Quasi-Continuous Symbol Rate Tunability for Maximum Capacity in Links Constrained by ROADM Filtering

Steven Searcy, Thomas Richter, Sergey Burtsev, Sorin Tibuleac

ADVA, 5755 Peachtree Industrial Blvd, Norcross, GA, 30092, USA, ssearcy@adva.com

Abstract *Using real-time transceivers with symbol rates up to 72 GBd, we investigate the impact of ROADM filtering on optimum symbol rate and fractional m-QAM modulation required to maximize channel capacity. Granularity below 5 GBd is shown to yield maximum margin for a given link passband.*

Introduction

In many terrestrial networks, optical filtering due to reconfigurable optical add-drop multiplexers (ROADMs) can have a significant impact on signal quality and also limit reach or capacity[1-3]. This is particularly true in metro and regional networks with higher density of ROADM nodes and a greater percentage of add/drop traffic. Modern ROADMs offer flexible-grid capabilities, with step sizes of 12.5 GHz or less[4]. At the first order, the optical passband of a ROADM is determined by the slot size assigned to a given channel. In real networks, choice of slot size may be constrained by multiple factors, including the inherent wavelength-selective switch (WSS) granularity, the bandwidth granularity used by the network management software, the current traffic wavelength assignments (i.e., the available spectrum), and any existing components in the network with a fixed passband. In particular, metro networks are more likely to carry a mix of legacy traffic, potentially operating with fixed-grid ROADMs and filters. Assuming a bandwidth-constrained link, it is desirable to use a flexible transceiver which can adapt the modulation and symbol rate to the net passband.

Most modern transceivers can tune the signal modulation with fine granularity, using methods such as time-domain hybrid modulation[5-6], probabilistic constellation shaping[1,7], and digital subcarrier multiplexing[7]. Such flexibility allows the modulation to be matched to the available signal to noise ratio (SNR) on a link. However, the most critical factor in a signal's resilience to optical filtering is the signal bandwidth (relative to the filter passband), which for spectrally shaped signals is determined primarily by the symbol rate. Many transceivers can operate at multiple symbol rates, but with varying step sizes.

To optimize the system performance, it is important to predict the tolerance of a certain signal type to the link passband, to limit filtering impairments. One solution is to avoid tight filtering by use of conservative slot size assignments or spectral guard bands between slots, to ensure that filter penalties are minimal. Such solutions offer good performance at the expense of spectral efficiency and net capacity. Another solution involves tailored modulation schemes, such as mapping of lower-order formats to digital subcarriers at the outer edge of a signal near the passband edge[7]. In this work, we explore the option to tune the signal symbol rate to match the net passband of a given link.

Some previous work has studied realistic filtering impairments in transceivers with high symbol rates and flexible modulation[1-2,8-9], but most studies to date have explored filter penalties in the context of one or two symbol rates. In this work we use a commercial flexible transceiver with quasi-continuous tunable symbol rate and fractional *m*-QAM modulation index on a multi-span transmission link with linear and nonlinear noise as well as passband narrowing from ROADMs. We show that there is an optimum combination of symbol rate and modulation relative to the net bandwidth of a filter cascade, and that symbol rate granularity below 5 GBd is advantageous for maximizing channel margin or capacity for a given link passband profile.

Experimental configuration and procedure

Experiments were carried out on a 1000-km transmission system as shown in Fig. 1. The link contains 12 spans of standard single-mode fiber (SSMF) with average length of 83.3 km (average span loss 16.6 dB), 4 route-and-select ROADMs (8 WSS modules) and one EDFA to compensate the loss of each fiber span and ROADM. The channels under test are located in the center of the spectrum and assigned 75 GHz slots, while the remainder of the C-band is filled with shaped ASE loading channels on the 50 GHz grid.

