OPTICAL MIMO MULTIMODE FIBER LINKS
Channel Measurements and System Performance Analysis

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Keywords: Multiple-Input Multiple-Output System, Singular-value Decomposition, Bit allocation, Wireless transmission, Optical fibre transmission, Multimode fiber.

Abstract: Wireless communication is nowadays one of the areas attracting a lot of research activity due to the strongly increasing demand in high-data rate transmission systems. The use of multiple antennas at both the transmitter and receiver side has stimulated one of the most important technical breakthroughs in recent communications allowing increasing the capacity and dropping the bit-error rate. However, multiple-input multiple-output (MIMO) systems are not limited to wireless MIMO systems and can be observed in a huge variety of transmission links and network parts and have attracted a lot of attention since the mid 90's. In the field of optical MIMO transmission systems, multi-mode (MM) fibre offers the possibility to transmit different signals by different mode groups. The perspective of the MIMO philosophy within the field of optical transmission systems is elaborated in this contribution based on channel measurements within a (2×2) MIMO system. For the channel measurements the second optical window and a fibre length of $1,4$ km was chosen. Computer simulations on an overall data rate of $10,24$ Gbps underline the potential of multi-mode fibres in optical high-data rate MIMO communication systems and show that in order to achieve the best bit-error rate, not necessarily all MIMO layers have to be activated.

1 INTRODUCTION

The increasing desire for communication and information interchange has attracted a lot of research since Shannon's pioneering work in 1948. A possible solution was presented by Teletar and Foschini in the mid 90's, which revived the MIMO (multiple-input multiple-output) transmission philosophy introduced by van Etten in the mid 70's (Telatar, 1999), (Foschini, 1996), (van Etten, 1975), (van Etten, 1976).

Since the capacity of MIMO systems increases linearly with the minimum number of antennas at both the transmitter as well as the receiver side, wireless MIMO schemes have attracted substantial attention (McKay and Collings, 2005) and can be considered as an essential part of increasing both the achievable capacity and integrity of future generations of wireless systems (Kühn, 2006), (Zheng and Tse, 2003). However, the MIMO technique isn't limited to wireless communication and a lot of scenarios can be described and outperformed by the MIMO technique.

In comparison to the wireless MIMO channel, the optical fibre is an important type of a fixed-line medium, which is used in several sections of telecommunication networks, where single- and multi-mode fibres are distinguished (Singer et al., 2008), (Winters and Gitlin, 1990).

Optimizing the transmission on high-data rate links is in particular of great practical interest for delivering voice or video services in mobile IP (Internet Protocol) based networks in the access domain. Unfortunately, the inherent modal dispersion limits the maximum data speed within the multimode fiber (MMF). In order to overcome this limitation, the well-known single-input single-output systems, also called SISO systems, should be transferred into systems with multiple-inputs and multiple-outputs, also called MIMO systems (Hsu and Tarighat, 2006), (Singer et al., 2008). Taking finally into account that delay-spread in wireless broadband MIMO transmission systems isn't any longer a limiting parameter, MMF links should be well suited for high-speed data transmission (Raleigh and Cioffi, 1998), (Raleigh and Jones, 1999).

Different research groups, e.g. (Schöllmann and Rosenkranz, 2007), (Schöllmann et al., 2008), have adapted the MIMO technique on optical com-

Ahrens A., Pankow J., Aust S. and Lochmann S..
OPTICAL MIMO MULTIMODE FIBER LINKS - Channel Measurements and System Performance Analysis.
DOI: 10.5220/0003437201280132
In *Proceedings of the International Conference on Data Communication Networking and Optical Communication System* (OPTICS-2011), pages 128-132
ISBN: 978-989-8425-69-0

munication channels. The experimental equalization of crosstalk within frequency non-selective optical MIMO systems has attracted a lot of research (Schöllmann and Rosenkranz, 2007), (Schöllmann et al., 2008). By contrast, frequency selective MIMO links require substantial further research, where spatio-temporal vector coding (STVC) introduced by RALEIGH for wireless MIMO channels seems to be an appropriate candidate for optical transmission channels too (Raleigh and Cioffi, 1998), (Raleigh and Jones, 1999).

