in a first stage of $N_{RX} \times N_{RX}$ FWF's and a second stage of $N_{TX} \times N_{TX}$ FBF's, see Fig. 2b [5].

To improve the performance of MIMO-DFE, receiver structures operating on the basis of ordered successive interference cancellation (OSIC) have been developed. In [5], the fully connected (FC-OSIC) MIMO-DFE receiver is defined as in Fig. 2c. This is constructed by N_{TX} sections each exactly equal to a MIMO-DFE as in Fig 2b. Although all data streams are detected in each section, only the data corresponding to the MMSE is retained and its contribution on the received signal is subtracted. Thereby, the co-channel interference (CCI) induced by previously detected streams is cancelled, and thus the detection of the later streams is improved.
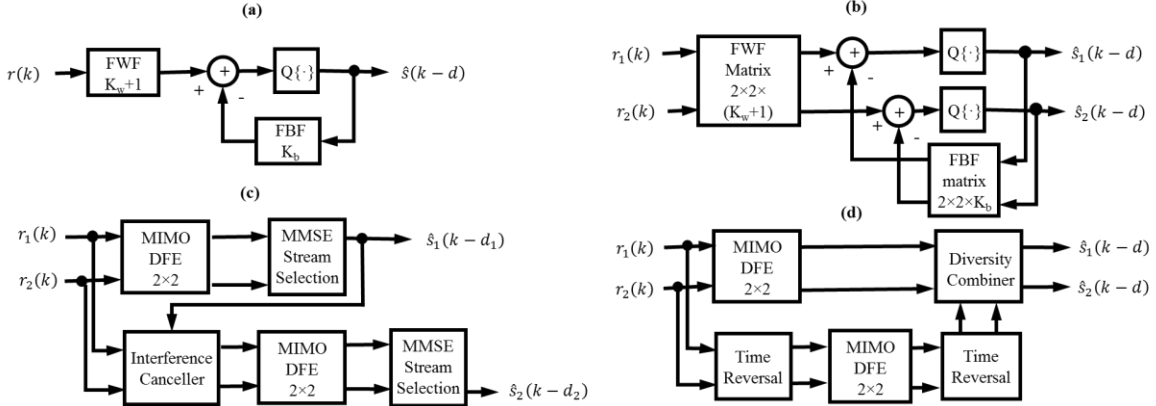
Fig. 2. Block diagram of SISO DFE receiver (a), and DFE (b), FC-OSIC DFE (c), and LC-BiDFE (d) MIMO receivers for $N_{TX} = N_{RX} = 2$.

The last MIMO scheme evaluated in this work is the linear combining bidirectional DFE (MIMO LC-BiDFE) [6]. As in Fig. 2d, the receiver is formed by 2 sections, one of which operates in time-forward and the other in time-reversal mode. The time-forward section is exactly equal to a MIMO-DFE as in Fig. 2b. On the other hand, the time-reversal section applies also a MIMO-DFE detection scheme but now over the reversed-in-time samples of the received signals, and then the equalized outputs are again reversed in time. The outputs of each equalized data stream from both sections are weighted and added attending their own MSE, so that each output is a linear combination of the outputs of both sections for each stream.

3. MIMO equalization to combat crosstalk in MDM

The receivers presented in this work are evaluated by means of numerical simulations. The simulation model consists in an intensity modulated and direct detected (IM-DD) optical SSMF link of 1 km length at 850 nm with fiber loss of 1.8 dB/km where the non-linear effects are neglected (see Fig. 1). The two 10 Gb/s OOK electrical input signals, modulating each one a narrow optical carrier, are previously filtered by an electrical Gaussian filter with step response $T_{20-80\%} = 47$ ps; at the receiver, Bessel filter of 4th order with a 7.5 GHz cut-off frequency is applied to both photodetected signals. We assume that the incoming optical signals to the MX are pure LP_{01} modes, and there exists no modal coupling along the SSMF due to the high DMD value. Therefore, the MX/DMX's are the unique source of coupling, which it is here modeled as crosstalk (XT) at the outputs of the MX and DMX, as is derived in equations of Fig. 1. In addition. the SSMF induces chromatic dispersion (~85 ps/(km·nm) for both modes), although its effect in pulse broadening at 10 Gb/s is lower than 1 % for 1 km length.

