# Experimental Realisation of 3 x 3 MIMO System with Mode Group Diversity Multiplexing Limited by Modal Noise

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**Abstract:** We show experimentally the feasibility of a 3x3 MIMO system based on Mode Group Diversity Multiplexing over GI-MMF. The main limiting effect of modal noise is reduced by large detection areas.

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## 1. Introduction

Silica multimode fibre (MMF) as well as plastic optical fibre (POF) seem to be the most promising candidates for the increasing demand for high speed local area networks and short optical interconnects in high performance computing (HPC) due to low cost components and easy handling compared to single mode fibre (SMF) [1]. However, MMF and POF are characterised by a low bandwidth distance product compared to SMF due to its multi mode character which implies mode dispersion as main limiting transmission effect. Recently, the mode group diversity multiplexing (MGDM) approach was discussed as a candidate with a high potential to overcome this bandwidth limitation [1]. Until now, several successful realizations of this approach have been presented for 2x2 MIMO environments [2,3]. In this paper, we show experimentally and by simulations the possibility to realise even a 3x3 MIMO system with this approach. However, we observed a strong influence of modal noise and interference between co-propagating signals which seems to be the main limiting effect of this setup.

## 2. Experimental setup of 3x3 MIMO system

In general, the 3x3 MIMO approach based MGDM is characterized by the assignment of three different signals $s_1(t)$, $s_2(t)$ and $s_3(t)$ to different mode groups (co-propagating over the fibre). This is realized by different launching positions at the transmitter. The received signals $y_1(t)$, $y_2(t)$ and $y_3(t)$ are detected at different areas of MMF's cross section. The correlation between the input and the output signals is mathematically described by the following formula: $\vec{y}(t) = \vec{H} \cdot \vec{s}(t)$. The vectors $\vec{y}(t)$ and $\vec{s}(t)$ represent the three input signals and three output signals. $H$ stands for a transfer matrix (coefficients: $h_{11}$, $h_{12}$, $h_{13}$; $h_{21}$, $h_{22}$, $h_{23}$; $h_{31}$, $h_{32}$, $h_{33}$) which describes the power influence from input signal $s_m(t)$ ( $m \in 1,2,3$ ) to output signal $y_n(t)$ ( $n \in 1,2,3$ ). This matrix has to be determined in a first step by a training sequence. Afterwards, the matrix is used for offline equalisation by matrix inversion of the crosstalk between the co-propagating signals [3]. This equalization process is based on the formula $\overrightarrow{y_{eq}}(t) = \overrightarrow{H^{-1}} \cdot \overrightarrow{y}(t)$, where $\vec{y}(t)$ stands for the vector of the received signal, $\overrightarrow{H^{-1}}$ for inverse transmission matrix and $\overrightarrow{y_{eq}}(t)$ for the equalised signal vector. Fig. 1 shows the setup of the investigated 3 x 3 MIMO system.

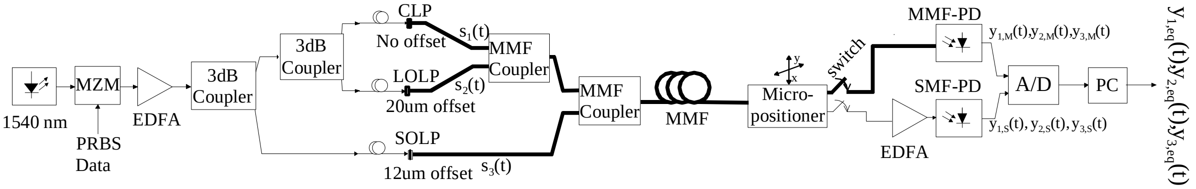


Fig. 1: Experimental setup with three launching positions at transmitter: centre launch position (CLP) with no offset, small offset launch position with 12 um offset (SOLP) and large offset launch position (LOLP) with 20 um offset; demultiplexing of three signals by three different detection positions realized by micropositioner with two detection setups: large detection area with MMF (upper arm) ($y_{1,M}(t)$, $y_{2,M}(t)$, $y_{3,M}(t)$) or small detection area with SMF (lower arm) ($y_{1,S}(t)$, $y_{2,S}(t)$, $y_{3,S}(t)$); offline equalization after detection with photodiode ($y_{1,eq}(t)$, $y_{2,eq}(t)$, $y_{3,eq}(t)$).

