

## TCM-QPSK PROVIDES 2DB GAIN OVER BPSK IN FESTOON LINKS

Pierre Mertz, Xiaohui Yang, Emily Burmeister, Han Sun, Steve Grubb,  
Serguei Papernyi (MPB Communications Inc.)

Email: pmertz@infinera.com

Infinera Corp., Sunnyvale, CA, USA

**Abstract:** Festoon links are single span subsea links that require no electrically powered amplifiers. Providing longer reach on these types of links enables cost effective, high bandwidth connectivity to more remote locations. TCM-QPSK is an innovative modulation format that works with the hard FEC generation of line cards to provide 2.0dB of extended reach on festoon links compared to differentially coded BPSK.

### 1. INTRODUCTION

Festoon links, also known as unrepeatered systems, are economical submarine cables operating over relatively short distances, typically under 500km. Both the advent of coherent modulation formats, and ultra-low loss and low nonlinearity fibers have increased the capacity of these links. Coherent PM-QPSK has been demonstrated as a high spectral efficiency modulation format with good reach with soft decision FEC using offline processing [1], or prototype real time processing [2]. PM-BPSK using hard decision FEC has also been demonstrated[3] with good reach. In this paper, we demonstrate an alternative modulation format, TCM-QPSK that has the same spectral efficiency as PM-BPSK, but with 2dB improved reach using hard decision FEC and legacy Z-PSCF fiber.

Trellis Coded Modulation (TCM) was first used in telephone modems[4] and is used in wireless and deep space communications. TCM is an error coding method whose overhead relies on more constellation points per symbol rather than more symbols per second. At the transmitter, the constellation point is chosen from a subset of the full

constellation depending on a hidden Markov state. The Viterbi algorithm is typically used at the receiver.

TCM-QPSK has been shown to outperform BPSK in the majority of repeatered subsea cables, providing benefits of up to 1.8dB.[5] However, it has also been shown that for dispersion managed trans-Pacific cables, BPSK is the preferred modulation, due to its higher tolerance to cycle slips. Results of testing on an unrepeatered link with co and counter Raman amplification as well as a remote optically pumped amplifier (ROPA) are presented. The per channel optical power in a festoon link is typically higher than in repeatered subsea links. This high power can lead to strong SPM and XPM, but it is shown that since there is only a single span, the cycle slip rate remains low. TCM-QPSK shows an improved festoon reach of 2dB compared BPSK.

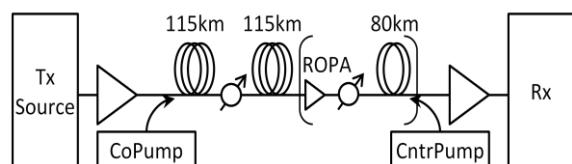


Figure 1: Lab Festoon Link

## 2. EQUIPMENT SETUP

The festoon link setup used to analyse the performance of the two modulation formats TCM-QPSK and BPSK is shown in [Error! Reference source not found.](#). All the fiber spools are pure silica core fiber (Z-PSCF), which is typically used in deployed festoon links due to its low loss, low Rayleigh backscattering, and low nonlinearity. 80km spools are removed. The co pump is spliced to first 115km spool, followed by a VOA and a second 115km spool. The second spool is used when testing non ROPA links, using counter and/or co Raman pumps. The VOA between the spools is used to adjust the span loss, and is at a position where the co and counter Raman pump powers are depleted and the signal powers are low enough to have negligible nonlinearities. In the tested configuration, the ROPA is placed before an 80km spool from the end. An additional VOA is used to optimize the ROPA span loss.

The transmitter of the submarine line terminal equipment (SLTE) setup, capable of full channel loading on a 25GHz ITU grid is shown in Figure 2. The channels under test originate from two production line cards, covering the red and blue halves of the C-band, respectively. Each 500G card has five 100G dual carrier channels in QPSK mode. The line cards can also run in half data rate, ultra long reach modes: BPSK or TCM-QPSK. The ten carriers per card are spaced 200GHz apart and have their performance individually measured in

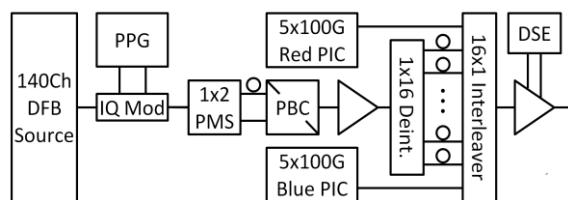


Figure 2: Transmitter setup with production line cards and loading channels.

terms of Q-factor, calculated from the bit error rate.

