Coherent Multi Channel Transmission over Multimode-Fiber and Related Signal Processing

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Abstract: Different aspects of transmission over multimode fiber are discussed with a focus on the requirements for outage free transport over a few mode fiber when applying MIMO processing at the receive side.

OCIS codes: (060.1660) Coherent communications, (060.4510) Optical communication

1. Introduction

To overcome these fundamental capacity limitations of the multimode fiber (MMF) introduced by modal delay (DMD), the exploitation of the transport on different fiber modes is topic of intense research since several years for access networks [1-3]. Recently this exploitation of the space domain has also been re-formulated for ultra-high bit-rate transmission to conform the steadily growing demand for capacity in metro and core network [4 5]. Specifically the MMF approach, i.e. the use the different modes of an MMF, has the advantage that a boost of capacity is not accompanied by an increase of fiber count and only one physical port has to be managed.

We can distinguish between two cases of optical signal paths depending on whether coupling of MMF fiber modes occur within the MMF: (i) In the case of short link lengths with negligible coupling the system design target commonly is to excite different modes or mode groups for the different channels, and to separate these different fiber modes/mode groups by optical [6] or electronic means at the receiver [7]. On the other hand, (ii) if mode mixing takes place due to micro or macro bending of the MMF [8] or coupling at connectors, electronic signal processing at receiver and/or transmitter appears inevitable. This so called MIMO (multiple-input multiple-output) processing has its roots in wireless communications [9] and has been discovered for optics about a decade ago [1].

So far, only a few reports are published highlighting that if mode conversion cannot be excluded, the quality of the different channels are statistically changing due to the drifting optical phases of the signals propagating along different modes [3]. Opposite to most applications in wireless, for optical transport systems a stable and reliable link between transmitter/receiver pair is mandatory or at least desirable.

Therefore we will mainly discuss the system requirements, i.e. modulation format and detection concept, fiber property, and the coupling between transmitters/receivers to the MMF in view of a stable transport over MMF.

System layout and modulation format

Due to MUI (multi user interference) at one receiver it matters whether phase noise of the different transmitters can be considered as sufficiently slow allowing the MIMO processing in the receiver to mitigate it, or whether they appear as additional noise. If (1) incoherent transmitters will be used such as different intensity modulated laser diodes, strong degradation by beat-noise will occur, as it was experimentally demonstrated in [7] and application for MGD and low mode coupling appears favorable. In the case of (2) coherent transmitters, all optical carriers are coming from the same lower linewidth laser source and are modulated by different external modulators [2]. Even in this case, either (i) direct detection (DD) receivers for intensity modulated symbols (bits) or phase modulated RF subcarrier (RF-SC) can be applied. Or (ii) we can take advantage of coherent detection allowing for polarization multiplexing of a single carrier or of optical OFDM signals. Specifically OFDM relaxes the requirements on differential modal delay of the MMF due to the inherent low symbol rate even for multi-Gigabit/s data rates.

Today, stable and outage-free operation is only understood for coherent transmission systems exhibiting a liner relation between optical signal fields and electrical signals in fiber and transmitter/receiver electronics, respectively. For direct detection systems [see e.g. 10] obeying the non-linear square-law detection process, the total elimination of outage appears questionable.

Multimode fiber design and signal propagation

Opposite to mobile communications where the total power received by all antennas increases with the number of transmission paths, in optics the upper bound of received power is fixed and thus the maximum possible capacity cannot be increased by increasing the modes. Nonetheless, the MMF mode number determines the statistical a spreading of the transmission quality. This is illustrated by Fig. 1 showing histograms of the theoretical maximum achievable capacity $C = \log_2 \left\{ \det \left(I_M + \rho \, HH^{*T} \right) \right\}$ (bits/s/Hz for a given signal to noise power ratio ρ) for the transmission of 4 channels with coherent transmitter and coherent receiver. A higher number of MMF modes leads to statistical spreading of the capacity, as shown by the right hand figure for a 10 mode MMF (few mode fiber FMF with 10 LP modes) with a maximum value not exceeding the capacity of four independent transmission links. On the other hand, when the number of modes in the MMF is adjusted to the number of receivers, MIMO processing of the 4 receivers allows always to demultiplex the 4 transmitted signals without loss, as illustrated by the negligible spreading of the left hand histogram in Fig. 1.

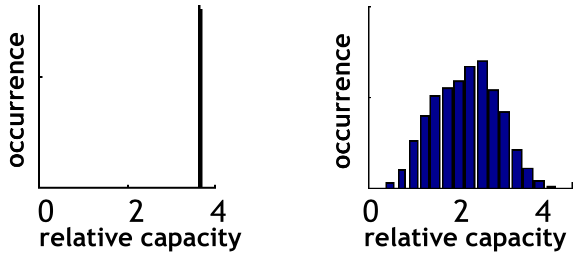


Fig. 1: Histograms of capacity for 4 channel coherent MIMO transmission over 4 mode MMF (left) and 10 mode MMF (right), resp.
Butt coupling or lense coupling of four SMFs was assumed.