The light of the single mode laser ($\lambda$=1540nm) is modulated by one Mach Zehnder Modulator (MZM) which is driven with a PRBS sequences of length $2^7$-1 (short length has to be used due to the limited memory space of the oscilloscope for crosstalk equalisation). The data rate is set to 2 Gb/s which gives a total data rate of 6 Gb/s (again, the data rate is set to a low level due to the limited memory space of the oscilloscope). Afterwards the signal is amplified by an EDFA and split into three different arms. The input signal power for each signal is set to -2 dBm and the three streams are decorrelated by means of different delays. Three different restricted launching positions from SMF (thin line) to MMF (thick line) are chosen for assigning $s_1(t)$, $s_2(t)$ and $s_3(t)$ to different mode groups: $s_1(t)$ to centre launch position (CLP) with no offset (realized by direct connection), $s_2(t)$ to small offset launch position

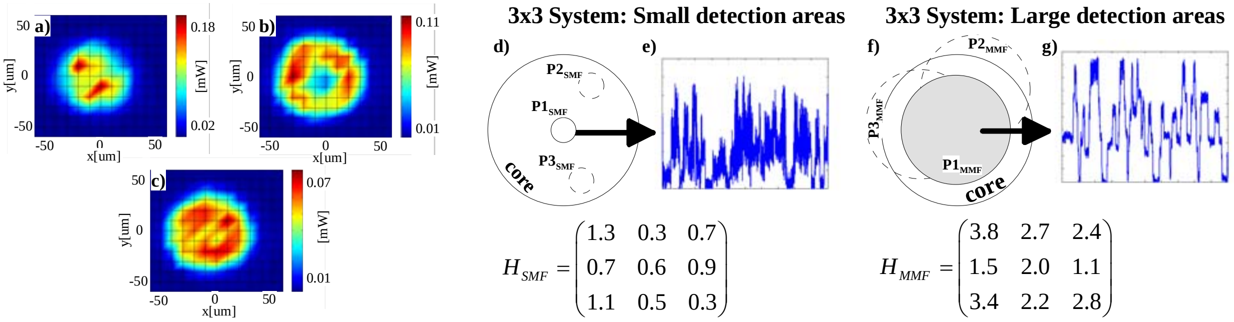
(SOLP) with 12 um offset (position optimized by means of simulations) realized by a micropositioner (MP) and $s_3(t)$ to large offset launch position (LOLP) with 20 um offset (realized by an offset connector consisting of a patch cord). Afterwards the signals are coupled together by two couplers and the multiplexed signal is transmitted over one meter of GI-MMF with core diameter of 62.5 um. This short length is taken due to the fact that we are primarily interested in the investigation of the combined influence of modal noise (highest influence for short distances [6]) and crosstalk distortions between co-propagating signals. In [3] a successful crosstalk equalisation is shown even for longer distances. The determination of the three output signals $y_1(t)$, $y_2(t)$ and $y_3(t)$ is realised by a micropositioner which gives the possibility to detect at three different positions of MMF's cross section. Thereby, two different detector sizes can be chosen to investigate the influence of interference and modal noise as well as crosstalk equalisation: 9 um diameter realized with a SMF ($y_{1,S}(t)$, $y_{2,S}(t)$, $y_{3,S}(t)$) and 50 um diameter realized with a MMF ($y_{1,M}(t)$, $y_{2,M}(t)$, $y_{3,M}(t)$). The signal has to be amplified only for SMF detection due to the loss (approximately 15 dB) resulting from small detection area. Finally, the signals are saved with an oscilloscope as analogue to digital converter followed by a crosstalk equalization offline at the PC ($y_{1,eq}(t)$, $y_{2,eq}(t)$, $y_{3,eq}(t)$).