The loading carriers are generated using a 140 channel, 25GHz spaced DFB source filling the unused spectrum between the channels under test. The CW carriers are routed to an IQ modulator driven by a dual lane pattern generator (PPG) at the same baud rate as the channels under test. These single polarization QPSK modulated carriers are then polarization multiplexed by splitting them with a polarization maintaining splitter (PMS), delaying one arm by about 100 symbols, and then recombining using a polarization beam combiner (PBC). The loading channels are then decorrelated in time by going through a 14 inputs of a 16-way, 25GHz spaced, deinterleaver and interleaver pair, connected with patch cords of varying lengths. The two line cards are connected to the remaining 2 inputs of the interleaver.

The output of the festoon link goes through a deinterleaver and back to the two production line cards.

## 3. TEST METHODOLOGY

Due to complex Raman interactions between channels, such as blue channels pumping red channels, the final OSNR per channel may not be flat when launching a flat transmit spectrum. In addition nonlinearities in the blue are higher than in the red. In order to get the maximum capacity, the transmit spectrum is pre-emphasized using the dynamic spectral equalizer (DSE) shown in [Error! Reference source not found.](#). The DSE is adjusted such that the Q factors are flat across the spectrum. The VOA between the 115km PSCF spools in Figure 1, the Raman pumps, and the total launch power are optimized to provide a received Q of 10dB, giving margin above the FEC limit. The reach in dB is quoted as the sum of all

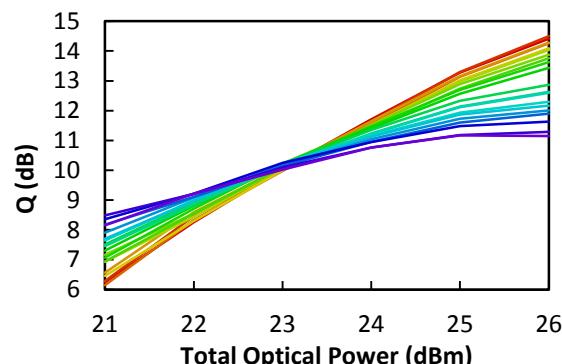
the appropriate insertion losses between the Raman pumps at 1550nm plus the VOA setting.

#### 4. TCM NONLINEAR PENALTY

The 8 state RI-TCM-QPSK[5] tolerates a significant amount of noise in a back-to-back configuration, having a required OSNR (ROSNR) of only 4.1dB at a HD FEC limit Q of 9.0dB (equivalent BER of  $2.4 \cdot 10^{-3}$ .) At the same FEC limit, BPSK requires an OSNR of 6.6dB. The slope of TCM-QPSK's Q vs. OSNR curve of about 1.5 is much steeper than BPSK's curve of about 1.0, so this 2.5dB OSNR benefit depends strongly on the FEC limit.

The back to back AWGN channel, equalized using a sufficient carrier recovery averaging window, results in a soft output with a low cycle slip rate, which is the rate of undesired QPSK constellation rotations of  $90^\circ$  due to excessive carrier recovery noise. The RI-TCM code, which can be decoded in any of the four possible rotations, incurs a penalty during a cycle slip due to changing of the hidden Markov state of the trellis code. It can be shown[6] that it takes at most S-1 steps to recover the state, where S is the number of states in the trellis, so the penalty in our case is a burst of errors less than 8 symbols long.

Optical nonlinearities create phase noise



that leads to higher cycle slip rates. As the

cycle slip rate increases, the burst errors induce a penalty on RI-TCM-QPSK compared to differentially coded BPSK, which is also invariant to constellation rotations.

