SPECTRALLY-EFFICIENT 200G PROBABILISTIC-SHAPED 16QAM OVER 9000 KM STRAIGHT LINE TRANSMISSION WITH FLEXIBLE MULTIPLEXING SCHEME

Kohei Nakamura* (1), Takanori Inoue(1), Shaoliang Zhang(2), Fatih Yaman(2), Eduardo Mateo(1), Yoshihisa Inada(1)
* Email: k-nakamura@gc.jp.nec.com

(1) Submarine Network Division, NEC Corporation, Tokyo 108-8001, Japan
(2) NEC Laboratories America, Inc., Princeton, NJ 08540, USA

Abstract: Flexible wavelength-multiplexing technique in backbone submarine networks has been deployed to accommodate the trend of variable-rate modulation formats. In this paper, we propose a new design of flexible-rate transponders in the scenario of flexible multiplexing scheme to achieve near-Shannon performance. Probabilistic-shaped (PS) M-QAM is capable of adjusting the bit rate at very finer granularity by adapting the entropy of the distribution matcher. Instead of delivering variable bit rates at the fixed baud rate, various baud rates of 200Gb/s PS-16QAM is demonstrated to fit into the flexible grid multiple 3.125GHz bandwidth. This flexible baud rate saves the limited optical bandwidth assigned by the flexible multiplexing scheme to improve bandwidth utilization. The 200G PS-16QAM signals are experimentally demonstrated over 9000km straight-line testbed to achieve 3.05b/s/Hz~5.33 b/s/Hz spectral efficiency (SE) with up to 4dB Q margin. In addition, the high baud rate signals are used for lower SE while low baud rate signals are targeting at high SE transmission to reduce the implementation penalty.

1. INTRODUCTION

Digital coherent transceivers has been fast evolving into a multi-rate, multi-format, variable-bandwidth paradigm in the past decade thanks to the advanced technologies in digital signal processing (DSP) algorithm and ASIC development [1]. The commercially-available transceivers modules are reported to support data rates from 50Gb/s up to 600Gb/s per wavelength [2] at a granularity of 50Gb/s or even lower. This flexibility of transceivers makes significant impact on the development of elastic optical networking by dynamically adjusting signal bandwidth/wavelength and modulation formats depending on the transmission characteristics of each link connection [3]. Although there are various ways to achieve flexible-rate transmission, the performance cannot be guaranteed to be as close to the Shannon limit due to the capacity gap from *M*-QAM formats [4].

Wavelength-selective switches (WSS) are the key component to achieve this flexibility with the targeted signal bandwidth and wavelength allocation [5]. Flexible wavelength-multiplexing technique in backbone submarine networks have been deployed to accommodate the trend of variable-rate modulation formats. As a result, the ITU-T has defined the latest flexible grid G.694.1 to aggregate any signal bandwidth into $N\times$12.5GHz spectral bandwidth [6]. In this paper, we review the design of variable-rate transponders in the scenario of flexible multiplexing technique to achieve near-Shannon performance.

2. DESIGN OF CAPACITY-APPROACHING AND FLEXIBLE -RATE TRANSPONDER

Various approaches can be applied to maximize the spectral efficiency at the given received signal-to-noise ratio (SNR), such as adaptive forward-error correction (FEC) codes, agile modulation formats, and pulse shaping. As shown in Fig. 1, the client data rate is fixed at, e.g., 200 Gb/s, at the assigned bandwidth in a 12.5GHz grid granularity to achieve various SE. Higher filling ratio (FR) is expected to achieve higher SE but is subjected to larger transmission nonlinearity.

In general, standard *M*-QAM formats or even set-partitioning (SP)-based QAM formats [7] or time-hybrid QAM formats [8] can be used to deliver the target data rates. However, these modulation formats are still far away from the Shannon limit based on information theory.

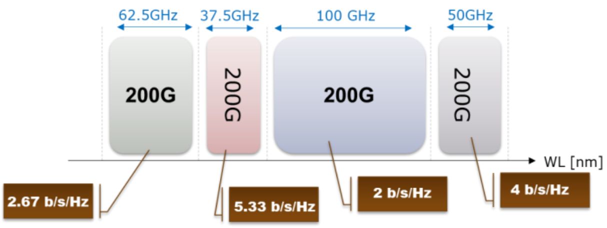

Fig. 1 Discrete 2-dimensional space to select baud rates and modulation format at the flexible 12.5GHz multiplexing scheme grid.