## 3. Experimental investigation of detector influences on diversity aspects and modal noise

Fig. 2a-2c show the intensity distributions for the CLP, SOLP and LOLP launching positions. These are measured by scanning (in steps of 10 um with micropositioner) the cross section of the MMF with a SMF (core diameter: 9um) if only one signal (CLP, SOLP or LOLP) is switched on. We observe two intensity maxima close to the centre of the core for CLP launching position (fig. 2a) whereas the intensity distribution for SOLP (fig. 2b) is characterized by approximately a donut shape. By launching in LOLP the intensity is nearly equally distributed (except for two small minima) over the whole core area (fig. 2c).

The concentration of the intensity for CLP in the centre of the core is due to the excitement of low order modes which are travelling mostly in the centre [4]. The fact that we observe two maxima instead of the expected single maximum [2, 4] might be explained by using two MMF couplers which seem to have an influence on the intensity distribution. By using SOLP high order modes are excited which are travelling mostly in the core cladding region. We would expect a similar distribution for the LOLP (shown in [2, 4]) but it seems that the second coupler changes significantly the intensity distribution.

In fig. 2d and fig. 2f the three detection positions (P1-P3 correspond to the three different output signals $y_n(t)$) for the small detection area and the large detection area are shown, respectively. In addition, the determined data output sequences are shown in fig. 2e (small detection area) and 2g (large detection area) for detection position 1. For detection with a small area, we see a very noisy signal. This noise influence is mainly based on modal noise and interference between the co-propagating signals (experiments showed that EDFA noise influence is negligible). As explained in detail in [5, 6], both influences gain significantly in importance by detecting small areas of a MMF's cross section and are highly sensitive to micro vibrations of the MMF and on frequency instabilities of the laser. This limiting influences can be reduced either by a sufficient intensity separation of the signals (shown in [2] for a 2 x 2 system] or by a large detection area [5, 6]. Due to the fact that a sufficient separation in the 3 x 3 system is not possible (fig. 2a-2c), we choose large detection areas to reduce the noise influence. The successful reduction of the noise influence is clearly visible by a nearly noiseless multilevel data sequence shown in fig. 2j. The influence of these limiting effects has to be investigated in more detail concerning the fibre length and input power.



$$H_{SMF} = \begin{pmatrix} 1.3 & 0.3 & 0.7 \\ 0.7 & 0.6 & 0.9 \\ 1.1 & 0.5 & 0.3 \end{pmatrix} \qquad H_{MMF} = \begin{pmatrix} 3.8 & 2.7 & 2.4 \\ 1.5 & 2.0 & 1.1 \\ 3.4 & 2.2 & 2.8 \end{pmatrix}$$

Fig. 2: Intensity distributions for CLP (a), SOLP (b) and LOLP (c); three different detection positions for small (d) and large (f) detection areas with corresponding transmission matrixes $H_{SMF}$ and $H_{MMF}$; received data sequences at position 1 for small (e) and large (g) detection area.

Finally, by using a training sequence we determine the transmission matrices (rows represent different detection points) $H_{SMF}$ and $H_{MMF}$ for the small and large detection area, respectively. Due to the strong noise influences that imply high intensity fluctuations it is very hard to determine an accurate power transfer matrix $H_{SMF}$ for the small detection area. Nevertheless, we find two positions where CLP signal (row one) and the LOLP signal (row two) is dominating. In contrast to that, we determined an accurate $H_{MMF}$ matrix (very small distortion due to intensity fluctuations) for the large detection area. However, it is impossible to find a position where LOLP signal is dominating due to the large detection area. In addition, we can see that row one and row three in the matrix show nearly no difference (small grade of diversity). In summary, this means that the reduction of modal noise by the large detection area is at the cost of a loss of diversity.

## 4. Experimental results of 3x3 MIMO system

Our experimental results for the investigated 3x3 MIMO system with the small and large detection area are shown in fig. 3a and fig. 3b, respectively. Thereby, the upper row represents the signal sequence saved by our oscilloscope. The normalised low pass filtered (Butterworth filter with cut off frequency of 2 GHz) and equalized signals (inversion of the transmission matrix) as well as the original input data (dotted line) are shown in the middle row. The corresponding eye diagrams of the equalized signals (solid line in the middle row) are drawn in the third row.

