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Linear Block-Coding across >5 Tb/s PDM-64QAM Spatial-Super-Channels in a 19-core Fiber

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Abstract *We apply linear block-codes across 228-bit, PDM-64QAM spatial super-channels in a 19-core fiber and observe upto 3 dB reduced OSNR requirement and additional transmission reach of 55% at BER=3.8×10^{-3} and 122% at BER=1×10^{-3} for a 10.5% code overhead.*

Introduction

Recent advancement of space-division-multiplexing (SDM) technology[1] has enabled the possibility of applying multi-dimensional modulation formats[2] and/or coding across multi-core fiber (MCF) cores[3] or fiber modes[4,5]. In particular, the relative uniformity of transmission characteristics among cores of an MCF[6] enables the possibility of combining such techniques with transmission schemes designed to gain advantages of MCF use beyond just multiplying capacity. In addition to the use of self-homodyne detection[7], such schemes include spatial super-channels[8] (SSCs), where the same wavelength in each core is considered a sub-channel of a superchannel. SSCs were proposed as a way of sharing digital signal processing between cores and simplifying switching in SDM networks[9].

Recently, multi-dimensional modulation formats including position modulation[10] and set-partitioning[3] have been applied to SDM systems, clouding the distinction between optical modulation formats and optical domain forward-error-correction (FEC). Since SDM systems with over 100 spatial channels[11] have been reported, applying error-correcting codes over SSCs containing thousands of bits becomes feasible and adopting optical coding as an inner FEC code[2] becomes an interesting avenue of study.

Here, we investigate this idea by applying linear block codes (LBC) across n=19×6×2=228 bit SSCs carrying >5 Tb/s data based on transmission of 25 GBd, PDM-64QAM symbols in each core of a 19-core fiber. We compare 3 different coding schemes, with coding overheads of 3%, 7%, and 10.5%, with transmitting independent PDM 64QAM in each core. Across a 19-core fiber span, we observe up to 3 dB reduction in the required optical signal-to-noise ratio (OSNR) at the bit error rates (BER) threshold commonly used for hard-decision (HD)-FEC systems. In transmission, we find that the 10.5% overhead LBC increased the transmission reach by 122%, 54%, and 15% for BER thresholds of 1x10^{-3}, 3.8x10^{-3} and 1.5x10^{-2} respectively. These results show that optical coding can reduce the noise sensitivity of high-order QAM formats and, in combination with an outer HD-FEC code, give comparable performance to soft-decision (SD)-FEC but with reduced complexity and requiring less analogue-to-digital converter (ADC) resolution.

Encoding and Decoding of SSCs

An (n,k,d) LBC takes k-bit messages and converts them into n-bit codewords with a code rate k/n and overhead n/k–1. This is done by appending n–k parity bits to each block of k message bits to maximize the minimum Hamming distance d, with the error-correcting capability t=(d–1)/2. Here, we use shortened Bose–Chaudhury–Hocquenghem (BCH) codes where (n,k,d)=(228,220,3), (228,212,5), and (228,204,7), which are the best known codes with these parameters (highest k for given n and d)[12]. They were obtained by shortening the corresponding BCH codes[13] of length n=255. The three codes with n=228, denoted as H3,

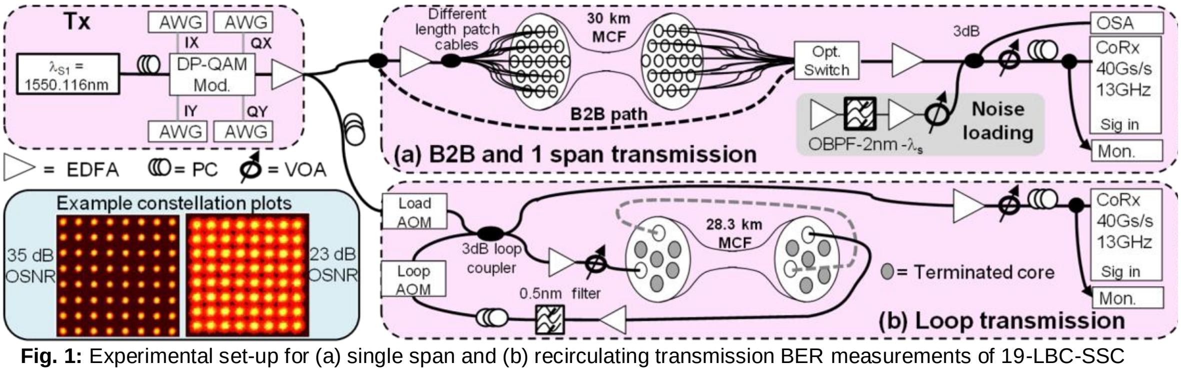

Fig. 1: Experimental set-up for (a) single span and (b) recirculating transmission BER measurements of 19-LBC-SSC

H5, and H7, have code rates of 0.965, 0.930 and 0.895, which correspond to an overhead of 3.5%, 7%, and 10.5% respectively.

