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Improving Single Mode Transmission Performance using Few-Mode Fibers and Space-Time Coding

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Space-time block codes can extend the optical signal to noise ratio tolerance in multiple-input multiple-output optical coherent spatial division multiplexing transmission systems with respect to single-mode transmission performance. The OSNR tolerance gain is achieved through exploiting the spatial diversity few-mode-fibers offer. An OSNR gain of 3.2, 4.1, 4.9, and 6.8 dB at the hard-decision forward error correcting limit with respect to single mode fiber back-to-back performance is shown for DP-QPSK, 8,16, and 32 DP-QAM, respectively.

Introduction

Enabled by multiple-input multiple-output (MIMO) digital signal processing (DSP), coherent transmission (Tx), and the development of key optical components, spatial division multiplexing (SDM) continues to be proposed as the solution to extend the capacity of a single optical fiber. Also known as Bell Laboratories Layered Space-Time (BLAST) in wireless communications [1], spatial multiplexing remains a key area of interest for increasing capacity. In optical transmission systems, SDM can be achieved by multi-core and multi-mode transmission [2-4]. Focusing on a specific case of the latter, namely few-mode fiber (FMF) transmission, 3 linearly polarized (LP) modes, the LP_{01}, LP_{11a}, and the LP_{11b} mode are excited and propagated [5]. Hence in this case, the capacity of a single fiber can be increased threefold with respect to single-mode fiber (SMF) transmission. Each LP mode contains two polarizations, which can be employed as transmission channels. Therefore, the total number of transmittable channels in FMFs is 3×2=6. Note that in SMFs, 2 polarization channels can be employed simultaneously.

Clearly, FMFs can offer an increased capacity with respect to SMF transmission. However, the FMF transmission systems can also be used to improve the transmission quality of single mode transmission through space-time coding (STC). The transmission quality improvement is investigated through optical-signal-to-noise ratio (OSNR) performance with respective bit error rates (BERs). For STC, there are three main contenders: space-time trellis codes (STTCs) [6], orthogonal STCs [7], and delay diversity. The latter two are linear space-time block codes (STBCs) and have a lower complexity than trellis codes. Although the STTCs offer better performance than the

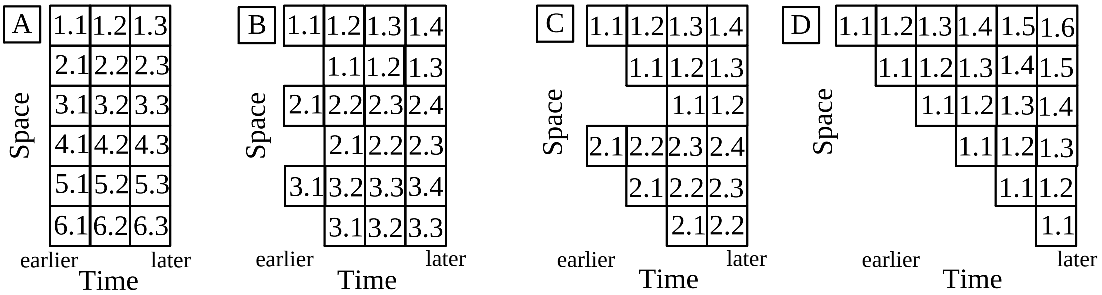

Fig. 1 Space and time allocation for FMF transmission blocks showing (A) 6, (B) 3, (C) 2, and (D) 1 transmitted channel. The first and second number denote the channel and block number, respectively.

linear variants, for high throughput optical transmission systems complexity is a key factor [8]. Therefore, we focus on the linear STBCs. The orthogonal STBCs are linear codes where the data is formed as unitary matrices. The most common orthogonal STBCs are Alamouti and Tarokh codes [7,8]. However, these only exist for certain numbers of transmitters. To this end, we use the simplest STBCs, purely exploiting the space and delay diversity. Fig. 1 shows the 4 cases of delay-diversity STBCs investigated in this work, where (A) 6, (B) 3, (C) 2 (SMF capacity), or (D) 1 polarization channel are received.

This work shows that either the capacity of a single fiber can be increased by transmitting an increased number of spatial channels, or that the transmission quality can be improved by employing STC with the existing spatial channels. In this work the resulting tradeoff is studied. The quality improvement is demonstrated through OSNR characterization of 28GBaud quadrature phase shift keying (QPSK), 8, 16, and 32 quadrature amplitude modulation (QAM) constellation sequence transmission over 41.7km FMF using a 6×6 MIMO frequency domain equalizer (FDE).

Experimental Setup

The experimental setup is depicted in Fig. 2. At the transmitter, a 1555.75 nm external cavity laser (ECL) is used. The output is guided through an IQ-modulator, where the laser light is modulated by a 28GBaud signal. The IQ-modulator is driven by two digital-to-analog converters (DACs), which represent the in-phase (real) and quadrature (imaginary) components of the transmitted constellations. The transmitted constellations under investigation are QPSK, 8, 16, and 32QAM.

