Energy efficient modulation formats for multi-core fibers

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ENERGY EFFICIENT MODULATION FORMATS FOR MULTI-CORE FIBERS

B. J. Puttnam[1], J.-M. Delgado Mendinueta[1], R. S. Luís[1], W. Klaus[1], J. Sakaguchi[1], Y. Awaji[1] and N. Wada[1]
1. Photonic Network System Laboratory, National Institute of Information and Communications Technology (NICT), 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8759, Japan. E-mail:ben@nict.go.jp

T. A. Eriksson[2], E. Agrell[3], P. A. Andrekson[2] and M. Karlsson[2]
2. Department of Microtechnology and Nanoscience, **3**. Department of Signals and Systems, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

Paper Summary
We propose and experimentally investigate a family of multi-dimensional modulation formats for multi-core-fibers. Such formats can have power or spectral efficiency advantages or lower symbol energies but implementation difficulties cause an OSNR penalty.

Introduction

Recent advancement of space-division-multiplexing (SDM) technology, including fibers with up to 19 cores [1] or 6 spatial modes in each polarization [2], have opened the prospect of using spatial channels to increase the dimensionality of modulation formats. Using many spatial channels may allow multi-dimensional formats at significantly higher baud rates than possible with time-interleaved variants and, in the multi-core fibre (MCF) case, also be compatible with spatial super-channels [3], recently proposed to simplify switching in SDM networks. Previously, high dimension formats have been investigated in single-core fibers, increasing the number of orthogonal dimensions by splitting symbol periods into multiple slots, called pulse-position modulation (PPM) [4-6], or by using optical frequencies [7]. In PPM, the presence or absence of light in one [4, 5] or more slots [6] is used to encode data, which may also be encoded in quaternary-amplitude modulation (QAM) symbols in each illuminated slot. Both PPM and frequency and polarization coding have been shown to enable power efficient modulation with most studies of high-dimension modulation formats to date focussing on improving the sensitivity and power efficiency of the format [8,9]. However, this approach does not necessarily minimize the energy consumption or transmitted energy per bit, $E_{bit,}$ which for the same minimum Euclidean distance between symbols (d_{min}) may enable energy savings at the transmitter and optical amplifiers [10,11], but also lower average optical power can reduce the impact of fiber nonlinearities along the transmission link [11], potentially increasing the transmission distance.

Here, we investigate whether energy savings may be achieved by using novel PPM-like formats in an additive white Guassian noise (AWGN) limited system. We replace time or frequency slots by cores of an MCF and allow a variable number of lit cores to code additional bits. We show that, compared to sending the equivalent QAM symbol in each core and/or polarization, this approach can produce some attractive features. For example for BPSK the spectral efficiency (SE) may be improved by 50% and for PM-QPSK this approach reduces the symbol energy by 50% without reducing the minimum distance. However, experiments reveal that the need to detect an intensity modulated signal envelope results in an optical signal-to-noise ratio (OSNR) penalty. For single polarization formats, we measure a penalty of 1.5 dB (BPSK) and 1 dB (QPSK) compared to transmitting the same QAM signal on all cores. Finally, we discuss implemetation problems and the possibility of reducing or eliminating the measured OSNR penalties.

Description of investigated formats

The proposed formats combine QAM modulation of dimensionality D, with additional dimensions, K, of an MCF to make a 'multi-core' modulation format (MCMF) with total dimensionality N_D=K × D. The number K is equivalent to the number of MCF cores when using a single polarization format or polarization multiplexed (PM) signals in each core, but will be twice the number of cores, when using two independent single polarization signals in each core. We refer to these formats as core-coded (CC) or core-polarization coded (CPC), respectively. The proposed formats encode K bits in each symbol timeslot as a binary word of length K, where each bit is determined by the presence or not of light on a core or core-polarization and we refer to these as intensity modulated (IM) bits. In addition, each illuminated core or polarization carries a QAM symbol containing N_{QAM} bits to code an average of N_{QAM}×K/2 additional bits. Hence, an average number of bits N_{bit} = K(1 + N_{QAM}/2) are encoded per symbol. This scheme

