Transmission Performance of Hybrid-Shaped 56APSK Modulation Formats from 34.7 to 74.7 GBd Over Transoceanic Distance

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Abstract: We experimentally study the impact of symbol rate on transmission performance. From 34.7 to 74.7Gbd SNR decreases by ~1.5dB; hardware and nonlinear transmission effects cause 0.7dB and 0.8dB respectively. NLC benefit decreases at higher rates. © 2020 The Author(s)
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1. Introduction

Digital coherent technology opened the door for 100G transmission over transoceanic distance, and broadband C+L amplification doubles the capacity of a single strand of optical fiber [1]. More than 200 or 400 transponders are needed to populate a single fiber pair in C- or C+L-band EDFA system respectively using 100 Gb/s transmission channels. Operating at higher rates is attractive from a terminal equipment perspective. Increasing the payload per wavelength through the increases in the symbol rate results in fewer channels and fewer components, translating into a reduction of terminal cost, operational cost, and space. Operation at 400 Gb/s compared to 100 Gb/s can potentially support the same fiber capacity using ¼ of the channel specific equipment. Data rates of 400Gb/s and higher have been extensively used in transmission demonstrations over transoceanic distances [2-6].

In this paper we experimentally quantify the potential performance losses at high symbol rates caused by hardware and transmission effects. We study transmission performance dependence on channel symbol rate in a C+L system by varying the symbol rate from ~34.7 to ~74.7 GBd and measuring channel performance with and without nonlinearity compensation. Using 4D-HS-9/12-56APSK modulation format, the back-to-back SNR penalty increases from ~0.5 dB (34.7 GBd) to ~1.3 dB (74.7 GBd). After 7,603 km transmission, Q-factor and effective SNR decreases by 1.16 dB and 1.5 dB respectively as symbol rate increases from 34.7 to 74.7 GBd. The SNR degradation is comprised of ~0.7 dB BtB penalty and ~0.8 dB penalty from nonlinear transmission effects. The observed decrease in NLC benefit with the increase of the symbol rate is caused by the decrease in DBP benefit.

2. Experimental Setup

Fig. 1 shows the schematic of the transmission experiment. The WDM signals are divided into three groups: a single measurement channel driven by a 100 GS/s DAC, 2 loading rails each having 4 channels driven by a 92 GS/s DAC, and flat ASE noise loading over the entire 9.74 THz C+L bandwidth. The measurement channel is modulated with a dual polarization I/Q modulator driven by a 100 GS/s DAC with 44 GHz BW. The 2 loading rails have eight (4 odd and 4 even) lasers that are modulated by two single polarization I/Q modulator driven by a 92 GS/s DAC. Polarization division multiplexing (PDM) of the 2 loading rails is emulated with a split and delay technique with 80 ns delay. The number of channels in the loading section varies with the channel symbol rate as shown in Table 1 in order to maintain the modulated spectrum bandwidth at ~350 GHz. The measurement channel, even and odd loading rails are carrying the same data but are delayed with respect to each other to de-correlate adjacent channels. Waveforms are generated off-line to produce raised cosine spectra with β=0.001.

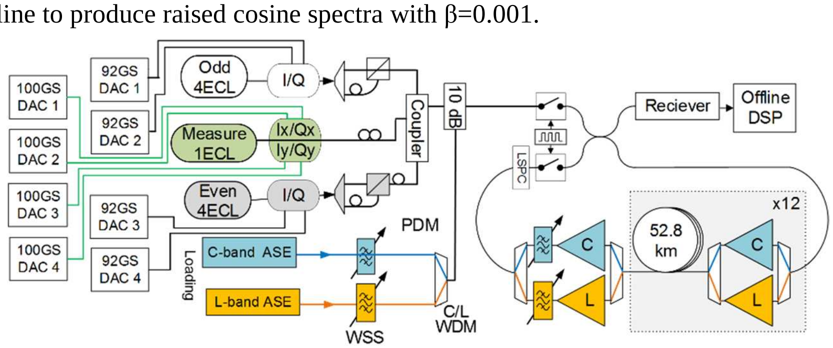

Fig. 1: Schematic of the transmission experiment.

Baud Rate GBd	Bit Rate Gb/s	Δf GHz	Notch BW for Chs GHz		
74.68	528.91	75	375		
69.69	493.52	70	350		
64.65	457.87	65	325		
59.67	422.58	60	300		
54.66	387.09	55		385	
49.68	351.84	50		350	
44.68	316.44	45		315	
39.67	280.94	40			360
34.67	245.57	35			315
# of Chs			5	7	9

Table 1: Experiment parameters.