The transmitted sequences are formed in the digital domain by a number of fully uncorrelated pseudo random bit sequences (PRBSs), each of length 2^{15}, which avoids correlation within the 2^{15} symbol sequence. The output of the IQ-modulator is split, and one arm is delayed by 1233 symbols for polarization decorrelation. After recombining the two arms, the uncorrelated dual polarization (DP) signal is noise loaded to characterize the optical OSNR system performance. To achieve 3 DP multiplexed mode channels, the noise loaded signal is split into three equal tributaries. Two arms are delayed for mode decorrelation by 3714 and 8233 symbols, respectively. Each arm is separately amplified before going into the mode multiplexer (MMUX). As a MMUX, a single prism spot launcher is used [9], resulting in equal excitation of the three LP

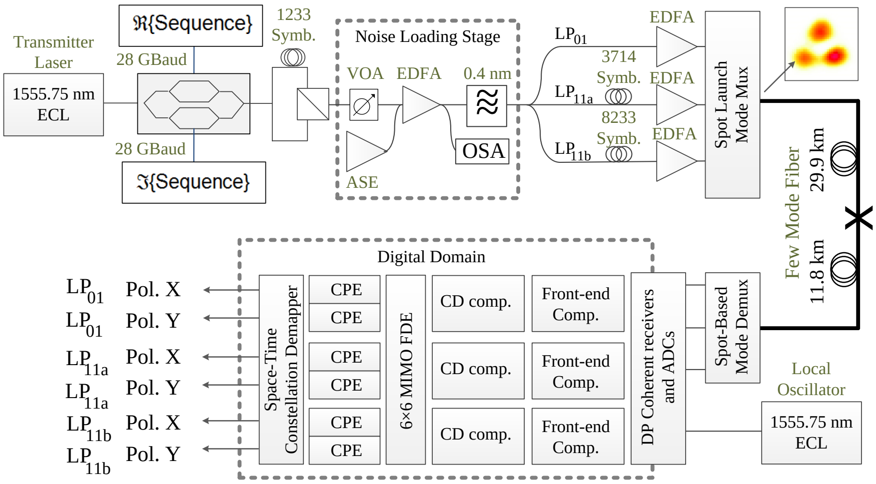

Fig. 2 Experimental setup (inset: measured alignment from spot launcher).

modes, guaranteeing full mixing. For all inputs, the losses are approximately 4.5 dB. The transmission link consists of two spans of few-mode fiber with lengths of 29.9 km and 11.8 km, respectively [5]. At the receiver side, a reciprocal setup of the MMUX comprising a single prism splits the FMF output into 3 separate outputs. Each output contains a mix of the 3 transmitted modes. The loss in the mode demultiplexer is approximately 4.5 dB for each output. After transmission, the three outputs from the mode demultiplexer are received using DP coherent receivers, where a second laser acts as the local oscillator (LO) and mixes with the signal. Real-time oscilloscopes act as 12 (3 modes × 2 polarizations × 2 real-valued axes of a complex symbol) analog to digital converters (ADCs). The captured data is post-processed offline.

In the digital domain, first the optical front-end impairments are compensated. Then, the chromatic dispersion (CD) is removed. To invert the channel mixing effects, a 6×6 MIMO FDE with adaptive step size is used [10]. The weight matrix of the FDE is heuristically updated using the least mean squares (LMS) algorithm during convergence and decision-directed least mean squares (DD-LMS) during data transmission. To compensate the frequency offset between the transmitter laser and LO, one carrier phase estimation (CPE) block per output channel in the form of a digital phase locked loop is used [11]. After this stage, the received constellations are demapped using a space-time demapper. The output of the space-time demapper can be 6, 3, 2, or a single output, depending on the STBC setup used. Note that single-mode transmission performance has 2 output channels, as each of the polarizations is employed.

Results

Fig. 3 shows the performance results of the space-time coded FMF transmission experiment for (A) QPSK, (B) 8, (C) 16, and (D) 32QAM. As the primary benchmark indicator, the 7% overhead hard-decision forward error correcting (HD-FEC) limit is used. If the BER is below this threshold, after error correction, theoretically the data transmission can be seen as error free ($<10^{-9}$). As there are 3 LP modes transmitted, and hence 6 polarization channels, the system capacity versus performance can be subdivided into 3 categories; 3, 1.5, 1, and 0.5×SMF capacity using no STBC, STBC over 2, 3, and all 6 transmitted channels, respectively.

For QPSK transmission, as shown in Fig. 3a, for threefold capacity increase there is a 0.6 dB OSNR penalty at the HD-FEC limit with respect to SMF back-to-back (BTB) performance. When applying STBC on 2 polarizations for a single channel, the performance is already better than the theoretical SMF performance. However, the FMF transmission capacity is reduced to 1.5× the SMF capacity. When using a 3 channel STBC, the FMF capacity equals the SMF capacity. The OSNR gain between STBC transmission and SMF BTB is approximately 3.2 dB.