Table 1: Comparison of single core QAM formats (left side) with core-coded (CC) and core and polarization-coded (CPC) formats (right side)

Format	d^2_{min}	$N_{bit/core}$	E_s	E_{bit}	γ (dB)	SE	Format	d^2_{min}	$N_{bit/core}$	E_s	E_{bit}	γ (dB)	SE
BPSK	4	1	1	1	0	2	CPC-BPSK	1	3	1	0.33	-1.25	3
PM-BPSK	4	2	2	1	0	2	CC-PM-BPSK	2	2	1	0.5	0	2
QPSK	4	2	2	1	0	2	CPC-QPSK	2	4	2	0.5	0	2
PM-QPSK	4	4	4	1	0	2	CC-PM-QPSK	4	3	2	0.67	1.76	1.5
PS-QPSK	4	3	2	0.67	1.76	1.5	CC-PS-QPSK	2	2.5	1	0.4	0.97	1.25

may be considered as a variant of L-out-of-K-PPM [6], with L as the number of utilized dimensions, transposed to core and/or polarization space, with a variable number of lit cores/polarizations between symbols.

Table 1 shows a summary of common single-core fiber modulation formats and a comparison with the corresponding CC and CPC formats. The symbol energy, $E_{s,}$ is the normalised transmitted optical power. For CC and CPC formats the E_s value is calculated per core assuming each utilized spatial dimensions is lit 50% of the time. The energy of each transmitted bit, E_{bit} is then E_s/N_{bit}, where $N_{bit} = N_{QAM}$ for single core formats and is again normalised per core for MCMFs. The SE is defined as $N_{bit}/(N_D/2)$ and the normalized asymptotic power efficiency (γ) is defined for the AWGN limited system as $\gamma = d_{min}^2/(4E_{bit})$ [8,9], where d_{min} is calcualted for constellation geometries of (±1) for BPSK, (±1, ±1) for PM-BPSK and QPSK, (±1, ±1, ±1, ±1) for PM-QPSK and (±1, ±1, 0, 0), (0, 0, ±1, ±1) for PS-QPSK. Table 1 shows that a reduction of E_{bit} is possible for all MCMFs. However, the different constellation geometries of the MCMFs, which determine the symbol energies and d_{min} do not necessarily translate to sensitivity improvements, as evident in the reduction of γ for all MCMFs, with the exception of CC-PM-QPSK, where E_{bit} is reduced by for the same d_{min}. It is worth noting that E_s is reduced for all MCMFs with the exception of CC-PM-QPSK, so transmitter or amplifer power savings [10] or non-linear tolerance may still be improved by adopting MCMFs.

Experimental Set-up

In this paper, we experimentally investigate core-coding with BPSK and QPSK using 4 spatial dimensions. For experimental simplicity, we use each single polarization format in separate cores of an MCF and from here onwards refer to them as 4-CC-BPSK and 4-CC-QPSK where K=4 refering to the number of core and/or polarization dimensions used. We note that these formats are not included in Table 1, but share the properties of 4-CPC-BPSK and 4-CPC-QPSK which use 2 cores and 2 polarizations, instead of 4 cores. The experimental set-up used to investigate these formats is shown in Figure 1. An external cavity laser with approximately 700 kHz linewidth tuned to 1550 nm wavelength was modulated with a 10 GSymbol/s QAM signal pseudo-random bit sequence (PRBS) of period 2^{15}-1. This signal was then amplified and filtered before being split between 4 Mach-Zehnder modulators (MZMs), driven by independent PRBSs, used to pass or block the QAM symbols. Polarization controllers (PCs) and variable optical attenuators (VOAs) were used at the input of each modulator and optical delays were used before each MZM to align the IM symbol-slots with the QAM symbols. The output of each MZM was then connected to 4 outer cores of a 46 km, trench-assisted 7-core fiber with average chromatic dispersion (CD) of 18.8 ps/m/nm and at a launch power of 0 dBm.