In this contribution the spatial multiplexing (SM) is implemented at the transmitter side via different sources launching light with different offsets into the fibre. At the receiver side, i.e. at the fibre end, various spatial filters are implemented (Pankow et al., 2011). By launching light with different offsets into the fibre, different mode groups are activated, which propagate along the fibre with different speed and attenuation. Together, with the crosstalk between the different mode groups, the classical MIMO channel is formed, where the most beneficial choice of the number of activated MIMO layers and the number of bits per symbol offer a certain degree of design freedom, which substantially affects the performance (Ahrens and Benavente-Peces, 2009).

Against this background, the novel contribution of this paper is that based on channel measurements within a (2×2) optical MIMO system, the perspective of the MIMO philosophy within the field of optical transmission systems is elaborated. Our results show that even for relatively long (e. g. $1,4$ km) transmission lengths high data rates (e. g. $10,24$ Gbps) are feasible and that the choice of the number of bits per symbol and the number of activated MIMO layers substantially affects the performance of a MIMO system, suggesting that not all MIMO layers have to be activated in order to achieve the best BER.

The remaining part of this paper is organized as follows: Section 2 introduces the optical MIMO channel. The crosstalk impact within the optical MIMO channel is studied in section 3, while the associated performance results are presented and interpreted in section 4. Finally, section 5 provides some concluding remarks.

2 OPTICAL MIMO CHANNEL

In order to comply with the demand on increasing available data rates, systems with multiple inputs and multiple outputs, also called MIMO systems (multiple-input multiple-output), have become indispensable and can be considered as an essential part of increasing both the achievable capacity and integrity of future generations of communication systems (Kühn, 2006), (Zheng and Tse, 2003).

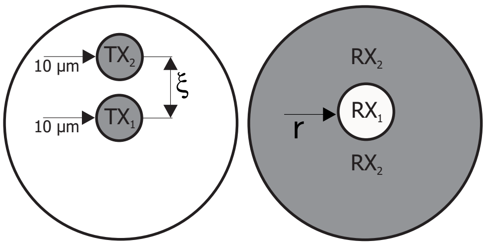

Figure 1: Forming the optical MIMO channel (left: light launch positions at the transmitter side with a given eccentricity ξ, right: spatial configuration at the receiver side as a function of the mask radius r).

In this work the potential of the MIMO philosophy in optical channels is elaborated, based on channel measurements. Basically, light launched at different positions within the fibre activates different mode groups, which propagate along the fibre with different speed. Low order mode groups, activated by light launched into the center of the fibre, lead to a power radiation pattern concentrated at the center of the fiber end whereas higher order modes, activated by light launched at an off-center position, e. g., with a given eccentricity ξ, within the fibre, lead to power radiation pattern concentrated at the off-center of the fiber-end. Therefore, by launching light into the fibre with given eccentricities, as highlighted in Fig. 1, different spatially separated power distribution pattern can be obtained at the receiver side to form the optical MIMO channel.

According to Fig. 1, the optical input TX_1 was adjusted to launch light into the center of the core (center launch condition), whereas for the optical input TX_2 a given eccentricity ξ was chosen (off-center launch condition). The activated modes can be separated at the fibre end by the corresponding power distribution pattern. Fig. 2 illustrates the simulated power distribution pattern by activating low- and high-order modes. The simulations are in good agreement with the measured power radiation pattern as depicted in Fig. 3 for different parameters of the eccentricity ξ. Now, spatial ring filters at the end of the transmission line as depicted in Fig. 1 have been applied for channel separation. These spatial filters have been produced by depositing a metal layer at fiber end-faces and subsequent ion milling (Pankow et al., 2011), (Pankow et al., 2010).

