Successive Interference Cancellation in Spatially Multiplexed Fiber-optic Transmission

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Abstract

The multiple-input multiple-output (MIMO) concept is of high interest in fiber-optic communication since it is able to overcome the capacity limits of current transmission systems. In this work different receiver-side interference compensation techniques are studied in a spatially multiplexed fiber-optic transmission through 0.5 km multi-mode fiber with a gross bit-rate of 5 Gbps using intensity modulation and direct detection. Broadband successive interference cancellation (SIC) and broadband zero forcing (ZF) equalization are compared as electronic interference compensation methods in a (2×2) MIMO transmission. The results show that ordered SIC can significantly improve the transmission quality compared to the ZF equalization approach in the studied testbed configuration. Also, spatial filtering as an interference reduction technique is studied with respect to its effect on the bit-error rate (BER) performance, showing that in the analyzed channel scenario the use of such a filter is beneficial. Using a spatial filter improves the mode group separation at the receiver and hence reduces the MIMO signal processing complexity.

1 Introduction

In fiber-optic communication dense wavelength division multiplexing, polarization multiplexing, high order modulation formats and coherent transmission were technologically the key enablers to satisfy the need for cost effective transmission so far. However, the exponential growth of data traffic requires more advanced techniques. Spatial multiplexing, which has long been established in wireless communication, seems to be a promising approach for fiber-optic data transport. Implementation obstacles and cost factors, such as the need for specific low differential mode group delay fibers in long-haul transmissions or the high signal processing complexity required to compensate the additional modal dispersion, prevent a dissemination in commercial products.

In this contribution spatial multiplexing is implemented with standard graded-index multi-mode fibers over a distance of 0.5 km at an operating wavelength of 780 nm for

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potential in house communication applications. Single-mode fiber (SMF) to multi-mode fiber (MMF) splices with different radial offsets are used for the excitation of individual mode groups which are later multiplexed (MUX) and demultiplexed (DEMUX) with a multi-mode fusion coupler [8]. Considering the receiver-side signal processing, two broadband MIMO equalization schemes are studied, one is a simple zero-forcing approach and the other uses ordered successive interference cancellation [11, 3]. The latter one is expected to show superior performance in channel environments where the MIMO output signals have different qualities.

The novelty of this contribution is the performance comparison of using a spatial filter for increasing the optical MIMO system orthogonality to pure electronic MIMO interference removal.

This paper is structured as follows: Section 2 illustrates the general concept of spatial multiplexing in fiber-optic transmission. In section 3 the testbed setup is introduced. The studied receiver structure and broadband MIMO equalization algorithms are described in section 4. Section 5 presents the transmission results and compares the different receiver-side interference compensation concepts. Finally, section 6 gives some concluding remarks.

2 Spatial Multiplexing in Fiber Optic Transmission

In an optical spatial multiplexing system multiple data streams are transmitted on different modes through a fiber that supports multiple modes. The maximum transmission capacity can be achieved when transporting each data stream on just a single spatial and polarization mode as shown in the concept in Fig. 1. In this idealized model each mode, e.g. LP_{11a}, carries a unique data stream. Theoretically, an operating wavelength of 780 nm and a transmission through a 50/125 graded-index (GI) MMF with a numerical aperture of 0.2 allows more than 400 parallel data streams. However, the excitation of just a single mode requires complex optomechanical constructions, e.g. with phase plates or spatial light modulators [10, 5]. An alternative is the use of photonic lanterns [6]. In such mode multiplexed systems strong mode mixing effects especially between modes of the same group need to be countered with e.g. expensive signal processing [2]. Therefore, in this contribution different mode groups are used to lower the signal processing costs. Here, SMF to MMF splices with different radial offsets are used for mode-selective excitation and multi-mode fusion couplers are used for mode MUX and DEMUX [8].

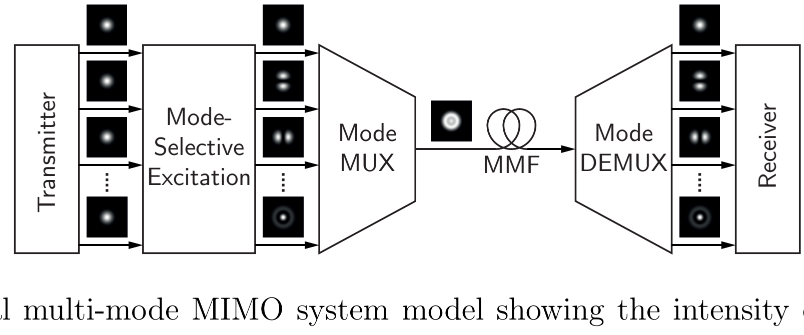


Figure 1: Ideal multi-mode MIMO system model showing the intensity distributions in the fiber cores