After the fiber, in the absence of 4 coherent receivers, an optical switch was used to select each core in turn for reception in an optical modulation analyzer (OMA), consisting of a polarization diverse optical coherent receiver connected to a digital sampling oscilloscope with 13 GHz analogue bandwidth. The receiver path also contained an EDFA and a 3 dB coupler, which was used to add amplified spontaneous emission noise from filtered EDFA outputs to enable BER measurements as a function of the OSNR. VOAs and optical taps were used to control and monitor optical power levels. An internal ECTL was used for intradyne coherent detection with the signal polarization optimized before each acquisition to maximize the received signal amplitude and the 4-channel signal was then digitized at 40 GS/s. Traces were taken for each core with a common trigger for timing alignment and the receiver DSP performed offline in MATLAB. Initially, skew and CD compensation, normalization, multiple input-multiple output (MIMO) polarization tracking and residual carrier phase recovery were performed on the traces for each core individually before being combined for error counting. BER measurements were calculated from the average of three traces each containing 500,000 symbols.

In practice, the variable number of bits per symbol present new challenges for the receiver design since errors in the IM bits will change the length of the expected sequence. It is envisaged that this will require data to be sent in fixed length frames, as is currently performed to address cycle slips in commercial transmission systems. For simplicity, this was not fully addressed in this first demonstration but sequences were identified by the presence of a 32 bit IM header in each PRBS sequence. We then used a simplified error counter in which the IM bits were first detected for each core and compared with the transmitted sequence. For each IM-bit error, additional errors (2 for QPSK and 1 for BPSK) were added to the error total for the additional or erased QAM symbol. Finally, the QAM symbols of the correctly received 1's were then compared with the

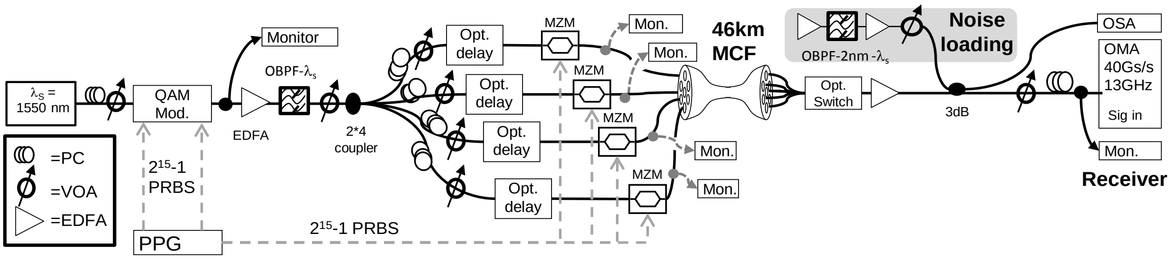

Fig. 1: Experimental set-up for BPSK, 4-CC-BPSK, QPSK and 4-CC-QPSK transmission

transmitted sequence to identify any remaining errors.

Experimental Results and Discussion

Figure 2(a) and (b) show the measured BER as a function of the OSNR for CC-BPSK and CC-QPSK, respectively. Also included for comparison are curves for BPSK and QPSK measured using the same transmitter and replacing each PRBS coding IM bits with a pattern containing only 1's. We consider the received CC-QAM signals consisting of 2 components; the QAM bits, transmitted in the logical 'one' symbols and the IM bits, which provide the core coding. Hence, in addition to the entire multi-core format, Figure 2 also shows the received error rates of the individual core sequences for IM and QAM sequences and example constellations for the low and high noise cases are shown as insets.