Together, with the crosstalk between the different mode groups, the classical MIMO channel is formed (Fig. 4) (Pankow et al., 2011), (Pankow et al., 2010).

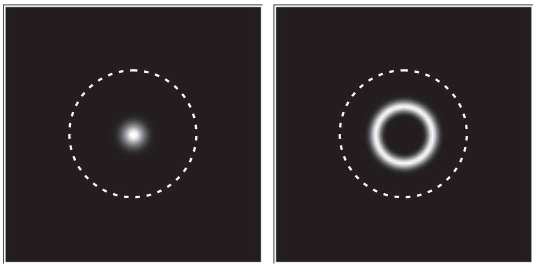

Figure 2: Simulated mean power distribution pattern (left: by the LP_{01} mode, right: by activating all solutions of LP_{81} modes); the dotted line represents the $50\,\mu$m core size.

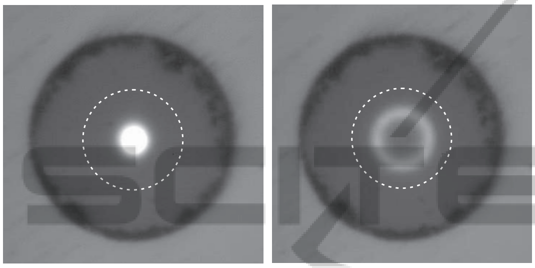

Figure 3: Measured mean power distribution pattern as a function of the light launch position (left: eccentricity $\xi = 0\,\mu$m, right: eccentricity $\xi = 18\,\mu$m); the dotted line represents the $50\,\mu$m core size.

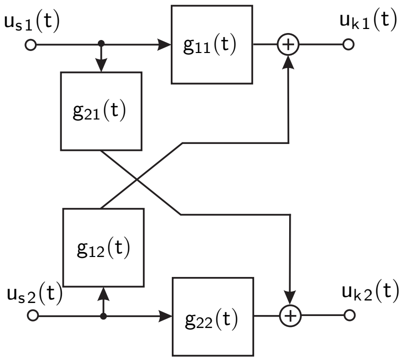

Figure 4: Electrical MIMO system model (example: $n = 2$).

3 CROSSTALK IMPACT

In this section it is studied, how the crosstalk impact depends on the MIMO system configuration. Therefore at this point the eccentricity of the transmitter side MIMO configuration as well as the mask radius of the ring filter configuration at the receiver side are investigated in an exemplary system according to Fig. 5. It is assumed, that each MMF input is fed by a system with identical mean properties with respect to transmit filtering, pulse frequency $f_T = 1/T_s$, the number of signalling levels and the mean transmit power P_s.

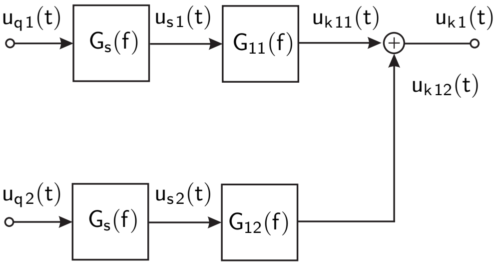

Figure 5: Electrical system model of transmitter and MMF with crosstalk (example: $n = 2$).

The source signals $u_{q1}(t)$ and $u_{q2}(t)$ traverse the transmit filters with the transfer function $G_s(f)$. Then the wanted transmit signal $u_{s1}(t)$ passes the MMF, modelled by the transfer function $G_{11}(f)$ and causes the signal $u_{k11}(t)$ with power P_{k11} at the MMF output, whereas the crosstalk signal $u_{k12}(t)$ (with power P_{k12}), which is fed into the MMF with a given eccentricity ξ, originates at the MMF output, after the transmit signal $u_{s2}(t)$ passed the filter with the transfer function $G_{12}(f)$, which models the coupling from optical input 2 to the output 1 (Fig. 5).