The Q vs power curves of TCM-QPSK in **Error! Reference source not found.** were performed after the DSE and VOA were adjusted on the test link to provide 10dB of Q at an optimized optical power of 23dBm. In this case the festoon link had no Raman amplification, and the higher curvatures of the blue channels show they have higher nonlinearities than the red channels.

In addition, the simulated power profile in **Error! Reference source not found.** shows that the blue channels experience more Raman gain in the first 20km, and will thus experience higher nonlinearities

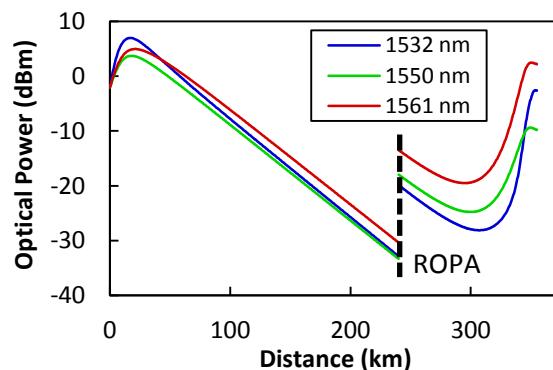


Figure 2: Propagation power in the fiber for Case C with co and counter Raman pumps and a ROPA

than the red channels.

These varying nonlinearities across the spectrum in the link result in varying performance benefits of TCM vs BPSK, and thus different optimum power profiles over wavelength are required: a change of tilt of approximately 0.7dB is required when switching between the modulation formats.

#### 5. TCM VS BPSK PERFORMANCE

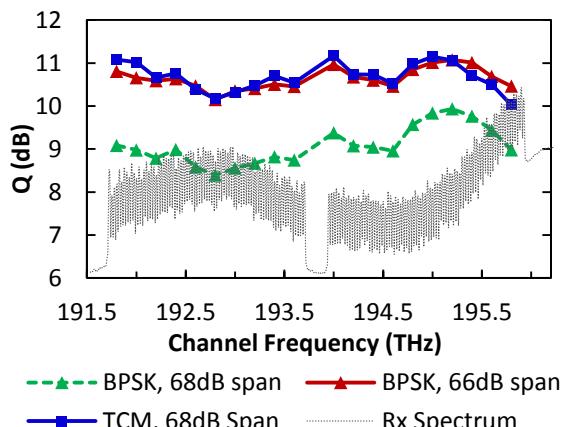


Figure 3: TCM and BPSK reach on ROPA link with 4 Terabit capacity

Figure 5 compares TCM performance against BPSK. The solid curves compare TCM with 2.0dB higher reach than BPSK, but without changing the pre-emphasis or tilt between the two measurements. Link loss was increased by 2dB using the VOA between the 115km PSCF spools in Figure 1. On the red wavelengths, where nonlinearities are lower, TCM Q's are 0.3dB higher than BPSK Q's, whereas on the blue wavelengths, the higher nonlinearities decrease TCM Q's to 0.3dB below BPSK Q's. Adding the proper pre-emphasis equalizes the Q's, giving TCM a 2.0dB reach benefit over BPSK on festoon links.

Also shown by the dashed trace in Figure 5 are the BPSK Q values measured at the TCM's reach, again without changing pre-emphasis. As the nonlinearities increase from the red to the blue wavelengths, the resulting higher cycle slip rates cause the TCM's gain over BPSK to go from just over 2dB to just over 1dB.

## 6. CONCLUSIONS

For transmission equipment that can operate at full and half data rates, it is shown using production line cards that TCM-QPSK provides 2.0dB longer reach on festoon links than BPSK. Although

only full capacity 25GHz channel spacing is presented, the same benefit is observed at lower capacity when the channels have 50GHz or 100GHz spacing.

TCM's high festoon reach using the generation of line cards based on hard decision FEC is comparable to that of the next generation cards using soft decision FEC with BPSK.

## 7. ACKNOWLEDGEMENTS

We would like to thank MPB Communications for allowing us to demonstrate the advantages of TCM-QPSK on repeaterless link using their equipment.

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Figure 3: TCM power dependence across spectrum from 191.8 THz to 195.8 THz of PSCF with no Raman amplifiers.

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