Paper Review: Evaluation of Elastic Modulation Gains in Microsoft’s Optical Backbone in North America

M. Ghobadi, J. Gaudette, R. Mahajan, A. Phanishayee, B. Klinkers, and D. Kilper, "Evaluation of elastic modulation gains in microsoft's optical backbone in North America,"*Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1-3, March 2016.

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Friday, April 5, 2019.
Netlab’s Group Meeting

Agenda

- Adaptiveness of Core Network
- Capacity Gain of Elastic Optical Network
- Modulation Format Adaptable Transmitter
- Transparent Reach for Coherent Optical Transmission
- Paper Review: Evaluation of Elastic Modulation Gains in Microsoft's Optical Backbone in North America

Adaptiveness of Core Network

Bit rate, Baud rate, Modulation Format, OSNR limit, Reach etc.

Fixed Baud-rate

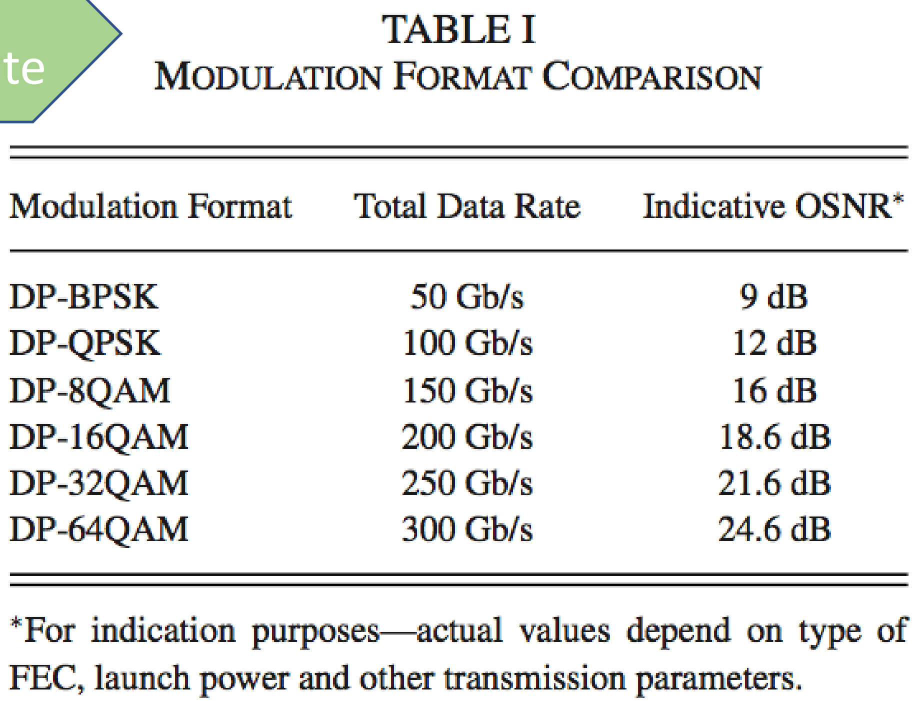
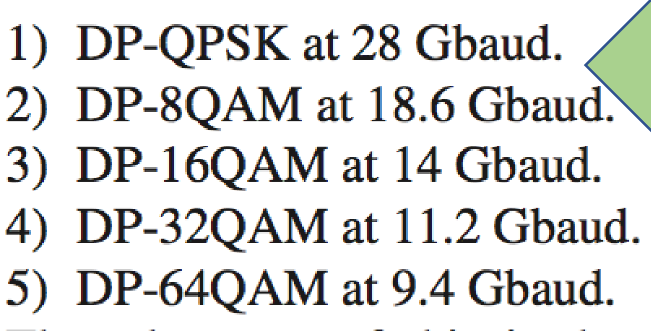


TABLE I
MODULATION FORMAT COMPARISON

Modulation Format	Total Data Rate	Indicative OSNR*
DP-BPSK	50 Gb/s	9 dB
DP-QPSK	100 Gb/s	12 dB
DP-8QAM	150 Gb/s	16 dB
DP-16QAM	200 Gb/s	18.6 dB
DP-32QAM	250 Gb/s	21.6 dB
DP-64QAM	300 Gb/s	24.6 dB

*For indication purposes—actual values depend on type of FEC, launch power and other transmission parameters.