3 Optical MIMO Testbed

The testbed setup is depicted in Fig. 2. At the transmitter two independent intensity modulated data streams with on-off keying are generated with lithium niobate modulators and are transmitted at an operating wavelength of 780 nm. Two independent $2^{15} - 1$ pseudo-random binary sequences with different generator polynomials and initialization vectors are repeatedly transmitted. SMF to MMF splices with centric launch excite the

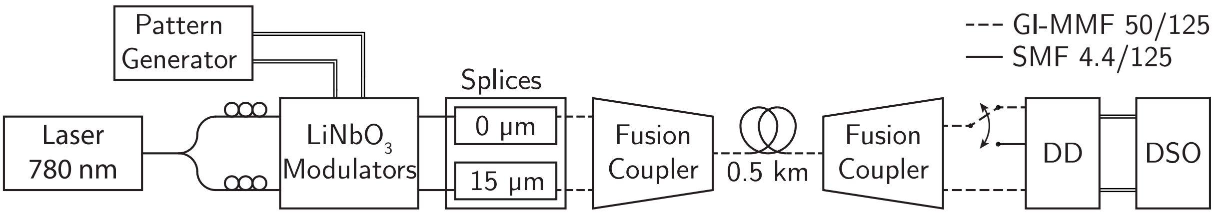


Figure 2: MIMO testbed configuration

low order modes (LOM) and an eccentric launch with 15 µm offset transfers the data stream to high order modes (HOM). The two data streams are combined with a fusion coupler and are transmitted through a 0.5 km graded-index (GI) MMF. Figure 3 shows the resulting intensity distributions of the two streams, highlighting the spatial diversity. An additional fusion coupler is used for the demultiplexing process, splitting the LOM and HOM nearly symmetrically to both outputs. This procedure is illustrated in detail in Fig. 4. At the first output the HOM can be removed by optionally attaching a SMF to the MMF output for spatial filtering. Increasing the orthogonality with a spatial filter reduces the MIMO signal processing costs compared to a pure electronic interference removal. Different concepts, e.g. pure electronic MIMO equalization or the use of an additional spatial filter, are compared with respect to their transmission quality later on. Subsequently, direct detection (DD) is applied and the data is saved at the digital storage oscilloscope (DSO) and processed offline.

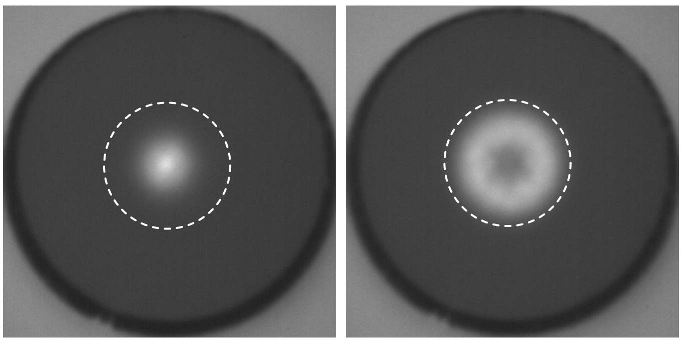


Figure 3: Intensity distributions at the end of a MMF when launching centric $\delta = 0$ µm (left) and with an eccentricity of $\delta = 15$ µm (right); the dashed line represents the 50 µm core size

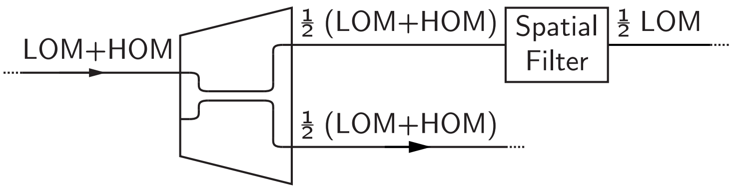


Figure 4: Idealized demultiplexing of the low order modes (LOM) and high order modes (HOM) with a fusion coupler

4 Broadband MIMO Receiver Signal Processing

The first processing step at the receiver is the application of a receive filter for improving the signal-to-noise ratio (SNR). Symbol clock recovery based on nonlinear distortion is applied to extract the symbol frequency without requiring to transmit a dedicated clock signal. Symbol-spaced sampling is applied to the receive filtered signals and an additional offset removal is conducted. It requires the transmission of balanced symbols. In order to detect the beginning of a new frame and to locate the pilot symbols a frame synchronization is performed by correlation of the received signals with the transmitted pilot symbols [7]. A least squares estimator is used to obtain the informations of the frequency-selective MIMO channel state [4]. Based on this knowledge an equalizer is designed to remove the occurring interferences. Finally, hard decision is applied to estimate the transmitted symbols.