In all tests the terminal ROADM is used for multiplexing and demultiplexing the channels before and after the link with individual WSS ports for each test channel. The mid-link ROADMs are reconfigured to selectively apply filtering to the test channels. Each ROADM (2xWSS) may be configured to apply no filtering by having all channels pass through a single port (emulating a node with all express traffic) or apply filtering to

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

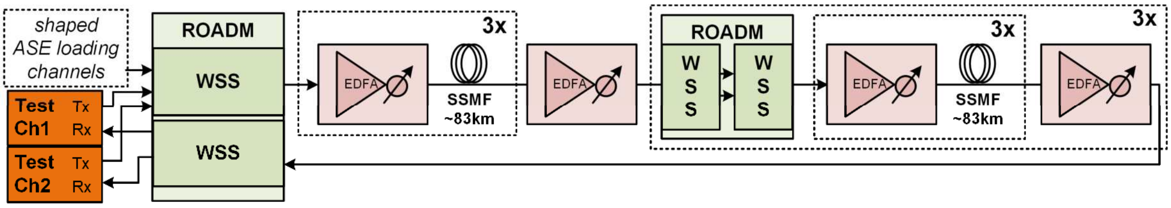

Fig. 1: Diagram of experimental transmission link with 1000 km (12 spans) standard single-mode fiber and in-line ROADMs

the test channels by routing adjacent channels through different ports (emulating a node with a mix of express and add/drop traffic). The test channels may experience filtering from 2xWSS (first/last) up to 8xWSS (all ROADMs in the link). Excellent models exist for predicting the net passband of a WSS cascade[10-12]. In this study we measured the passband of each WSS using a swept tunable laser, to determine the net passband for each test channel in each link filtering condition. We represent the net passband by the 6 dB bandwidth of the filter cascade. This has been shown to be a relevant metric for assessing WSS filtering penalties[12].

The test channels are from a commercial transceiver[6] with symbol rates from 24-72 GBd, variable in steps of <0.3 GBd across the full range, and time-domain hybrid modulation from QPSK up to 64QAM, variable in steps of 0.008 bits/symbol. Two different SD-FEC overhead rates are available (15%, 27%) and data rates up to 600 Gb/s in 50 Gb/s increments. Signals are root-raised cosine shaped with 0.1 roll-off.

For transmission testing, the optimum launch power of +1 dBm/75 GHz was determined empirically by scanning launch power to find the optimum Q for test channels at 400 Gb/s 16QAM (69.44 GBd). All launch power levels were kept fixed at this condition so that the link (G)OSNR was approximately constant throughout the tests, which consisted of reconfiguring the mid-link ROADMs to change the net link passband and reconfiguring the transceiver to vary the test channel symbol rate and modulation. For each test condition we measured OSNR and BER of the test channels. Q factor was computed from the measured BER, and Q margin was computed as the difference between the measured Q and the nominal FEC threshold (Q = 5.0 dB or 6.0 dB for 27% and 15% FEC modes respectively).

Results and discussion

Figure 2 presents results for a single test channel (for clarity) at 400 Gb/s with four different filtering conditions, showing how the narrowing link passband induces penalties at higher symbol rates. The optimum symbol rate becomes smaller as the link bandwidth decreases.

A larger set of results is shown in Fig. 3(a), including data from both test channels, two FEC modes, and three data rates, for a single WSS configuration. On the x-axis we introduce a new metric, Δ*B*, which represents the difference between the link 6 dB bandwidth and the symbol rate. This proves to be a useful metric in assessing filtering tolerance, with smaller values indicating tighter filtering conditions. We observe that 350 Gb/s can be achieved with ample margin and operates with similar performance across a wide range of symbol rates (>10 GBd). 400 Gb/s can be achieved with up to 2 dB of margin around the optimum point, which spans a smaller range of symbol rates (~4-5 GBd) due to the impact of filtering. Results at 450 Gb/s show very low margin (~0.5 dB max), with an even narrower range of optimum symbol rates spanning only a few GBd. These results show the benefit of fine symbol rate tunability, where granularity below 5 GBd would be required to achieve the max rate of 450 Gb/s on this particular link (assuming minimum operating margin of ~0.5 dBQ).