Figure 2 shows the penalty in the required OSNR for a given BER caused by the increased OSNR required to receive the IM bits. In both cases, we observe that the QAM bits can be received with OSNRs lower than that of the equivalent QAM format since the peak power of each symbol is 3 dB higher than the average used to measure OSNR. However, it also shows that receiving the IM bits in this way results in an overall OSNR penalty. For CC-BPSK we observe an overall penalty of 3.2 dB in required OSNR at BER=10^{-3}. However, since the data-rate of CC-BPSK increased by 50% compared to BPSK, Figure 2(a) also contains a simulated plot of BPSK at 15 Gb/s. Compared to BPSK at the equivalent data rate the penalty for CC-BPSK becomes 1.5 dB. Figure 2(b) shows that CC-QPSK has a 1dB penalty

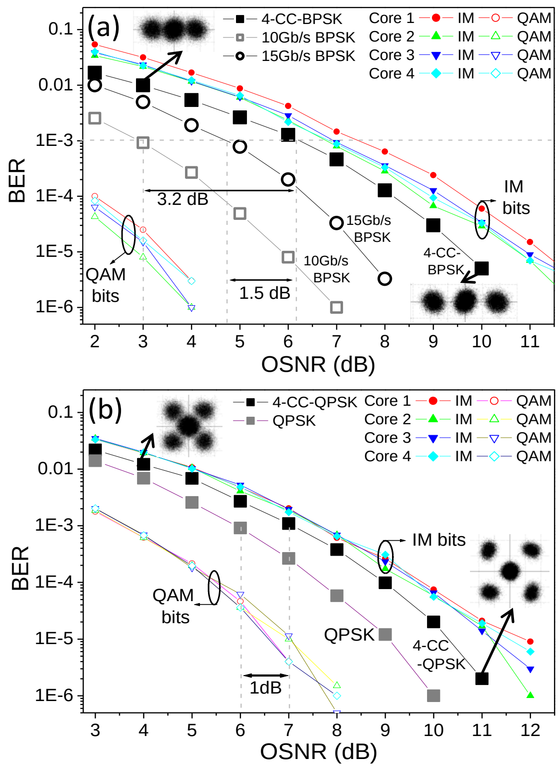

Fig. 2: BER vs receiver OSNR for (a) 4-CC-BPSK and BPSK, and (b) 4-CC-QPSK and QPSK

compared to QPSK in all cores. These results show that although the proposed formats have some attractive attributes which may translate into improved resilience to fiber nonlinearities and overall reduction of the energy consumption, their overall usefulness in noise limited transmission links may be restricted by the high OSNR required to receive the IM bits. If it becomes possible to reduce or eliminate this penalty, then the use of such formats can become more attractive and may become an interesting area of future research.

It should be possible to reduce the OSNR requirement of the IM bits by using coherent OOK detection and improved DSP techniques using the received signals for all cores for optimal detection of the multi-core symbol instead of the 2-stage individual core apprach used here. Furthermore, it may be possible that improvement can be gained from more sophisticated coding or data framing. As mentioned in the receiver description, one of the challenging features of such formats is the variable number of bits and the bit-error probability between symbols. This means that IM errors lead to erasures and additions to the transmitted sequence that will likely require data framing. Additionally, another interesting possibility could be to exploit error detecting codes and optimize the FEC protection for the IM bits to reduce the unequal bit error probabilities of the respective QAM and IM bits after decoding. If such coding could be applied, then the attractiveness of these formats could be greatly increased.

Summary

We have experimentally investigated novel modulation formats for multi-core fibers where data is encoded both as a binary word by the presence or absence light in each fiber core and in QAM symbols in illuminated cores. Using both BPSK and QPSK in 4 spatial dimensions, we find that such formats may have some advantages compared to single core formats including 50% improvements in spectral efficiency for BPSK and 3dB reduction in symbol energy for PM-QPSK. However, experimental investigations revealed that with the currrent receiver implementation the higher OSNR required to receive the intensity modulated part of the signal results in a penalty in the required OSNR of 1.5 dB (BPSK) and 1 dB (QPSK) compared to transmitting the same QAM signal and equivalent data rate on all cores.

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