Frequency-selective MIMO channels produce interferences between neighboring symbols, i.e. inter-symbol interference, as well as interferences between different transmission channels, i.e. inter-channel interference. In order to counter these interferences hereinafter two equalization approaches are debated.

4.1 Zero-Forcing Broadband MIMO Equalization

Linear zero forcing MIMO equalization is the first method being discussed on the example of a (2×2) MIMO channel [9]. The overall transmission relation is shown in Fig. 5. Here, $s_\mu(k)$ denote the discrete-time transmitted symbols at input $\mu = 1, \dots, n_\mathrm{T}$, with n_T and n_R being the total number of MIMO inputs and outputs. The signals $r_\nu(k)$ and

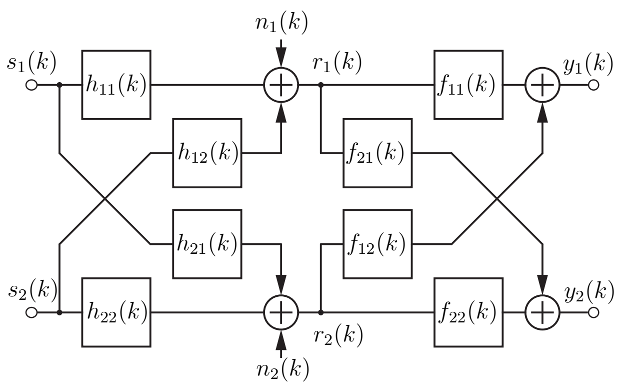


Figure 5: (2×2) MIMO channel and ZF equalizer

$n_\nu(k)$ describe the received data and noise influence at MIMO output $\nu = 1, \ldots, n_\mathrm{R}$. Furthermore, $h_{\nu\mu}(k)$ are the impulse responses of the frequency-selective MIMO channel. The structure of the ZF equalizer with its impulse responses $f_{\mu\nu}(k)$ is similar to the MIMO channel as shown in Fig. 5.

For the evaluation of the transmission quality the SNRs of the equalizer output signals are used [1]. They are defined by

$$\varrho_\mu = \frac{(\text{half vertical eye opening})^2}{\text{noise power}} = \frac{U_\mathrm{A}^2}{P_{\mathrm{R},\mu}} \quad . \tag{1}$$

Since the zero forcing approach is designed to fully open the eye diagram, the half vertical eye opening equals the half level transmit amplitude. In contrast the noise signal $n_\nu(k)$ with power P_R is influenced by the equalizer and is weighted as follows

$$P_{\mathrm{R},\mu} = P_\mathrm{R} \cdot \theta_\mu \quad . \tag{2}$$

The noise weighting factor at the μth equalizer output is given by

$$\theta_\mu = \sum_{\nu=1}^{n_\mathrm{R}} \sum_{k=0}^{L_\mathrm{f}-1} \left| f_{\mu\nu}[k] \right|^2 \quad , \tag{3}$$

with $f_{\mu\nu}[k]$ denoting the kth equalizer coefficient and L_f is the total number of coefficients per impulse response. Consider a scenario where the noise weighting factors highly differ between the two layers, then the overall transmission quality is limited by the layer with the lower SNR. Bit- and power allocation techniques for compensating these effects at the transmitter-side are also not the best option since they require a feedback channel. Therefore, a second equalization strategy is studied in the next subsection.