Fig. 2 compares the simulated generalized mutual information (GMI) among *M*-QAM, time-hybrid QAM (solid lines) and SP QAM (dashed lines) at the typical received SNR of interested. The results suggest that 16QAM is the best candidate to approach the capacity limit among all the studied schemes. However, if 16QAM is chosen as the constellation, variable FEC coding rates have to be used in order to achieve variable SE, thus increasing the design and implementation complexity. In addition, the DSP algorithm could be susceptible to excessive cycle-slips and instability due to the high symbol error rate in the case of low SE where SNR is lows.

Despite discrete baud rates discussed above, flexible-rate can be achieved in theory together with capacity-approaching modulation formats. The revival of capacity-approaching modulation formats culminates the probabilistic shaping (PS) over M-QAM to close the 1.53dB shaping gain towards the Shannon limit [9]. The key enablers are the distribution matcher (DM) and FEC encoding/decoding without altering the shaping [10]. The PS technology is quickly evolved into all the transmission aspects to provide both shaping gain and flexible-rate without changing modulation formats and FEC coding rates [9, 11].

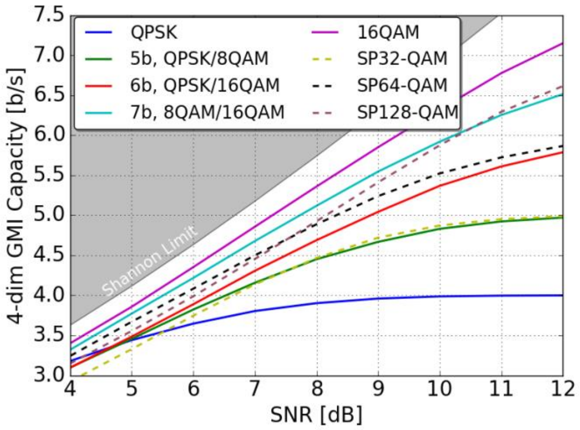

Fig. 2 The GMI of M-QAM, time-hybrid QAM and SP-QAM.

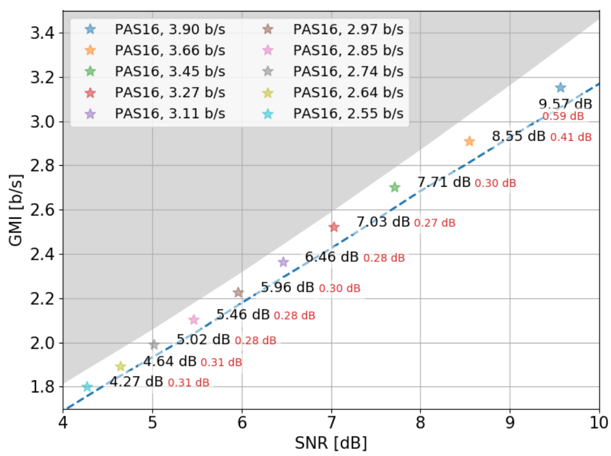

Fig. 3 The GMI of 200 G PS-16QAM (FR = 0.92, *N*×3.125 GHz multiplexing scheme bandwidth). The numbers in black and red fonts show the required SNR and SNR gap towards the Shannon limit at the target data rates, respectively. The blue dashed line shows the GMI of standard 16QAM.

