Spatial Pulse Position Modulation for Multi-mode Transmission Systems

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Abstract: A spatial pulse position modulation is proposed and experimentally validated for a 12 spatial channel transmission over 53km multi-mode fiber. Improved data rates up to 30% are demonstrated with respect to conventional QPSK.

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1. Introduction

Space division multiplexing (SDM) has the potential to increase single fiber capacity by several orders of magnitude [1]. In addition to the impressive data rates that are achieved in SDM experiments [2], the employed few/multi-mode, multi-core, and multi-mode/multi-core fibers open a new dimension for coding schemes as well. Various modulation schemes have been investigated to increase diversity or to reduce the impact of mode dependent loss (MDL) [3]. In this work, we investigate a modulation scheme that reduces the average signal power and increases spectral efficiency (SE). Although, few/multi-mode fibers have a higher non-linear tolerance due to the larger effective areas in comparison to single mode fiber (SMF), a lower signal power is desirable because it increases tolerance to nonlinear transmission effects. Our modulation scheme, is based on pulse position modulation (PPM), where the switching of channels is used to encode data [4]. As a result of the proposed switching, this method reduces average signal power. PPM in SDM has been demonstrated by Puttnam et al. [5], where PPM is applied on polarizations and/or cores in a multi-core fiber. An added benefit for multi-mode fiber (MMF) transmissions is that as the spatial channels propagate in the same core, all spatial channels benefit from lower signal power. In addition, in multi-mode transmission all spatial channels have to be co-propagated and received simultaneously, therefore coding over the spatial channel utilizes this added dimension to increase capacity. These properties make space pulse position modulation (SPPM) an interesting option for multi-mode transmission systems. In this work, we discuss the implementation of SPPM for multi-mode transmission and verify the performance of a 12 spatial channel quadrature phase shift keying (QPSK) variant over a 53km long MMF-link.

2. Space Pulse Position Modulation

SPPM is an extended version of PPM, where data is encoded in the position of the pulse. In its simplest variant, only one symbol, for example a QPSK or quadrature amplitude modulation (QAM) symbol is transmitted in a single spatial channel, resulting in lower signal power but also a reduction in SE. The inverse of PPM (iPPM), where only one channel is disabled every frame, has a smaller reduction in average power, but is able to maintain or (depending

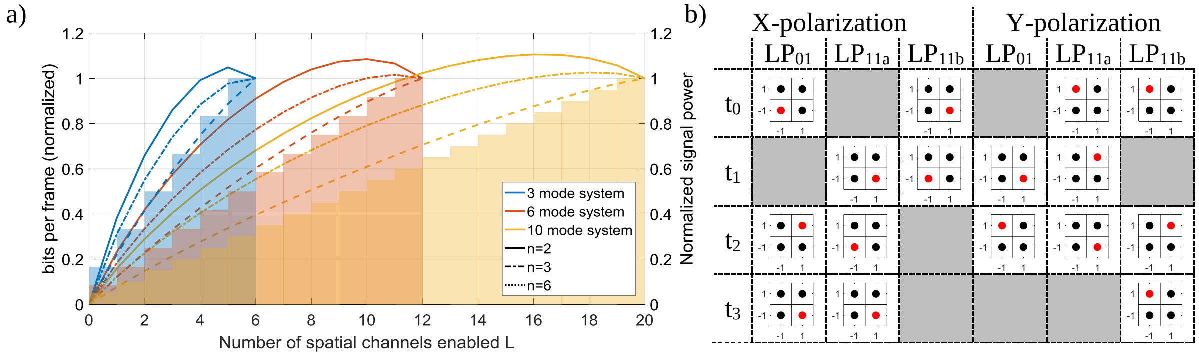

Fig. 1. a): Average number of bits per frame for SPPM with n = 2, 3, and 6 bits/symbol for 3, 6 and 10 mode transmission systems. Highlighted area represents the average signal power. Values are normalized to the case where all spatial channels are loaded with the conventional modulation formats of order n. b): Example for SPPM with 6 spatial channels and QPSK. t_0 can be demapped as 101011 (enabled/disabled channels), 00 (symbol LP_{01}X), 10 (LP_{11b}X), 01 (LP_{11a}Y) 01 (LP_{11b}Y). t_1:011110 10 00 10 11, t_2: 110111 11 00 01 10 11, t_3: 110001 10 10 01.

on the modulation format) even increase the SE. For any number of enabled spatial channels, L, in a single frame out of a total of M available spatial channels in the SDM transmission system, the number of bits per frame can be described as: $\log_2(M!/L!(M-L)!)+nL$, where n is the number of bits encoded in each symbol transmitted in the enabled channels. Fig.1a shows a graphical representation of this formula over a range of spatial channels (L) and order of modulation formats (n). All values are normalized with respect to the conventional modulation formats of order n. Note that with respect to SE this method scales well for higher numbers of spatial channels encoded with low-order modulation formats. The highlighted area in Fig. 1a indicates the average signal power, normalized to the conventional multi-mode transmission where all spatial channels are active at all times. Assuming an uniform symbol distribution, the reduced signal power is independent of the chosen modulation format.