In general, the MIMO performance is affected by both the mask radius r and the eccentricity ξ. As highlighted in Fig. 6, the power of the wanted signal $u_{k11}(t)$ at the MMF output, distributed in the inner ring, increases monotonically with rising mask radius r, whereas at the same time the power of the wanted signal $u_{k22}(t)$, distributed in the outer ring, decreased with increasing mask radius and increased eccentricity. In addition a channel asymmetry can be observed which is caused by the larger differential mode attenuation of the higher order mode groups. From this point of view it can be concluded that a mask radius in the range of 5μm to 15μm should be chosen in order to have adequate power at both outputs.

From a practical point of view the power $P_{k12}(\xi, r)$ of the crosstalk signal $u_{k12}(t)$ at the MMF output is an interesting indicator for the strength of the crosstalk disturbance, which depends on the mask radius r and the eccentricity ξ. In order to assess the effect of crosstalk on the wanted signal not only the pure crosstalk signal power is of interest, but rather the behaviour of the powers of the wanted signal and the crosstalk signal to each other. This behaviour may be investigated by a signal-to-crosstalk-interference ratio (SCIR)

$$\rho_{k11}(\xi, r) = \frac{P_{k11}(0, r)}{P_{k12}(\xi, r)} \quad \text{and} \quad \rho_{k22}(\xi, r) = \frac{P_{k22}(\xi, r)}{P_{k21}(0, r)} \ . \tag{1}$$

Since MIMO makes use of the interference for channel improvement the SCIR should not be chosen as high as possible like in orthogonal transmission. Referring to Fig. 7 this means for lower order modes

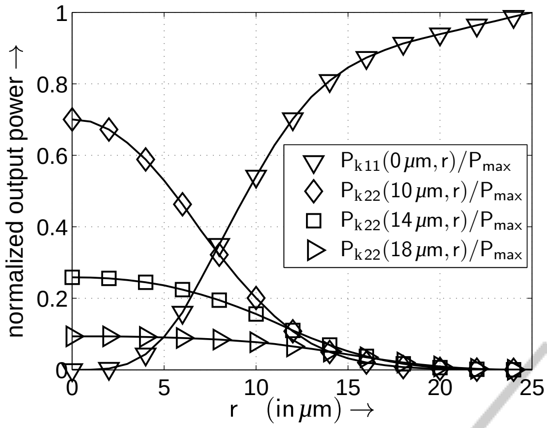

Figure 6: Measured electrical signal power $P_{\mathrm{k}\nu\mu}(\xi, r)$ at the MMF output as a function of the mask radius r for given parameters of the eccentricity ξ.

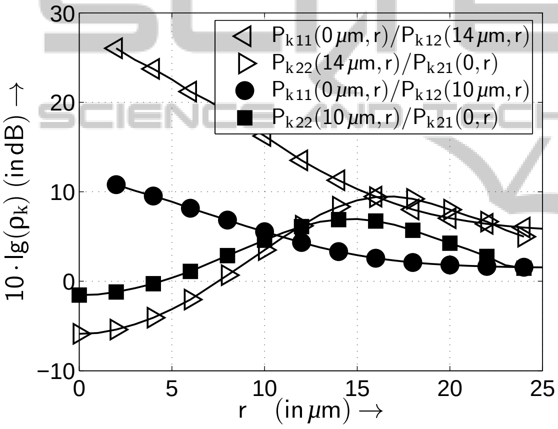

Figure 7: Electrical signal-to-crosstalk-interference ratio (SCIR) ρ_{k} at the MMF outputs as a function of the mask radius r and the eccentricity ξ.

(output 1) a movement towards larger mask radiuses and vice versa for higher order mode groups (output 2).

Though a relationship between the spatial mode location and the channel's impulse response needs to be established for an exact BER (bit-error rate) tradeoff it can already been concluded from Fig. 6 and Fig. 7 that mask radiuses in the range of about $5\,\mu$m to $15\,\mu$m should be used for further BER analyses.

