High Speed Transmission over MMF and PF-POF using MIMO Approach

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Motivation

Initial Point: High speed transmission over short distances (< 300m)

Multi Mode Fibre & Plastic Optical Fibre

- Easier handling compared to SMF
  - Bending
  - Connectors
  - Cheaper components

- Short reach at high speed
  - Low bandwidth distance product

Research Topic: Increase of bandwidth distance product

Existing
- Coarse (C)WDM
- Equalization

Alternative
- Mode Group Diversity Multiplexing
Outline

• Motivation
• Introduction
  – Multi Mode Fibre (MMF) and Plastic Optical Fibre (POF)
  – Optical Multi Input Multi Output (MIMO) system
• Experimental Investigations
  – Intensity distributions for different launching positions
  – Mode dispersion
  – Crosstalk
  – Equalization
• Conclusion and outlook
**Introduction (1)**

**MMF and POF**

- Large core diameter
  (MMF: 50 – 62,5 μm; POF: 62,5 -1000 μm)
  - Multi mode character
    - Mode dispersion
    - Mode coupling

**Impulse Response**

\[ h(t) = \sum_{m=0}^{M-1} P_m \delta(t - \tau_m) \]

- \( M \) = Number of excited mode groups
- \( P_m \) = Power of mode group \( m \)
- \( \tau_m \) = Time delay of mode group \( m \)

With the effect of mode coupling

\[ P_m = \sum_{n=0}^{N-1} \gamma_{n,m} \cdot P_n \]
Introduction (2)

Principle of Mode Group Diversity Multiplexing as MIMO approach

- Multiplexing: Assignment of different signals to different mode groups
- De-Multiplexing: Separation of different mode groups

Transmitter:
- Restricted launching spots
- High order modes
- Low order modes

Receiver:
- High order modes
- Low order modes

Power distribution in MMF/POF

Introduction (2)

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Power distribution in MMF/POF

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Experimental Setup

![Experimental Setup Diagram]

**Mode Mux**

- 1540 nm
- 5.35 Gb/s Data
- VOA
- GI-MMF/POF
- Mode Mux
- SMF
- MMF
- OLP

**Mode DeMux**

- Micro-positioner
- 2x1 Coupler
- SMF
- BER

**Experimental Setup Details**

- **s_1(t)**
- **s_2(t)**
- **y_1(t)**
- **y_2(t)**
- **h_11**
- **h_12**
- **h_21**
- **h_22**

**Fixed MMF/POF**

- Moveable MMF
- SMF
- d = 62.5 um
- d = 9 um

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Experimental Results (1)

Intensity distributions for different launching positions on MMF

Centre Launch Position
- Concentration of power in the centre of the core

Offset Launch Position
- Power is distributed over complete core radius (closer to core cladding)
Experimental Results (2)

Intensity distribution after 300 m GI-MMF

CLP, 0 um  OLP, 20 um

No significant change for intensity distributions at CLP and OLP
Experimental Results (3)

Demultiplexing of the signals (MMF)

- 1 x 10.7 Gb/s
  - Transmitter
  - MMF’s core
  - Overfilled launch position
  - Receiver
  - MMF’s core
  - Complete detection area

- 2 x 5.35 Gb/s with MGDM

- Completely distorted eye based on mode dispersion
- No error free transmission
- Reduction of mode dispersion,
- Wide open eyes \(\rightarrow\) error free transmission is possible
- Reduced influence of mode dispersion
- Widened one level \(\rightarrow\) higher influence of crosstalk

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Experimental Results (4)

Performance analysis: MGDM with different power levels for $s_1(t)$ and $s_2(t)$

Equal power levels

- Strong mode coupling from low order modes to high order modes for equal power levels
- **Equalization**

Unequal power levels

- **Significant reduction for increasing** $\Delta P = P_2 - P_1$

$\Delta P_{dB} = (P_2 - P_1)_{dB}$
Experimental Results (5)

Intensity distributions after 10m GI-POF

CLP

OLP, 20 um

No significant change in intensity distributions for CLP and OLP
Experimental Results (6)

Demultiplexing of the signals (POF)

- Wide open eye for CDP
  - low influence of mode dispersion
  - low interference from second channel

- Wide open eye for ODP
  - more distorted due to
    - Mode dispersion
    - High crosstalk from second signal
Revised Experimental Setup

Influence of slight variations at CLP

- Only Centre Launch Position is varying
  - Realized with a second micropositioner
  - Variation from 0 um to 6 um offset
  - Crosstalk is measured by BER measurements in the second channel
Experimental Results (7)

Influence of slight variations at CLP

- 0 um to 3 um offset
  - no significant performance change
- 4 um and 5 um offset
  - significant performance reduction to a BER of $10^{-4}$
- 6 um offset
  - BER of $3\times10^{-3}$ → Correction by standard FEC is not possible
  - Equalization
Equalization

Reduction of crosstalk by zero forcing in a 2 x 2 MIMO system

\[ y_1(t) = h_{11} \cdot x_1(t) + h_{21} \cdot x_2(t) \]
\[ y_2(t) = h_{12} \cdot x_1(t) + h_{22} \cdot x_2(t) \]

- Until now: Assumption \( h_{12} = 0 \) und \( h_{21} = 0 \)

**New approach:**

Determination of transmission coefficients \( h_{11}, h_{12}, h_{21} \) and \( h_{22} \)

\[
x_1(t) = \frac{y_1 \cdot h_{22} - y_2 \cdot h_{21}}{h_{11} \cdot h_{22} - h_{12} \cdot h_{21}}
\]
\[
x_2(t) = \frac{y_1 \cdot h_{12} - y_2 \cdot h_{11}}{h_{12} \cdot h_{21} - h_{22} \cdot h_{11}}
\]
Experimental Equalization Setup

Two MMF detection points

- Two detection points with different power influence of the signals (Distance: 10 um)
- Determination of the transmission coefficients \( h_{11}, h_{12}, h_{21}, h_{22} \)
- Sampling the bit sequences with the oscilloscope at both points \( (y_1 \text{ and } y_2) \)
- Offline equalization
Experimental Results (8)

Two MMF detection points

Detection Point 1

Detection Point 2

- Both eye diagrams show four different power levels (00, 01, 10, 11)
- Completely distorted eye due to crosstalk
Experimental Results (9)

Determination of transmission coefficients

Detection point 1

- Determination of the transmission coefficients by detecting only one signal
- Only power influence is measured

Influence of signal 1

\[ h_{11} \]

Influence of signal 2

\[ h_{21} \]
Experimental Results (10)

Without equalization

With equalization

Successful equalization of crosstalk
Conclusion & Outlook

- Experimental investigations of MIMO approach using MMF/POF
- Experimental realization of a 2 x 2 MIMO setup based on MGDM
  - Reduction of the mode dispersion influence
  - Investigation of crosstalk between the channels
    - Dependant on the power levels in the channels
    - Dependant on the exact launching positions
  - Successful equalization of crosstalk by zero forcing method
- Investigation of modal noise in optical MIMO systems