In order to apply SPPM, independent modulation of all spatial channels is required. This requirement is fulfilled by default in any real world implementation, yet emulating independent data streams by transmitting delayed copies is used in research in an attempt to reduce the costs of required laboratory hardware. These decorrelation delays might cause undesired symbols, for example when multiple spatial channels are disabled in the $L = M$ -1 situation. Because of this limitation, only the case where all possible values of L are used to build the constellation is considered in our experimental verification of SPPM. This also allows a simplified (de)mapping scheme, where the first M bits correspond to the switching of the spatial channels, followed by a variable number of bits encoded on the activated spatial channels. An example of SPPM mapping using 6 spatial channels and QPSK symbols is visualized in Fig.1b. Assuming uniform symbol distribution, a 25% reduction in signal power is expected independent of the modulation format and number of spatial channels.

3. Experimental Setup

In order to experimentally verify the proposed modulation scheme, the transmission setup depicted in Fig.2a is employed. An optical carrier at 1550nm generated by an external cavity laser (ECL) is guided through an IQ modulator driven by two digital-to-analog converters (DACs), where it is modulated with waveforms of length 2^{15} symbols. Consequently, uncorrelated signals for polarization and modal channels are emulated by creating delayed signal copies. Erbium doped fiber amplifiers (EDFA) on each SMF input allows independent control of launch powers and to compensate for any variation in insertion losses of the 6-port mode selective photonic lantern (PL). This PL is fabricated by adiabatically tapering down a low refractive index capillary filled with SMFs. The positions of the fibers are carefully chosen to match the modal symmetry of the MMF. By varying the core size of the SMFs, mode selectivity can be obtained [6]. The high mode selectivity of the employed lantern is visible in the far-field images captured at the multi-mode facet of the PL by a near-infrared camera (fig2.d).

The 53 km transmission link is obtained by splicing 5×8.9 km and 2×4.5 km reels of MMF. This MMF, reported in [7], has a standard core diameter of 50 µm. It is optimized for multi-mode transmission around 1550 nm. The supported 30 LP modes are grouped in 10 fiber mode groups (Fig.2b). The effective index differences within these fiber mode groups are small, stimulating high coupling between the LP modes, while the large effective index difference minimizes coupling between the fiber mode groups. Coupling losses between fiber and multiplexer are minimized by splicing a short length of 6-LP fiber as intermediate fiber between MMF and PL.

At the receiver side another 6-port PL is employed to convert the multi-mode signal to 6 SMFs. Note that every SMF output carries a combination of the launched signals as result of the mode mixing in the fiber and demultiplexer. The signals are digitized by a TDM-SDM receiver architecture [2] consisting of two dual polarization

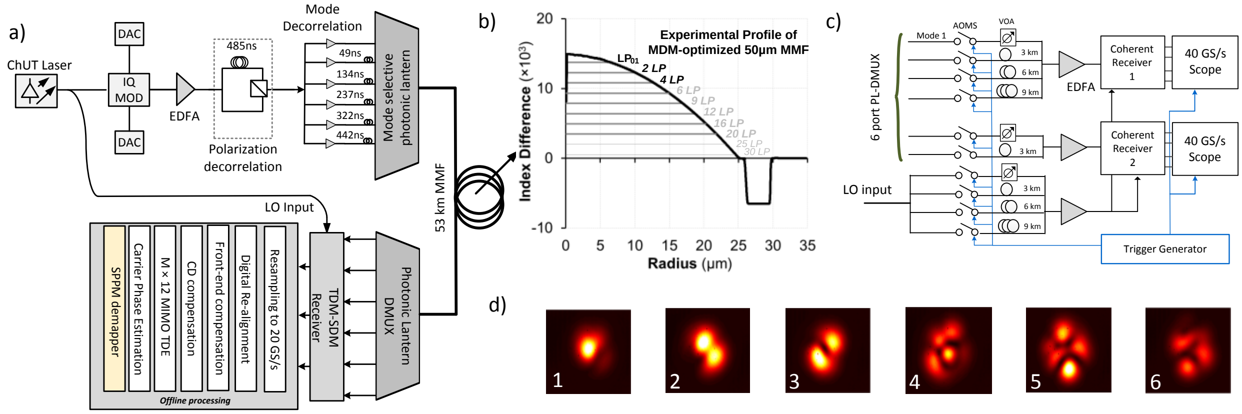

Fig. 2. a) 6-Mode 53km MMF experimental setup, including proposed SPPM demapper. b) Effective index profile of transmission fiber. c) 6 to 2 TDM-SDM receiver architecture. d) Mode profiles of the mode selective photonic lantern captured with a NIR camera.