4 PERFORMANCE ANALYSIS

For BER analysis, a frequency selective SDM (spatial division multiplexing) MIMO link, composed of n_{T} inputs and n_{R} outputs, is considered. The block-oriented system for frequency selective channels is modelled by

$$\mathbf{u} = \mathbf{H} \cdot \mathbf{c} + \mathbf{w} \ . \qquad (2)$$

In (2), the transmitted signal vector **c** is mapped by the channel matrix **H** onto the received vector **u**. Finally, the vector of the additive, white Gaussian noise (AWGN) is defined by **w** (Pankow et al., 2011), (Ahrens and Benavente-Peces, 2009). The interference between the different input's data streams, which is introduced by the off-diagonal elements of the channel matrix **H**, requires appropriate signal processing strategies. A popular technique is based on the singular-value decomposition (SVD) (Haykin, 2002) of the system matrix **H**, which transfers the whole system into independent, non-interfering layers having unequal gains (Pankow et al., 2011), (Ahrens and Benavente-Peces, 2009).

In this contribution the efficiency of fixed transmission modes is studied regardless of the channel quality. Assuming predefined transmission modes, a fixed data rate can be guaranteed.

For numerical analysis it is assumed, that each optical input within the MMF is fed by a system with identical mean properties with respect to transmit filtering and pulse frequency $f_{\mathrm{T}} = 1/T_{\mathrm{s}}$. Within this work, the pulse frequency f_{T} is chosen to be $f_{\mathrm{T}} = 5,12$ GHz. The average transmit power is supposed to be $P_{\mathrm{s}} = 1\,\mathrm{V}^2$ and as an external disturbance a white Gaussian noise with a power spectral density N_0 is assumed. In order to transmit at a fixed data rate, an appropriate number of MIMO layers has to be used, which depends on the specific transmission mode, as detailed in Tab. 1 for the investigated (2×2) optical MIMO system.

Table 1: Investigated transmission modes.

throughput	layer 1	layer 2
2 bit/s/Hz	4	0
2 bit/s/Hz	2	2

The obtained BER curves are depicted in Fig. 8 for the different ASK (amplitude shift keying) constellation sizes of Tab. 1. For the investigations, an eccentricity of $\xi = 10\,\mu$m and a mask radius of $r = 15\,\mu$m was assumed, which was found to be beneficial for minimizing the overall BER at a fixed data rate. Assuming a uniform distribution of the transmit power over the number of activated MIMO layers, it turns out that not all MIMO layers have to be activated in order to achieve the best BERs.

5 CONCLUSIONS

In this paper the perspective of the MIMO philosophy

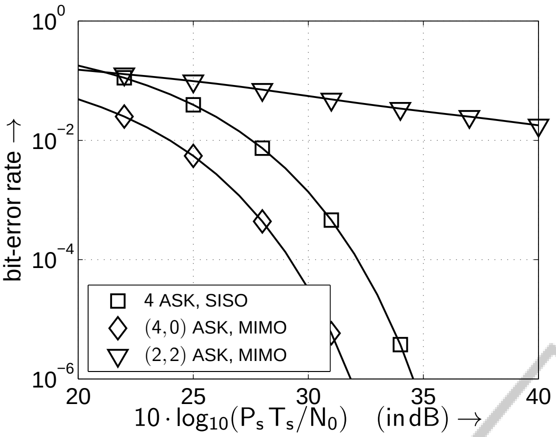

Figure 8: BER when using the transmission modes introduced in Tab. 1 and transmitting 2 bit/s/Hz over frequency selective optical MIMO channels.

within the field of optical transmission systems is investigated. Our results, obtained by channel measurements and computer simulations, show the potential of MIMO techniques in the field of optical transmission systems. In combination with appropriate MIMO signal processing strategies, an improvement in the overall BER was obtained.

ACKNOWLEDGEMENTS

The authors wish to thank their co-worker, Mr. Ralph Bornitz, for supporting the measurement campaign.

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