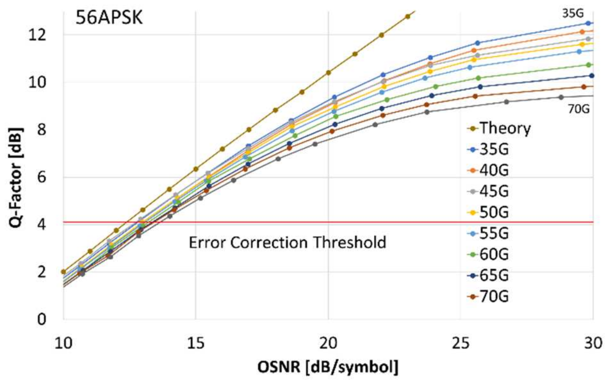

Fig. 2a: BtB Q-factor of 56APSK format vs OSNR at different symbol rates.

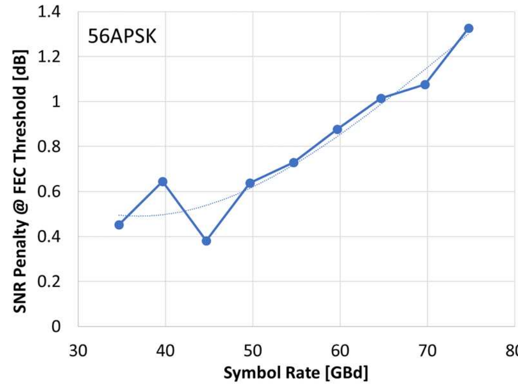

Fig. 2b: BtB SNR penalty at 25% FEC threshold vs symbol rate.

We use the hybrid shaped (HS) 4D-HS-9/12-56APSK modulation format in this study that was characterized in previous experiments [7-9]. The format is designed to approach the Shannon limit and to improve the utility of our nonlinear compensators. The format employs two codes - an outer FEC code (LDPC) and an inner nonlinear 9/12 code. The 9/12 code varies the probability distribution of the constellation points (probabilistic shaping), resulting in 56 constellation points of the 2D symbol. The radii of the constellations are optimized based on Gaussian distribution (geometric shaping). The FEC code used is a quasi-cyclic (QC) LDPC; and the LDPC frames are designed for joint polarization coding. The information bit-stream is a truncated 2^{20}-1 PRBS pattern. An additional 1.67% symbols are added as pilots. The channel information rate (removing all codes and pilots) increases from ~246 Gb/s to ~529 Gb/s as the symbol rate increases from 34.7 to 74.7 GBd (Table 1). The details of the modulation format and LDPC can be found in [7, 8].

The coherent receiver is based on a 90° optical hybrid, 70 GHz photo detector, 200 GS/s digital sampling scope and offline DSP. The receiver DSP is comprised of both traditional optical coherent techniques to compensate for linear effects as well as algorithms targeting nonlinear (Kerr) effects. The traditional DSP chain includes chromatic dispersion compensation, clock recovery, polarization mode dispersion compensation, carrier frequency offset compensation and carrier phase estimation (CPE). For nonlinearity compensation (NLC), we apply a combination of techniques: single channel digital back propagation (DBP) is performed with 2 steps per span followed by fast LMS equalizer and generalized filter. The details of the three NLC techniques and the receiver DSP can be found in [7, 9].

The circulating loop testbed is described in detail in [7]. The testbed consists of twelve 52.8 km fiber spans with 0.150 dB/km loss, 20.9 ps/nm/km dispersion, and ~150 μm^2 effective area, all at 1550 nm. Amplification is provided by C and L-band EDFAs with a signal bandwidth of 9.74 THz. Total C+L band power launched into transmission fibers is 22.5 dBm, which is near optimum power when all three NLC techniques applied. A loop synchronous polarization controller is used to randomize polarization evolution in the loop testbed.

3. Experimental Results

Fig. 2a shows the measured Q-factor vs OSNR in back-to-back (BtB) with noise loading for different symbol rates. To minimize the effects of OSNR variations and distortions of the transmitter with symbol rate, the modulation loss of the dual-polarization I/Q modulator is kept constant by varying the driving power to the modulator. Fig. 2b shows the BtB penalty (relative to the theory curve in Fig. 2a) at the error correction threshold (4.1 dBQ). The BtB penalty

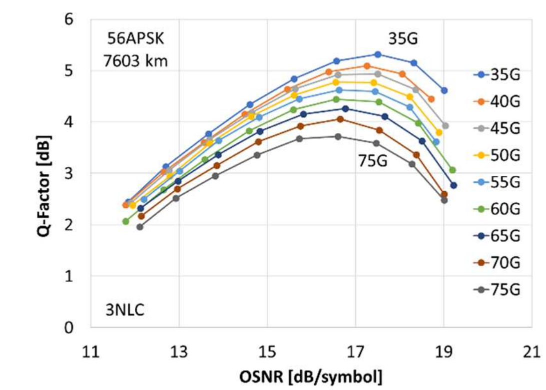

Fig. 3a: Pre-emphasis of 56APSK format across symbol rates.