The data rate of PS-*M*QAM can be calculated as

$$DR = 2\frac{H_a - (1-r)m}{1+OH_{pilots}} \times BR, \qquad (1)$$

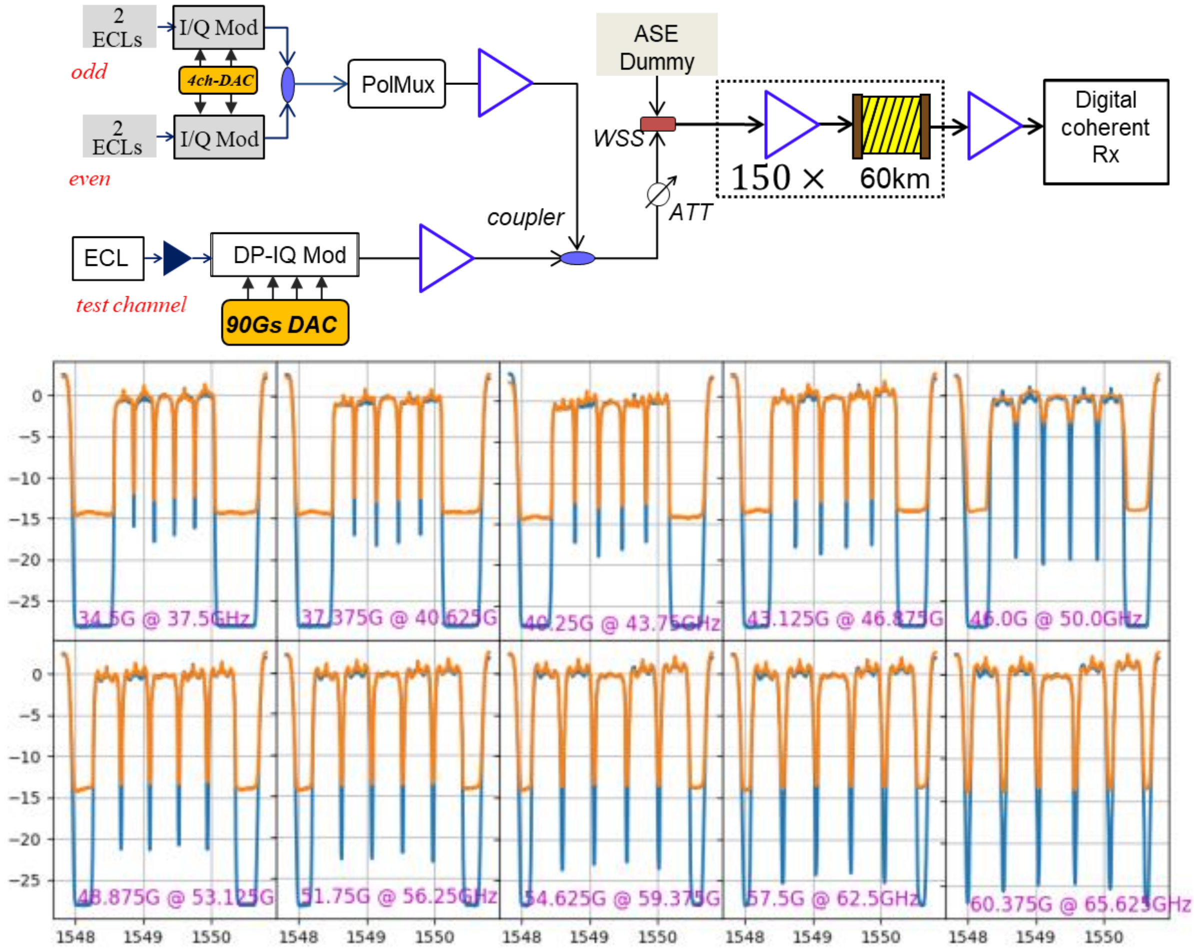

Fig 4: System setup and OSA spectra at TX/RX side

where H_a stands for the entropy of the resulting PS-*M*QAM, $m = \log_2 M$, r is the FEC coding rate, OH_{pilots} is the overhead of the pilots and BR is the baud rate of the signal. Note that the coefficient 2 takes into account of dual polarizations. Clearly, given the fixed baud rate, modulation format and coding rate, the signal data rate can be adapted via entropy H_a in the DM. As a result, the PS scheme simplifies the design of flexible-rate transponders without incorporating all the M-QAM modes and adaptive FEC.

Fig. 3 shows the GMI of 200Gb/s PS-16QAM over 3.125GHz flexible-grid spanning from 37.5 GHz up to 65.625 GHz at FR = 0.92 assuming 25% FEC OH and 5% pilot OH. About 0.6 dB to 0.3 dB SNR penalty are observed at the SE of interest. The rate adaptation in PS-16QAM is reflected in the variable baud rates when fitting the fixed data rate into the assigned frequency slot. In addition, the high baud rate is used for low-SE regime while low baud rate is designed for high-SE to mitigate the implementation penalty from limited ENOB of DAC.

3. EXPERIMENTAL SETUP AND RESULTS

Fig.4 shows the system setup to generate 5-channel WDM signals using high-speed DACs and 150 spans of 60km SMF link. The insets plot the spectra at both the transmitter and receiver side at the selected SE. The flexible multiplexing scheme is emulated by a WSS operating at 3.125GHz granularity. Only the center channel is selected to check the back-to-back (BTB) and transmission performance.