Figure 3(b) shows similar results for one data rate with multiple filtering conditions. By using the Bandwidth-Symbol Rate difference Δ*B* on the x-axis we can easily compare results from different filtering conditions and observe that a similar optimum is shared across all the results. This means the optimum symbol rate is different for each link passband case. It is also important to note that in cases with tighter filtering (smaller Δ*B*) the signal is susceptible to timing recovery failure at the receiver. Therefore, symbol rates above the optimum for a given link may not be viable even with apparently sufficient margin.

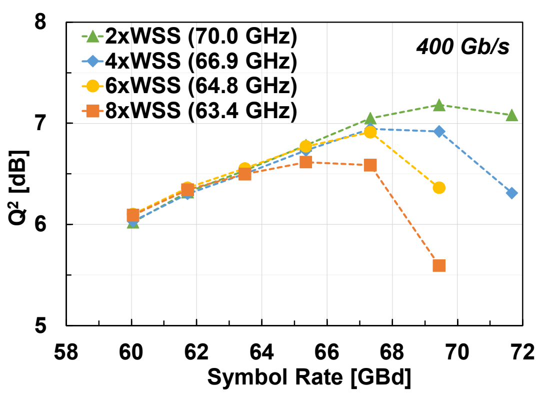

Fig. 2: Experimental results for 400G test channel with 27% FEC, varying modem configuration (3.875…4.625 bits/symbol) and filtering conditions (Net 6 dB Bandwidth).

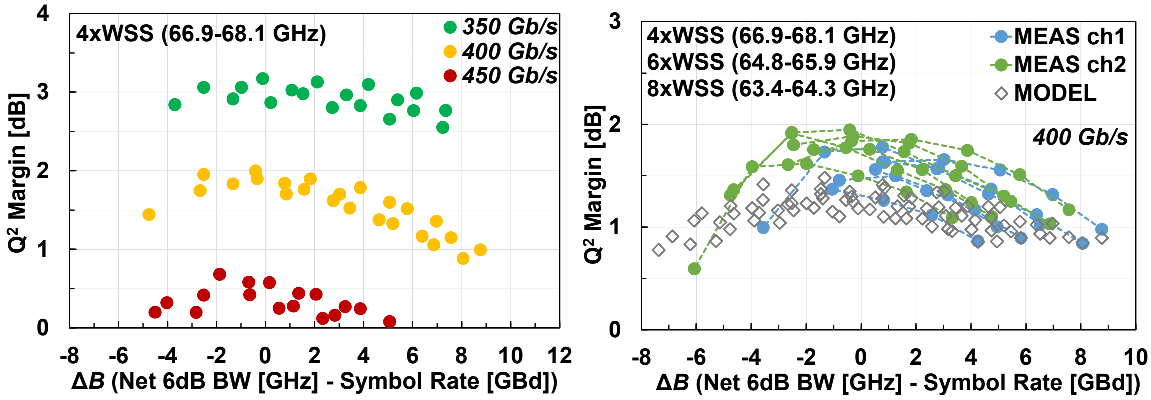

Fig. 3: Experimental results from two test channels with two FEC modes (27%, 15%), and varying modem configurations (3.125…5.25 bits/symbol, 59.5…71.7 GBd): (a) with multiple data rates and a single ROADM filtering condition (Net 6 dB Bandwidth), and (b) with a single data rate and multiple ROADM filtering conditions, along with model prediction.

To further validate the experimental results and predict performance in other scenarios, we use a simplified model to compute Q factor. We start with a conventional GOSNR-based model which was shown to have sufficient accuracy on the transceiver used in these tests[6]. We augment this model with another additive noise term to include WSS passband impairment[13], with a function for equivalent noise derived from empirical studies scanning modem configuration and filter bandwidth in back-to-back experiments. Such calibration tests were performed with noise loading before and after filtering, representing the best and worst-case conditions[9,14-15]. The model uses an average of these cases since the real link has both ASE noise addition and filtering distributed across the link. These generalizations to treat the passband impairment as noise and to approximate the impact of distributed ASE and filtering are used to create a very simple model for predicting performance. Other studies and models have examined these aspects in greater detail, with more complex modeling[9,14].