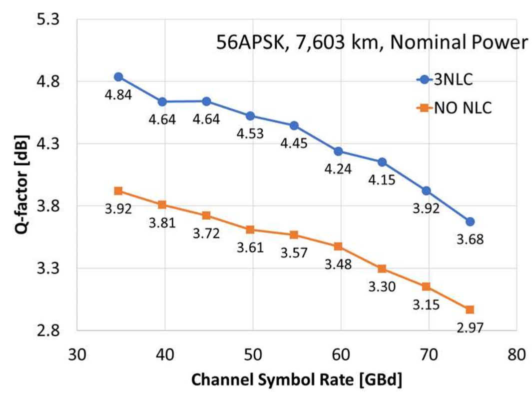

Fig. 3b: Performance vs symbol rate after 7,603 km.

increases from ~0.5 dB (34.7 GBd) to 1.3 dB (74.7 GBd). We estimate the BtB SNR limit of our transmitter and receiver decreases from 23.6 dB to 19. 1 dB as the symbol rate increases from 34.7 GBd to 74.7 GBd.

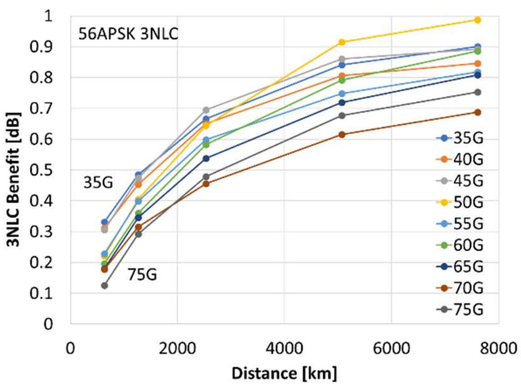

Fig. 4a: 3-Stage NLC benefit vs distance across symbol rates

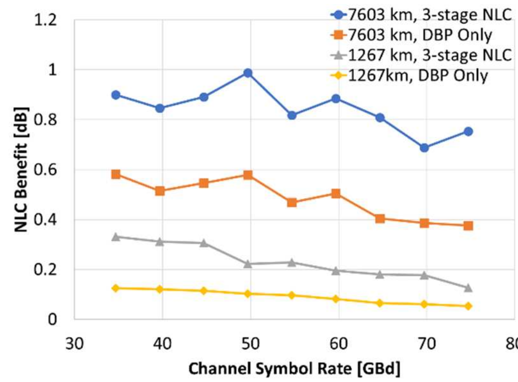

Fig. 4b: NLC and DBP-only benefit vs symbol rate at two distances

We perform transmitter power pre-emphasis using a group of channels in the center of the C-band after 7,603 km transmission. The power of a group of 5, 7 or 9 modulated channels are varied at the transmitter. Total pre-emphasis bandwidth ranges between 300 and 385 GHz as shown in Table 1. Fig. 3a shows a center channel performance with 3-stage NLC compensation vs received OSNR after 7,603 km, and Fig. 3b shows the performance vs symbol rate at nominal power (0-dB pre-emphasis) for the cases with and without 3-stage NLC compensation. For the cases using 3 stage NLC, performance degrades by ~1.5dB SNR (1.16dB Q) as the symbol rate increases from 34.7GBd to 74.7GBd. This SNR degradation is comprised of ~0.7 dB increase in BtB penalty and ~0.8 dB increase in nonlinear transmission penalty. For the cases without NLC, the Q-factor degrades by 0.95dB from 34.7GBd to 74.7GBd. Despite the increased non-linear transmission penalty at higher symbol rates, the benefits of NLC decrease by 0.3dB as shown in Fig 4b. Most of the reduction in NLC benefit is from DBP (0.2dB decrease) which we attribute to the larger effects of PMD at larger symbol rates. High symbol rate transmission at transoceanic distances may benefit from subcarrier modulation with DBP performed separately on the subcarriers. We further explore channel performance and NLC benefit vs transmission distance from 633.6 km to 7,603 km. Fig. 4a shows that the 3-stage NLC benefit increases with transmission distance. Fig. 4b shows NLC benefit vs channel symbol rate for 4 cases as indicated in the legend.

4. Conclusions

We experimentally study transmission performance dependence on channel symbol rates ranging from 34.7 to ~74.7 GBd. We use the 4D-HS-9/12-56PASK multi-dimensional coded modulation format based on hybrid shaping in experiments. As the symbol rate increases from 34.7 GBd, BtB SNR penalty increases by ~0.7dB. After 7,603 km transmission distance these penalties increase to 1.5 dB SNR and 1.16 dBQ respectively. The SNR degradation after the transmission, apart from the B2B penalty, is caused by ~0.8 dB penalty from nonlinear transmission effects. The NLC benefit drop comes predominantly from a decrease in DBP compensation benefit. This makes subcarrier multiplexing an attractive solution for higher symbol rate signals in order to fully utilize NLC with DBP.

5. References

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