In the experiment, 228 bit coded data blocks **x** were generated according to **x**=**u**·**G** where **u** is a *k*-bit block of randomly generated data, **G** is the code's generator matrix, and the matrix multiplication is carried out modulo 2. **x** was then divided in to 6-bit sections with each section mapped onto a 64QAM symbol using Gray mapping for modulation onto each polarization component of each fiber core. This process was repeated until reaching 2^{15}–1 multi-core symbols for experimental investigation.

At the receiver, the 228-bit blocks were reassembled from the received data streams of each fiber core after hard detection and then decoded by syndrome decoding[13], with the syndromes located from a pre-computed syndrome table using a bisection search. The BER of the whole transmitted sequence and decoded data bits could then be compared.

Experimental set-up

The experimental set-up and example constellation of 64QAM symbols at 23 dB and 35dB OSNR is shown in Fig. 1. Signal modulation of light from a 100 kHz linewidth laser tuned to 1550.116 nm was performed using a dual parallel Mach-Zehnder modulator, referred to as DP-QAM modulator in Fig. 1, driven by 4 independent arbitrary waveform generators (AWG). Each AWG had an analogue bandwidth of 14 GHz and used a sampling rate of 50 GS/s to generate pre-equalized PDM 64QAM signals at 25 GBd with root-raised cosine pulse shape and a roll-off of 0.01. Using independent AWGs allowed the programming of specific core-dependent bit patterns to each quadrature and polarization for coding over each SSC core. After modulation, an erbium-doped-fiber-amplifier (EDFA) boosted the signal power.

Initially, OSNR characterization was performed in back-to-back (BTB) configuration and over a single span of a 19-core fiber as shown in Fig.1 (a). For single span measurements, the transmitter (Tx) output was further amplified and then split between each input port of a 19-core free-space SDM MUX[1] with patchcords used to decorrelate the signals in each core. In the absence of 19 independent modulators, each core-specific bit sequence was received in turn with the optical switch used to select the appropriate core under test. For BTB measurements the Tx was connected directly to one port of the optical switch for all core patterns. To perform BER measurements as a function of OSNR, the signal was combined with spontaneous emission noise from a filtered EDFA and further amplified before a variable optical attenuator (VOA) for power adjustment.

In the absence of an independent Tx, receiver and loop set-up for each of the 19 cores, transmission measurements were emulated using an existing recirculating loop set-up based on a 7-core MCF as shown in Fig 1(b). Each recirculation used 2 outer cores of a 28.35km MCF span giving a total length of 56.7 km and round trip time of 278 µs. The loop contained 2 further EDFAs and a noise-limiting 100 GHz bandwidth optical filter with optical taps and VOAs used for fiber launch power setting and monitoring. A single pair of AOM switches, with 80MHz frequency upshift, was used to gate loading and loop transmission, controlled by a single delay generator, which was also used for receiver triggering. The sequence corresponding to each core was loaded in turn with separate BER measurements performed as a function of transmission distance for each sequence and combined for decoding as described.

For all measurements, signal reception was performed in a polarization-diverse optical coherent receiver (CoRx) connected to a digital sampling oscilloscope with 32 GHz analogue bandwidth operating at 80 GS/s. Offline processing was used to recover the signal, consisting of resampling to 50 GS/s, followed by normalization and dispersion compensation. Polarization de-multiplexing was performed using a multiple-input-multiple output (MIMO) structure whose equalizers were 17-tap filters updated using a decision-directed least-mean squares (DD-LMS) algorithm. Carrier recovery was embedded in the equalizer loop. The data streams were computed using hard decision and combined for decoding. All BER measurements were calculated from the average of three 1 µs traces, each containing 250,000 symbols.