As shown in Fig. 3(b), this simplified model can perform reasonably well in the practical

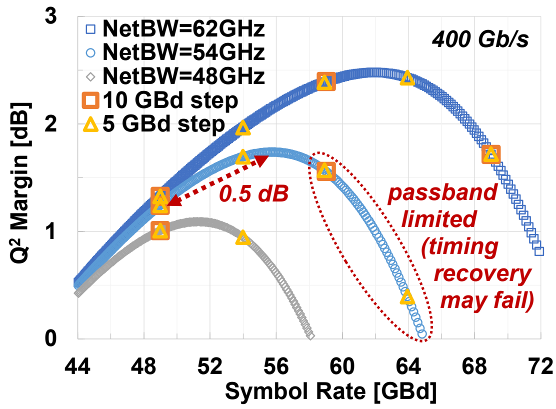

Fig. 4: Modeling results for different filtering conditions with fixed GOSNR (27 dB) and varying modem configs (3.5…5.75 bits/symbol) for quasi-continuous symbol rate (circles), steps of 5 GBd (triangles), or 10 GBd (squares).

region of interest (light to moderate filtering). The absolute Q is predicted within ~0.5 dB, and the approximate optimum value of Δ*B* predicted by the model matches well with the experiments. The largest model limitation is in the tight filtering regime, which would typically be avoided in practice due to high penalties and chance of timing recovery failure. In this region the simplifying assumptions break down, particularly the approximation of filtering impairments by an additive noise term.

Finally, we use the simple model to explore the impact of filtering in hypothetical network scenarios. In Fig. 4 we model the performance of a 400 Gb/s signal for a link with fixed GOSNR (linear+nonlinear noise) and three net bandwidth values representing different ROADM cascades or slot sizes (e.g., 62.5GHz). We compare results for quasi-continuous symbol rate versus larger discrete steps. In these examples, a symbol rate step of 5 GBd can achieve close to the optimum performance (~0.1 dB gap). However, symbol rate step of 10 GBd can have a significant gap in performance relative to the optimum (up to ~0.5 dBQ). These results indicate that symbol rate tunability of ~5 GBd or less can help optimize performance for practical link passbands.

Conclusions

The impact of ROADM filtering on performance of a transceiver with quasi-continuous tuning of symbol rate and modulation was analyzed experimentally in a realistic link including fiber nonlinearity. Optimization of symbol rate maximizes the margin and enables higher capacity in a bandwidth-constrained link. Using a simplified model to account for passband impairment in system budgeting we show that for a given link passband there is an optimum combination of modulation and symbol rate, and that symbol rate granularity <5 GBd can achieve performance within 0.1 dB of the optimum.

References

[1] T. Zami, B. Lavigne, I. F. de Jauregui Ruiz, M. Bertolini, Y.-H. C. Kao, O. Bertran-Pardo, M. Lefrancois, F. Pulka, S. Chandrasekhar, J. Cho, X. Chen, D. Che, E. Burrows, P. Winzer, J. Pesic, and N. Rossi, “Simple self-optimization of WDM networks based on probabilistic constellation shaping,” *J. Opt. Commun. Netw*., vol. 12, no. 1, pp. A82-A94, 2020.

[2] T. Zami, I. F. de Jauregui Ruiz, A. Ghazisaeidi, and B. Lavigne, “Growing impact of optical filtering in future WDM networks,” in *Optical Fiber Communication Conference (OFC)*, March 2019, paper M1A.6.