4.2 Successive Interference Cancellation

Successive interference cancellation (SIC) for MIMO systems is also known as the vertical BLAST (Bell Laboratories Layered Space-Time) architecture [11]. The corresponding system model is shown in Fig. 6. For notation purposes, let the quality of the first MIMO

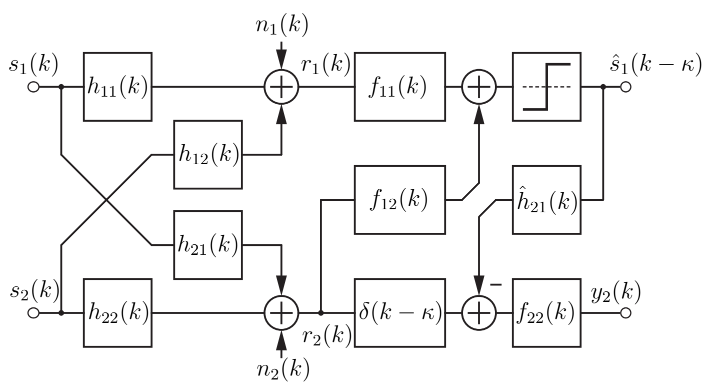


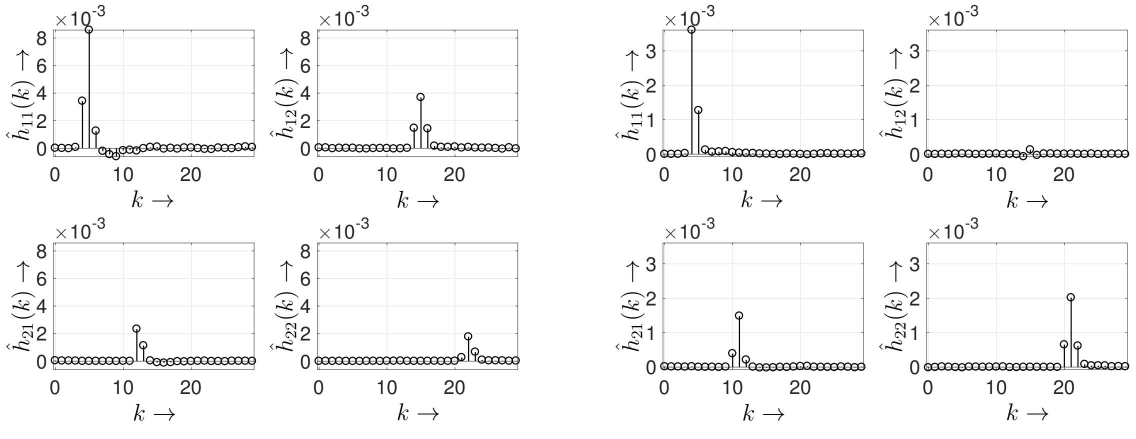
Figure 6: (2×2) MIMO channel and SIC equalizer

output signal be superior to the second output signal, i.e. $\theta_1 < \theta_2$ when considering the noise weighting factors of the ZF equalization as a quality indicator. In such conditions the SIC approach estimates the transmitted bits denoted by $\hat{s}_1(k-\kappa)$ of that specific channel with zero-forcing equalization and hard decision as shown in the block diagram. The parameter κ describes the delay induced by the equalization process. Based on these estimated transmit symbols the interference on the second output is calculated by convolution with the estimated channel impulse response $\hat{h}_{21}(k)$. Finally, the interference is subtracted at the second output taking κ into account by appropriately delaying the received signal $r_2(k)$. The remaining interference $h_{22}(k)$ is removed with the single-input single-output ZF equalizer $f_{22}(k)$. For simplicity the zero forcing criterion is used in the equalizer designs.

With the SIC approach the noise weighting factor of the second layer is smaller and just depends on the equalizer coefficients $f_{22}[k]$ as given by

$$\theta_{2,\mathrm{SIC}} = \sum_{k=0}^{L_\mathrm{f}-1} \left|f_{22}[k]\right|^2 \ , \tag{4}$$

resulting in an improved SNR compared to the ZF equalization. The noise weighting on the first layer is identical for both equalization methods, i.e. $\theta_{1,\mathrm{SIC}} = \theta_1$, since for SIC the same ZF equalizer is applied on this layer. However, wrong decisions at the first output affect the second output signal negatively. Therefore, the output with the lower BER, i.e. lower θ_μ when using equal modulation formats, should be detected first to reduce error propagation. This procedure is referred to as ordered SIC (OSIC). Also, the calculated interference subtracted from the second output is based on the estimated channel impulse response and therefore channel estimation errors affect the SIC approach negatively. A positive aspect of SIC is that the two equalizers can be designed independently.