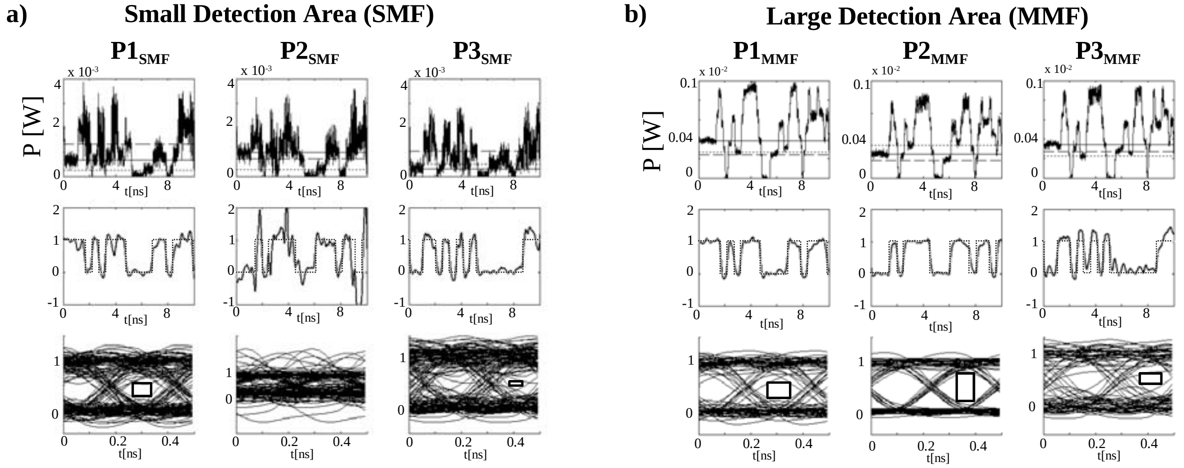


Fig. 3a and fig. 3b: Experimental results for 3x3 MIMO system with small detection area (left) and large detection area (right); upper rows: data saved by oscilloscope; middle rows: low pass filtered and equalized (by matrix inversion) signals; lower rows: corresponding eye diagrams.

By detecting with the small area in all detection positions ($P1_{SMF}$, $P2_{SMF}$, $P3_{SMF}$) we observe very noisy data sequences (fig. 3a). This underlines the high modal noise and interference influence for all detection positions. The equalized and low pass filtered signals (middle row) show strong deviations from the original signals (dotted line in the second row). Thereby, the SOLP launched signal is of the worst performance which is explained by the noise influence and strong crosstalk from CLP and LOLP (also visible in the transmission matrix $H_{SMF}$). Therefore, we only observe small opened eyes for the CLP and the LOLP signal and a strongly degraded eye for the SOLP signal. In contrast to that, we see for all detection positions of the large detection area ($P1_{MMF}$, $P2_{MMF}$, $P3_{MMF}$) (fig. 3b) multilevel data sequences (first row) which are only slightly influenced by noise. In addition, we see only slight deviations between the input signals and the equalized and low pass filtered signals (second row). We observe only for the LOLP signal stronger deviations which are explained by the small grade of diversity (see $H_{MMF}$ in fig. 2) by detecting with the large area (this includes high values in the inverse matrix which amplifies noise influences). Nevertheless, for all detection positions we see opened eyes which show the feasibility of a 3 x 3 MIMO system based on MGDM. We expect a system performance improvement if the detection area size will be between SMF and MMF diameter because we would achieve a high grade of diversity as well as a moderate noise influence.

## 5. Conclusion

We show experimentally the feasibility of using a 3 x 3 MIMO system based on Mode Group Diversity Multiplexing (MGDM) to overcome the bandwidth limitation of GI-MMF. Three different detection areas are investigated. Thereby, it is observed that small detection area suffers strongly from modal noise and interference influences of co-propagating signals. These limiting influences can be significantly reduced by using a larger detection area. Therefore, after equalization all three signals can be successfully received.

## Acknowledgment

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