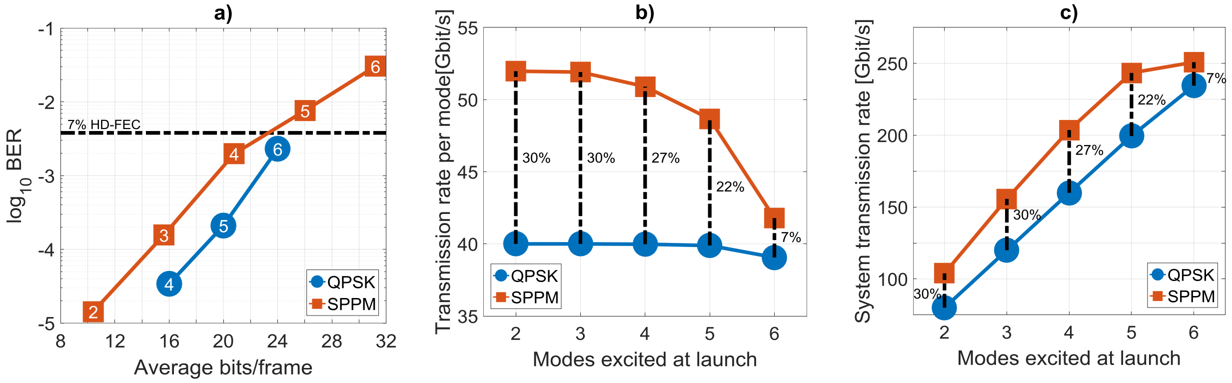

Fig. 3. a): Bit error rate for QPSK and SPPM versus the average number of bits per frame. Numbers inside markers represent the number of modes excited at the transmitter. Gross transmission rate per mode (b) and system (c) versus the number of excited modes at launch.

coherent receivers and real-time oscilloscopes (Fig.1c). In the digital domain the captured data is first aligned in time. After this, compensation of IQ offsets, front-end impairments and chromatic dispersion is performed. Next, the channel mixing is unraveled by a M×12 minimum mean squared error (MMSE) time domain equalizer (TDE) based on the least means squares (LMS) algorithm (M is the number of launched spatial channels). The carrier phase estimation (CPE) is performed on the equalized symbols. Performance metrics such as symbol error rate (SER) and bit error rate (BER) are estimated over ~125000 (demapped) symbols.

4. Results and discussion

Fig.3a shows the BER for the proposed SPPM and conventional QPSK versus the average number of bits per frame after 53km transmission over MMF. Smaller multi-mode systems are emulated by only launching in a subset of the spatial channels. Note, that the maximum bits per frame for QPSK is limited to 24 bits for 6 modes, where the throughput for SPPM (5 excited modes) is 26. Although the BER is slightly higher for the SPPM case, the average signal power is lower and a smaller MIMO (10×12 instead of 12×12) equalizer can be employed.

As shown in [8], mutual information (MI) is a better metric to compare different modulation formats. To compare the two modulation formats in terms of net data rates, the hard-decision MI is employed, where the channel is replaced by a binary symmetric channel (BSC) [9]. In this case, $\mathrm{MI} = 1 + p\log_2(p) + (1-p)\log_2(1-p)$, where p is the BER as shown in Fig 3a. From the estimated MI and transmitted bitrate, the achievable transmission rate per mode (Fig.3c) and the system (Fig.3b) can be calculated. Both Fig. 3b and c show increased throughput for SPPM, from 7% for a 6 mode transmission and up to 30% for 3-mode transmission system.

The minimum Euclidean distance of SPPM is smaller compared to conventional QPSK, which leads to higher bit error rates. However, SPPM carries more bits per symbol, and thus, is able to compensate for the decreased minimum Euclidean distance and give larger net data rates. This data rate increase holds well for high optical signal to noise ratios (OSNRs) (i.e., small number of spatial channels), but no longer holds for larger number of copropagating spatial channels (i.e., low OSNRs).

5. Conclusion

In this work we investigated the use of pulse position modulation for multi-mode transmission systems. The proposed space pulse positioning modulation encodes data by switching of spatial channels. By experimental verification, using a 53km 6-mode transmission setup, an increased throughput of up to 30% compared to conventional QPSK has been demonstrated.

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