(a) Without spatial filter (b) With spatial filter

Figure 7: Estimated MIMO channel impulse responses of a selected frame

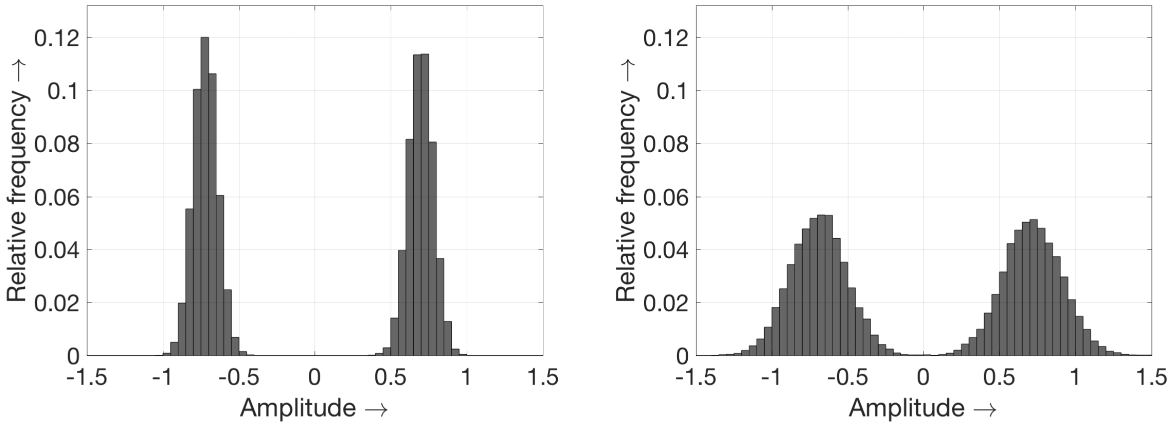


Figure 8: Relative frequencies of the zero forcing equalized sample amplitudes of the signals $y_1(k)$ (left) and $y_2(k)$ (right) with using a spatial filter when considering a selected frame

5 Results

A symbol rate of 2.5 GHz is used to transfer data through the 0.5 km MMF channel at an operating wavelength of 780 nm. The estimated (2×2) MIMO channel impulse response is shown in Fig. 7 for two testbed configurations. In the first configuration no spatial filters are implemented resulting in all MIMO sub channels to show significant contributions. Here, $h_{11}(k)$ represents the symbol-spaced channel impulse response with centric launch at the transmitter-side and the direct path through the fusion coupler DEMUX at the receiver-side. The second configuration uses a spatial filter to reduce the cross-talk from $h_{12}(k)$. However, this filter also attenuates the channel $h_{11}(k)$ as it can be seen from the estimated impulse responses. Figure 8 shows the histogram of the equalized received amplitudes of the signal $y_\mu(k)$, applying the ZF equalizer to the testbed configuration with spatial filter. Since the effort to remove the interferences at MIMO output $\nu = 2$ is higher, the equalized sample amplitudes show a higher variance compared to the samples at the first equalizer output.

The noise weighting factors θ_μ and the bit-error rate (BER) results of a selected frame for the two testbed configurations and equalizer concepts are compared in Table 1. Successive interference cancellation reduces the noise weighting θ_2 particularly in the case without using a spatial filter. It can also help to significantly reduce the BER. Comparing

Table 1: Comparison of different testbed configurations and equalization approaches analyzing a selected frame

Configuration	Without spatial filter		With spatial filter	
Equalization	ZF	OSIC	ZF	OSIC
$\theta_1 \cdot 10^{-5}$	2.98	2.98	0.85	0.85
$\theta_2 \cdot 10^{-5}$	**16.84**	4.83	5.15	4.94
BER Layer 1	$4 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	0	0
BER Layer 2	$73.2 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$	$6.98 \cdot 10^{-5}$	$10.46 \cdot 10^{-5}$
Total BER	$38.6 \cdot 10^{-3}$	$4.15 \cdot 10^{-3}$	$\mathbf{3.49 \cdot 10^{-5}}$	$5.23 \cdot 10^{-5}$

the different testbed configurations shows that using a spatial filter greatly improves the BER performance.

In Figure 9 the BERs dependency on different transmission frames is illustrated as empirical complementary cumulative distribution functions (CCDF). Both equalization approaches with spatial filter achieve BER results below the 10^{-3} forward error correction (FEC) threshold.