Even though only single polarization transmission and only statistical phase variation during MMF propagation was assumed in the calculations for Fig. 1, a complete description of coherent MIMO transport includes a doubling of the MIMO channels by considering both polarizations. In addition, coupling between originally orthogonal LP modes via fiber bending and coupling between differently polarized modes has to be included as well [11]. For polarization coupling, which is nothing more than the polarization transformation property of the fiber, penalty-free MIMO processing is already well established in polarization multiplexed coherent detection systems such as single carrier QPSK and optical OFDM. That this is also the case for fiber bending induced coupling can be shown by analysis of the differential equations for mode coupling induced by an incremental microbend. The coupling coefficients between the different LP modes are imaginary and hence the transfer matrix for the concatenation of small bends should lead to power conserving unitary matrices which can be inverted without penalty by processing in the receiver.

Transmitter/receiver coupling to MMF

In addition, special attention has to be paid to the coupling efficiency between single mode fiber pigtails and a few mode MMF. The lower the mode number of the MMF, the lower the power which can be collected by the MMF at the input port and the lower the power which is coupled form the MMF modes to the SMF receiver pigtails at the output. For example, a simple mapping of 4 SMF end facets to the core of a 4 mode MMF by a lens system can exhibit a high loss exceeding 4dB which finally introduces a high system penalty. Therefore, alternative solutions appear to be indispensable for low loss coupling elements between transmitter or receiver pigtails and the MMF.

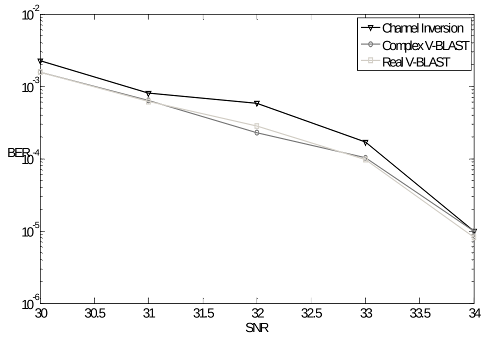
Nevertheless, selective and low-loss excitation of discrete fiber modes by a transmitter via lense coupling with phase holograms appears to be possible [12, 13]. A remaining challenge is the mode separation at the receiver. Even though a multiple of receivers forming a phased array allows to electronically separate the modes by DSP, a desirable reduction of the receiver count to the number of fiber modes seems only possible by appropriate optical mode splitters. Especially solutions are lacking for optical splitting of the degenerated mode pairs existing for each higher order LP mode with non vanishing azimuthal dependency such as the two degenerated LP_{11} modes having a 0 degree and a 90 degree rotated mode field.

MIMO signal processing and channel estimation

As already indicated above, if the optical signal path can be described by a product of unitary matrices and coherent receivers are incorporated, theoretically loss-free demultiplexing of the transmitted channels is possible and can be accomplished by simple transfer matrix inversion (zero forcing) in the DSP of the receiver. This implies, that for the output coupler the ideal mode splitters is available. Alternatively, with a receiver number exceeding the fiber mode number and an appropriate output coupler, a phased array receiver can be formed allowing to electrically split the modes in the DSP chip prior to channel inversion.

For other MIMO transmission schemes such as the ones incorporating direct detection receivers, the probability of inevitable outages can be reduced by using more complex processing schemes such as horizontal decision feedback equalization (V-BLAST) [14]. But also in the case of coherent detection, mode selective attenuation within the signal path will degrade demultiplexing of the transmitter signals by channel inversion at the receiver. This case can already be studied for the 2x2 MIMO processing of a polarization multiplexed signal propagating along a single mode fiber when polarization dependent loss (PDL) is present. For a coherent 10-Gbit/s polarization multiplexed OFDM signal, the measured BER versus OSNR is shown for a PDL of 3 dB in Fig. 2. A moderate BER improvement of about the factor of 2 was measured by replacing channel matrix inversion (upper black curve) by two versions of the V-BLAST algorithm [15].

Fig. 2:
BER vs. relative OSNR (dB) of different MIMO processing schemes in the coherent receiver of a polarization multiplexed 10-Gbit/s optical OFDM signal.
The optical path exhibits a PDL distortion of approx. 3 dB. leading to BER = 2x10^{-5} at 32dB rel. OSNR
- upper black line: channel transfer matrix inversion (zero forcing)
- lower gray line: horizontal decision feedback equalization (complex V-BLAST) inverted channel matrix(complex 2x2)
- lower fair gray line: horizontal decision feedback equalization (real V-BLAST) after decomposition of the inverted channel matrix(complex 2x2) into a real valued 4x4 matrix



Conclusion

Numerical simulations for multi-channel transport over MMF with MIMO processing in the receivers have been performed. They show that stable, outage-free operation even in the presence of fiber mode cross coupling due to depolarization and bending is possible, if coherent detection is incorporated and the number of transmitters and is identical to the number of MMF modes. The receiver number can be reduced to the MMF mode number, if solutions for optical mode splitters are identified. MIMO schemes based on direct detection receivers with intensity modulation transmitters will suffer from outages due to the poor statistics of optical carrier amplitude.

The author would like to thank Roman Dischler from Bell Labs in Germany for conducting the transmission experiments with the coherent OFDM lab set-up and Ralf Rojahn from University Erlangen for performing the simulations.

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