To evaluate the performance of the equalizers, the bit error rate (BER) of each data stream, also called layer, as a function of the optical signal to noise ratio (OSNR) is compared with an ideal MDM system, which does not suffer from mode coupling (XT = ∞), where each output is detected without equalization. As an example, in Fig. 3a-b the BER curves for each detected layer for different receivers are plotted. They include results of an ideal MDM system with a conventional receiver without equalization, and of a system with XT = 6 dB in both MX and DMX. In this latter case results are shown for a conventional receiver without equalization, and for three MIMO receivers: DFE, FC-OSIC and LC-BiDFE, all of them with filter lengths $K_w = 5$ and $K_b = 25$. Also in Fig. 3c-f the MIMO channel impulse response of this case is showed, where $h_{ij}(t)$ relates the i-th input and the j-th received stream. The ISI and CCI contributions caused by the XT at MX and DMX are marked by solid and dashed circles respectively.

The BER of the conventional receiver (SISO RX, in Fig. 3a-b) with mode coupling generated at MX and DMX is degraded severely compared with an ideal transmission without coupling (SISO RX XT = ∞ dB); the consequence of a XT = 6 dB is that it is required an increase of OSNR of 7.1 dB to achieve a BER = 10^{-12}.

As pointed out in [5], the decision delay in DFE is a critical parameter that must be chosen to minimize the MSE. In MIMO-DFE, the block detection requires that the FBF's delay has to be the same for all the layers. This feature limits strongly the performance of MIMO-DFE in high dispersive channels, as seen in Fig. 3a-b. In this case, the optimum delay coincides with the first contribution in each $h_{ij}(t)$ (around $t = 4T$, see Fig. 3c-f). When detecting layer 1 (Fig. 3a) the equalizer operates suitably as the delay corresponds to the high level of $h_{11}(t)$: the ISI (circled in Fig. 3c) and the CCI ($h_{21}(t)$, Fig. 3d) is compensated mainly by the FBF. However, the optimum delay matches with the lower contribution in $h_{22}(t)$ (Fig. 3f), and then the BER obtained after detecting layer 2 is reduced dramatically, as seen in Fig. 3b. Although the interference can be effectively cancelled by the equalizer, the SNR at its output is poor due to the low signal level at the detection delay and thus the OSNR penalty worsens too much and becomes prohibitive.
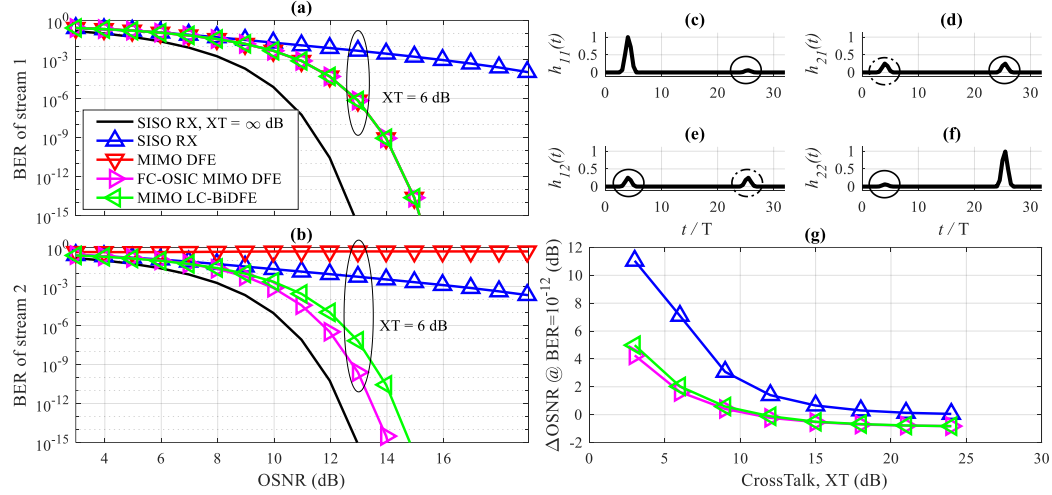
Fig. 3. BER as a function of OSNR for stream 1 (a) and 2 (b) of conventional (SISO RX) and MIMO receivers for XT = 6 dB in MX/DMX, and of SISO RX for XT = ∞; MIMO channel impulse response (c-f). The mean OSNR penalty between both streams to achieve BER = 10⁻¹² as a function of XT is showed in (g) for MIMO receivers with respect to the SISO RX with XT = ∞.