Results

Fig. 2 shows the OSNR characterization for the

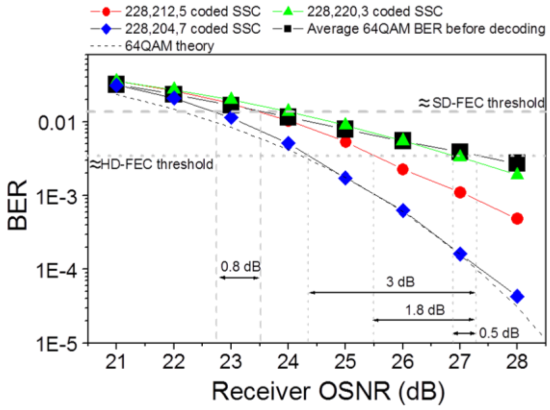

Fig. 2: BER vs OSNR after single span transmission of 19-core LBC-SSC

19-core LBC-SSC with each of the 3 codes after single-span transmission in a 19-core fiber. Also shown is the average BER of the transmitted sequence before decoding. The BTB data showed identical performance trends but revealed an additional penalty of 0.6 dB for transmission. Fig. 2 shows that at high BERs typical of soft decision (SD)-FEC systems (BER≈$1.5x10^{-2}$), the codes and unprocessed BERs converge with only the H7 code showing any improvement in required OSNR of 0.8dB, although we note that the hard detection LBC code would be incompatible with SD-FEC systems. The benefit of such codes appears to be at BERs typical of HD-FEC systems, BER≈$3.8x10^{-3}$. Here, a reduction in required OSNR of 0.5dB, 1.8dB, and 3dB is seen for the H3, H5, and H7 codes, respectively. For systems requiring even lower pre-FEC BERs, greater benefits are possible. For example, a reduced OSNR requirement of 4–5 dB can be estimated for the H7 code at BER=$1x10^{-3}$.

Fig. 3 shows the summary of the recirculating transmission experiment comparing the H7 code over 19-core SSCs with pre-decoding BER for the optimal fiber launch power of 0dBm. Again, at high BERs, the coded and pre-decoded BERs converge, and at BER=$1.5x10^{-2}$ only a 15% reach improvement over the pre-decoding BER is measured, but increasing to 54% and 122% for BER=$3.8x10^{-3}$ and BER=$1x10^{-3}$ respectively.

Hence, as proposed for coded modulation formats[2], these results show that optical coding across SSCs may help to improve efficiency in the overall system by being used as an inner FEC code in conjunction with a standard hard decision post-reception outer FEC code. For example, Fig. 2 and Fig. 3 show that in the receiver OSNR range of 24.3–27.3 dB or the transmission range of 560–870 km, the H7 code reduces the BER to below the usual threshold for HD-FEC ($3.8x10^{-3}$), meaning that a post-FEC BER in the region of $1x10^{-15}$ may be achieved with an additional 7% overhead on the 10.5% code overhead to give a total FEC overhead of 18.2%. In the same range, achieving the BER only with SD-FEC would not only incur an overhead in the region of 20%.

Hence, by carefully selecting appropriate codes for an inner optical FEC and an outer HD-FEC, it may be possible to achieve comparable error correcting power of SD-FEC codes without incurring the additional hardware costs and complexity required for its implementation. We note that such optical coding could also be implemented serially but it is envisaged that as well as latency advantages, coding across SSCs can be combined with joint core processing[8] and

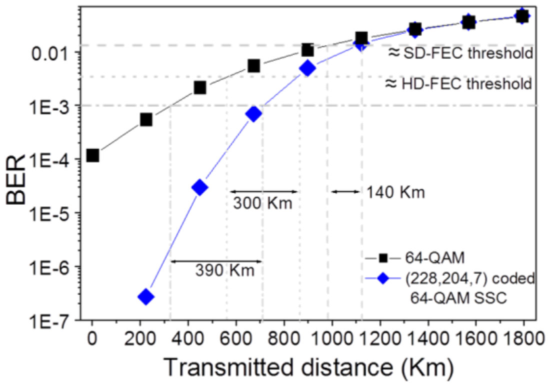

Fig. 3: Transmitted distance for PDM-64QAM before decoding and 228, 204, 7 PDM-64QM LBC-SSC

used in conjunction with phase noise cancelling self-homodyne detection[7] to enable efficient use of high-order modulation formats in order to maximise overall spectral and link efficiency.

Conclusions

We have investigated the performance of linear block-coding across >5 Tb/s spatial-super channels using 25 GBd PDM-64QAM modulation in each core of a 19-core fiber. Compared to BER of symbols before decoding, we observed up to 3 dB reduction in OSNR requirement at a BER of $3.8x10^{-3}$ and a 54% increase in transmission reach for the same BER, increasing to 122% at BER=$1x10^{-3}$. These results show that optical coding may be combined with standard HD-FEC systems to improve overall efficiency and may be used alongside other MCF system technologies.

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