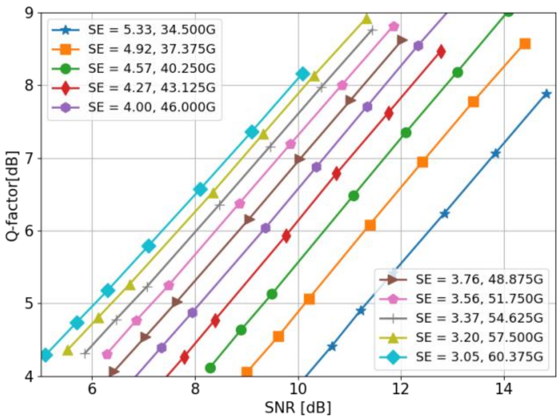

Fig. 5 The measured BTB Q versus SNR for 200G PS-16QAM at different SE.

Fig.5 plots the measured BTB Q-factor as a function of SNR for the selected baud rates. At the target pre-FEC Q limit (~5dB), the required SNRs range from ~6.0 dB at 3.05 b/s/Hz SE to ~11.3 dB at 5.33 b/s/Hz SE. The designed 200G PS16 is capable of covering about 5.3dB SNR range, which can be translated into about 3x reach difference. In this measurement, all the baud rates are generated by single transmitter which has limited DAC ENOB. As a result, the lower baud rate signals benefits from the ENOB to have higher quality signals compared to high baud rate signals. In general, the proposed design can be used for reducing the implementation penalty at higher SE. The post-FEC BER performance is further confirmed in Fig. 6 to show error-free correction at the target 5 dB pre-FEC Q-factor. The dotted lines show the Shannon limit at the target SE. Due to the limited length of LDPC codewords and DSP penalty, PS16 is still at least ~1.5 dB away from the Shannon limit in terms of required SNR.

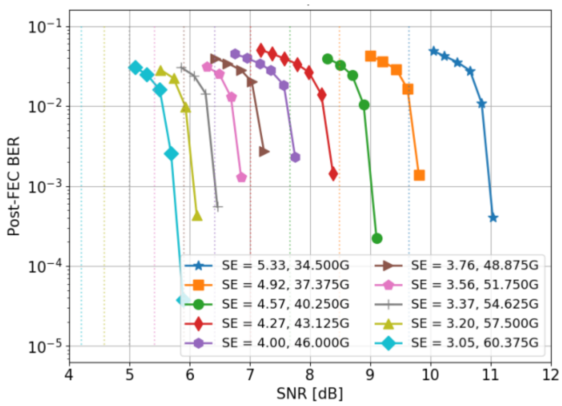

Fig. 6 The Post-FEC performance versus SNR for 200G PS-16QAM at different SE.

A 9000 km straight-line testbed is used to compare all the modes for transmission performance, shown in Fig. 7. At the optimum +2 dB pre-emphasis, the received Q-factor difference among all 200G PS16 modes is similar as BTB measurements to demonstrate that the nonlinearity tolerance of these modes is not affected much by constellation shaping. There is about 4 dB optimum Q-factor differences among these modes, thus corresponding to the estimated BTB Q shown in Fig. 5 at the received 11 dB SNR. For example, at the SE of 5.33 b/s/Hz, 200G PS16 is close to the borderline to achieve 9000 km transmission over 37.5 GHz bandwidth. However, the transmission distance could be extended to 3 times, e.g., 27,000 km, when packing 200G PS16 in 65.625 GHz bandwidth.

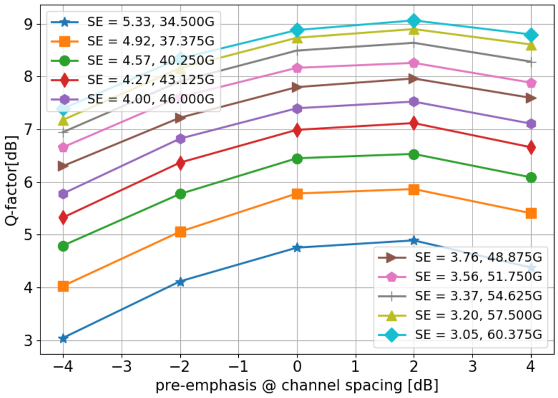

Fig. 7 The received Q-factor versus Tx-side Pre-Emphasis for 200G PS-16QAM at different SE.

4. CONCLUSION

Flexible rate transmission has been enabled by the advancement of flexible-rate transponders and flexible-grid WSS. At the designed filling ratio and given flexible bandwidth, variable-bandwidth PS-MQAM provides both of near-Shannon limit and flexible-rate submarine transmission. Experimental demonstration of 200G PS16 has been achieved from 3.05 b/s/Hz SE up to 5.33 b/s/Hz SE over 9000 km straight-line testbed.

5. REFERENCES

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