As for QPSK, the same STBCs can be applied to 8QAM transmission. Fig. 3b depicts the 8QAM transmission performance. For threefold capacity increase there is a 0.5 dB OSNR penalty with respect to SMF BTB performance. A performance increase of 2.7 dB and 4.1 dB is seen when comparing the FMF capacity of 1.5× and 1× the SMF capacity to SMF BTB, respectively.

16QAM transmission is the next constellation when further increasing the number of constellation points. 16QAM performance is shown in Fig. 3c. The 3× SMF capacity OSNR penalty with respect to SMF BTB is 1.5 dB. However, when applying STBCs, and reducing the FMF transmission system capacity to SMF capacity, an OSNR gain of

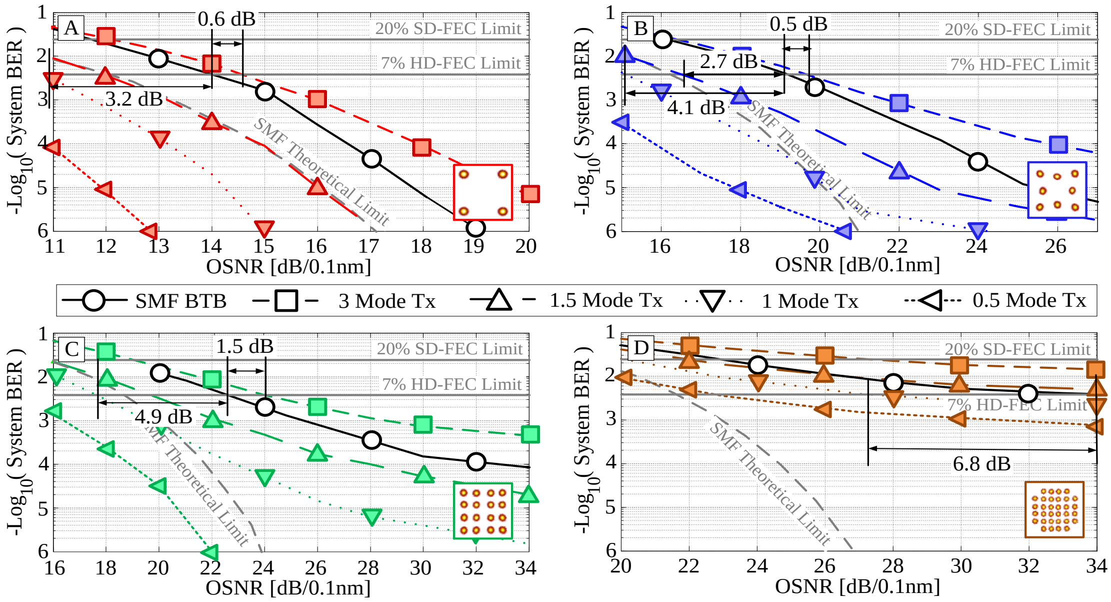

Fig. 3 (A) QPSK, (B) 8QAM, (C) 16QAM, and (D) 32QAM transmission performance for 6,3,2, and 1 channel using STC over a 41.7km FMF with respect to single mode BTB performance.

4.9 dB OSNR is observed. For 32QAM transmission, as depicted in Fig. 3d, the 20% overhead soft-decision FEC (SD-FEC) is required for successful transmission for 3-fold capacity increase with respect to SMF. However, after applying STBCs, a 6.8 dB OSNR performance gain is observed at the HD-FEC limit.

Conclusions

The successful transmission of 3×28GBaud DP-QPSK, 8, 16, and 32 DP-QAM over 41.7 km FMF has been demonstrated. Space-time coding was applied to improve the FMF transmission quality to outperform single mode fiber back-to-back performance. An OSNR gain of 3.2, 4.1, 4.9, and 6.8 dB at the hard-decision forward error correcting limit with respect to single mode fiber back-to-back performance is shown for DP-QPSK, 8,16, and 32 DP-QAM, respectively. Through STC, an additional dimensionality for potential FMF flex (flexible)-grid/flex-rate applications was demonstrated.

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References

[1] G.J. Foschini, Bell Labs Technical Journal, 41-59 (1996).
[2] V.A.J.M. Sleiffer et al., Optics Express **20**(26), B428-B438 (2012).
[3] R.G.H. van Uden et al., *Proc. OFC* (2014), Submitted.
[4] K Igarashi et al., *Proc. ECOC*, paper PD3.E.3 (2013).
[5] L. Grüner-Nielsen et al., Journ. Lightw. Techn. **30**(23), 3693-3698 (2012).
[6] V. Tarokh et al., Trans. on Inf. Theory **44**(2), 744-765 (1998).
[7] S.M. Alamouti, Journ. on Select Areas in Comm. **16**(8), 1451-1458 (1998).
[8] V. Tarokh et al., Trans. on Inf. Theory **45**(5), 1456-1467 (1999).
[9] H. Chen et al., *Proc. OECC*, PD3-6 (2013).
[10] R.G.H. van Uden et al., *Proc. ECOC*, paper Th.2.C.2 (2013).
[11] R.G.H. van Uden et al., Phot. Techn. Lett. **25**(14), 1381-1384 (2013).