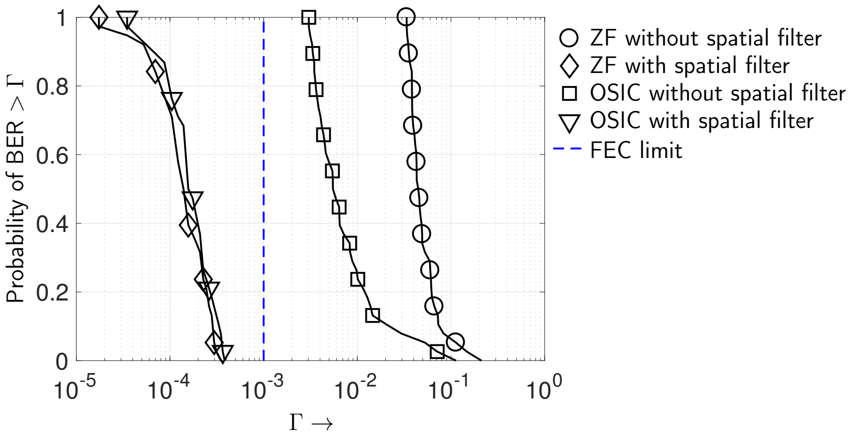


Figure 9: Empirical CCDFs showing the BER dependency on the analyzed 38 frames

6 Conclusion

In this contribution successive interference cancellation (SIC) known from wireless transmission has been compared to zero forcing equalization in an intensity modulated and directly detected optical (2×2) MIMO transmission with frequency-selective channel conditions. It has been shown that SIC can significantly improve the overall transmission quality in the analyzed MIMO testbed. It comprises a 0.5 km multi-mode fiber channel, fusion couplers for mode multiplexing and demultiplexing, SMF to MMF splices with different radial offsets for mode-selective excitation and an optional spatial filter. By employing the spatial filter in the testbed the BER performance is greatly improved in the analyzed configuration. A gross bit rate of 5 Gbps is achieved with an uncoded BER smaller than 10^{-3} at 780 nm operating wavelength.

References

[1] A. Ahrens and C. Benavente-Peces. Modulation-Mode and Power Assignment in Broadband MIMO Systems. *Facta Universitatis (Series Electronics and Energetics)*, 22(3):313–327, December 2009.

[2] J. Carpenter, B. J. Eggleton, and J. Schröder. 110x110 optical mode transfer matrix inversion. In *39th European Conference and Exhibition on Optical Communication (ECOC 2013)*, pages 1–3, September 2013.

[3] Donatella Darsena and Francesco Verde. Successive NBI Cancellation Using Soft Decisions for OFDM Systems. *IEEE Signal Processing Letters*, 15:873 – 876, December 2008.

[4] C. Fragouli, N. Al-Dhahir, and W. Turin. Training-based channel estimation for multiple-antenna broadband transmissions. *IEEE Transactions on Wireless Communications*, 2(2):384–391, March 2003.

[5] C. Koebele, M. Salsi, D. Sperti, P. Tran, P. Brindel, H. Mardoyan, S. Bigo, A. Boutin, F. Verluise, P. Sillard, M. Astruc, L. Provost, F. Cerou, and G. Charlet. Two mode transmission at 2x100Gb/s, over 40km-long prototype few-mode fiber, using LCOS-based programmable mode multiplexer and demultiplexer. *Opt. Express*, 19(17):16593–16600, August 2011.

[6] S. G. Leon-Saval, A. Argyros, and J. Bland-Hawthorn. Photonic lanterns: a study of light propagation in multimode to single-mode converters. *Opt. Express*, 18(8):8430–8439, April 2010.

[7] A. N. Mody and G. L. Stüber. Synchronization for MIMO OFDM Systems. In *Global Telecommunications Conference, 2001. GLOBECOM '01. IEEE*, volume 1, pages 509–513, 2001.

[8] S. Schöllmann and W. Rosenkranz. Experimental Equalization of Crosstalk in a 2 x 2 MIMO System Based on Mode Group Diversity Multiplexing in MMF Systems @ 10.7 Gb/s. In *Optical Communication (ECOC), 2007 33rd European Conference and Ehxibition of*, pages 1–2, September 2007.

[9] W. van Etten. An Optimum Linear Receiver for Multiple Channel Digital Transmission Systems. *IEEE Transactions on Communications*, 23(8):828–834, 1975.

[10] J. Wilde, C. Schulze, R. Brüning, M. Duparré, and S. Schröter. Selective higher order fiber mode excitation using a monolithic setup of a phase plate at a fiber facet. In *Proc. SPIE*, volume 9343, pages 93431P–93431P–11, 2015.

[11] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela. V-BLAST: An Architecture for Realizing Very High Data Rates over the Rich-Scattering Wireless Channel. In *International Symposium on Signals, Systems and Electronics (ISSSE)*, pages 295–300, Pisa, September 1998.