[3] A. Morea, J. Renaudier, T. Zami, A. Ghazisaeidi, and O. Bertran-Pardo, “Throughput comparison between 50-GHz and 37.5-GHz grid transparent networks,” *J. Opt. Commun. Netw*., vol. 7, no. 2, pp. A293-A300, 2015.

[4] Y. Ma, L. Stewart, J. Armstrong, I. G. Clarke, and G. Baxter, “Recent progress of wavelength selective switch,” *J. Lightwave Technol.*, vol. 39, no. 4, pp. 896-903, 2021.

[5] X. Zhou and L. Nelson, “Advanced DSP for 400 Gb/s and beyond optical networks,” *J. Lightwave Technol.*, vol. 32, no. 16, pp. 2716-2725, 2014.

[6] S. Burtsev, S. Searcy, and S. Tibuleac, “Experimental study of closed-form GN model using real-time *m*-QAM transceivers with symbol rate up to 69 GBd,” in *Optical Fiber Communication Conference (OFC)*, March 2020, paper M4K.6.

[7] H. Sun, M. Torbatian, M. Karimi, R. Maher, S. Thomson, M. Tehrani, Y. Gao, A. Kumpera, G. Soliman, A. Kakkar, M. Osman, Z. A. El-Sahn, C. Doggart, W. Hou, S. Sutarwala, Y. Wu, M. R. Chitgarha, V. Lal , H.-S. Tsai, S. Corzine, J. Zhang, J. Osenbach, S. Buggaveeti, Z. Morbi, M. I. Olmedo, I. Leung, X. Xu, P. Samra, V. Dominic, S. Sanders, M. Ziari, A. Napoli, B. Spinnler, K.-T. Wu, and P. Kandappan, “800G DSP ASIC design using probabilistic shaping and digital sub-carrier multiplexing,” *J. Lightwave Technol.*, vol. 38, no. 17, pp. 4744-4756, 2020.

[8] N. Rossi, T. Zami, and J. Pesic, “Does ageing of margins become more attractive in WDM networks with 64 GBaud transponders and regenerators?” in *European Conference and Exhibition on Optical Communication (ECOC)*, Sept. 2019, paper M2E.3.

[9] I. F. de Jauregui Ruiz, A. Ghazisaeidi, T. Zami, S. Louis, and B. Lavigne, “An accurate model for system performance analysis of optical fibre networks with in-line filtering,” in *European Conference and Exhibition on Optical Communication (ECOC)*, Sept. 2019, paper P78.

[10] C. Pulikkaseril, L. A. Stewart, M. A. F. Roelens, G. W. Baxter, S. Poole, and S. Frisken, “Spectral modeling of channel band shapes in wavelength selective switches,” *Opt. Express*, vol. 19, no. 9, pp. 8458-8470, 2011.

[11] J. Pan, C. Pulikkaseril, L. Stewart, and S. Tibuleac, “Comparison of ROADM filter shape models for accurate transmission penalty assessment,” in *IEEE Photonics Conference*, Oct. 2016, paper WD1.4.

[12] J. Pan and S. Tibuleac, “Real-Time ROADM filtering penalty characterization and generalized precompensation for flexible grid networks,” *IEEE Photonics Journal*, vol. 9, no. 3, pp. 1-10, 2017, Art no. 7202210.

[13] J. Pan and S. Tibuleac, “Real-time investigation and prediction of transmission penalties for PDM-8QAM/16QAM super-channels in flexible grid DWDM networks,” in *Optical Fiber Communication Conference (OFC)*, Mar. 2017, paper M2E.5.

[14] C. Delezoide, P. Ramantanis, and P. Layec, “Weighted filter penalty for QoT estimation,” in *Optical Fiber Communication Conference (OFC)*, Mar. 2018, paper W2A.56.

[15] J. Pan, T. Richter, and S. Tibuleac, “OSNR measurement comparison in systems with ROADM filtering for flexible grid networks,” in *Optical Fiber Communication Conference (OFC)*, Mar. 2018, paper Th1A.2.