The FC-OSIC MIMO-DFE operates over the layer 1 exactly as classic MIMO-DFE and so the BER is exactly the same in Fig. 3a. When the contribution of that detected layer is subtracted from the received signal, all the CCI is eliminated; it means that the MIMO channel impulse response for the second stage of the receiver becomes void for $h_{11}(t)$ and $h_{12}(t)$. Then, in the second detection stage, the optimum delay matches with the higher level of $h_{22}(t)$.

The LC-BiDFE receiver produces a similar BER in both layers. To detect layer 1, the diversity combiner gives a weight of 97% to the time-forward output and the obtained BER is similar to previous MIMO receivers (Fig. 3a); on the other hand, to detect layer 2, the diversity combiner gives a weight of 97% to the time reversal output. Due to the channel symmetry (as the same XT is used both at MX and DMX) the reversed in time channel impulse response for the layer 2 (Fig. 3e and f) almost coincides with the one of layer 1 (Fig. 3c and d). The main benefit of MIMO LC-BiDFE arises from the detection of layer 2 mainly through the time-reversal section; since for this case, the optimum delay matches with the higher level of the channel impulse response ($h_{22}(t)$) which does correspond with the first contribution in the time-reversed version.

Finally, in Fig. 3g the mean OSNR penalty between both layers to achieve a BER = 10⁻¹² for the conventional and MIMO receivers with respect to the conventional receiver with XT = ∞ is plotted as a function of XT. The penalty of conventional receiver becomes significant for XT<20 dB, as is denoted in [4], increasing progressively for lower values of XT. FC-OSIC and LC-BiDFE MIMO receivers present a good performance in reducing signal distortion generated by MX/DMX: both OSNR penalties are similar and always lower than conventional receiver. For very high values of coupling as XT = 6 dB, the FC-OSIC presents lower penalty than LC-BiDFE: 1.6 dB and 2.1 dB, respectively. That implies an improvement of at least 5 dB with respect to the conventional receiver. It can be seen that for low values of coupling (XT ≥ 12 dB) the penalty of both MIMO receivers is negative and trends asymptotically to -0.8 dB. The reason for this better performance is because the equalizers can compensate the residual ISI induced by the limited bandwidth of the system.

4. Conclusions

It has been shown under which conditions of the MX/DMX, the MDM over SSMF at 850 nm requires MIMO processing. Moreover, classic MIMO-DFE fails in this scenario with high modal dispersion and more developed receivers are needed to cope with it. The FC-OSIC and LC-BiDFE present both good performance in bimodal MDM over SSMF, though FC-OSIC can improve slightly LC-BiDFE over high coupling conditions. For a maximum allowed power penalty of 1 dB, the LC-BiDFE receiver admits up to a XT ≥ 7.9 dB and LC-BiDFE extends slightly the range to XT ≥ 7.3 dB, whereas a conventional receiver is limited to XT ≥ 13.4 dB.

5. References

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