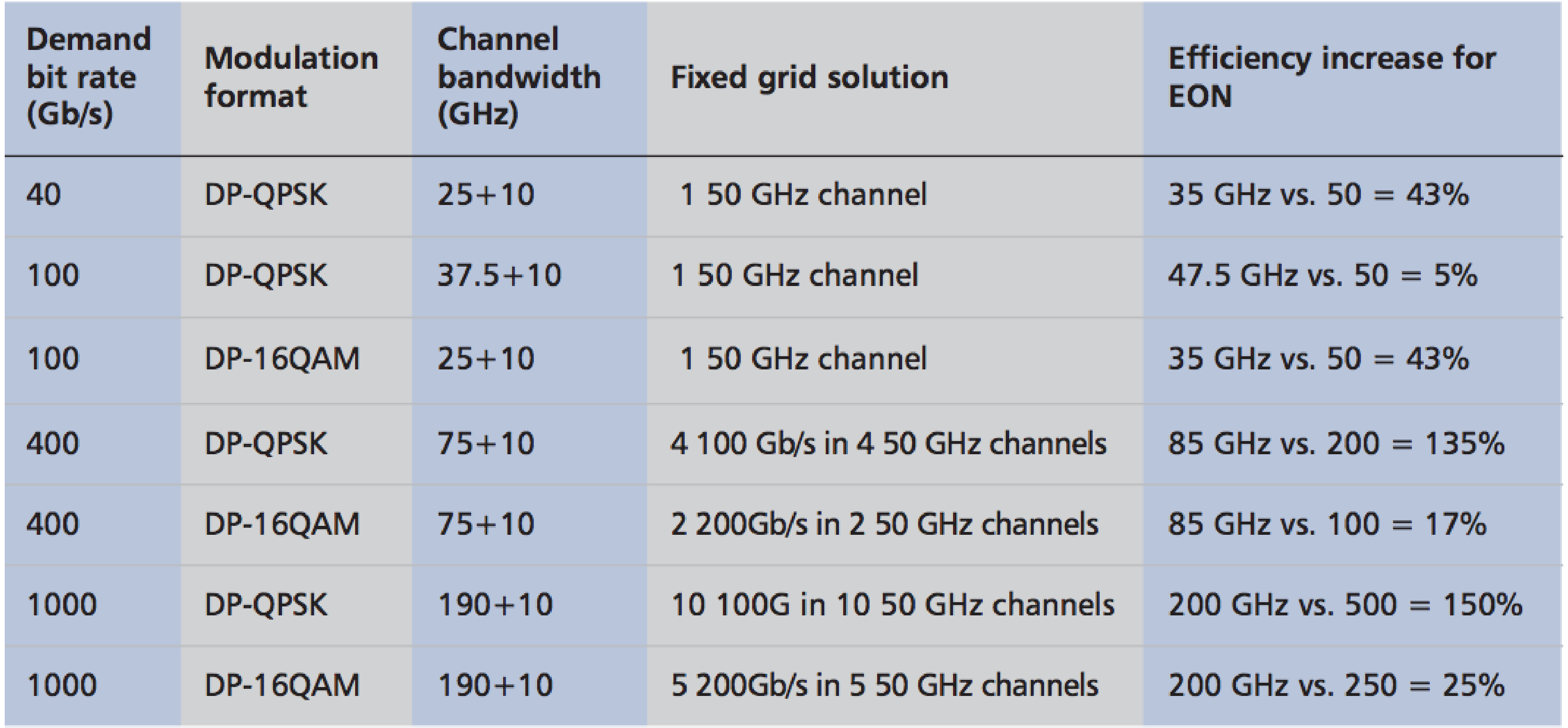


1) DP-QPSK at 28 Gbaud.
2) DP-8QAM at 18.6 Gbaud.
3) DP-16QAM at 14 Gbaud.
4) DP-32QAM at 11.2 Gbaud.
5) DP-64QAM at 9.4 Gbaud.

Fixed Bit-rate

A. Lord, P. Wright, and A. Mitra, "Core Networks in the Flexgrid Era," *Journal of Lightwave Technology*, vol. 33, no. 5, pp. 1126-1135, March 2015.

Capacity Gain of Elastic Optical Network



Demand bit rate (Gb/s)	Modulation format	Channel bandwidth (GHz)	Fixed grid solution	Efficiency increase for EON
40	DP-QPSK	25+10	1 50 GHz channel	35 GHz vs. 50 = 43%
100	DP-QPSK	37.5+10	1 50 GHz channel	47.5 GHz vs. 50 = 5%
100	DP-16QAM	25+10	1 50 GHz channel	35 GHz vs. 50 = 43%
400	DP-QPSK	75+10	4 100 Gb/s in 4 50 GHz channels	85 GHz vs. 200 = 135%
400	DP-16QAM	75+10	2 200Gb/s in 2 50 GHz channels	85 GHz vs. 100 = 17%
1000	DP-QPSK	190+10	10 100G in 10 50 GHz channels	200 GHz vs. 500 = 150%
1000	DP-16QAM	190+10	5 200Gb/s in 5 50 GHz channels	200 GHz vs. 250 = 25%

Table 1. *Efficiency improvement for flexible spectrum over a point-to-point link, assuming a 50 GHz grid for fixed DWDM and 10 GHz channel guard band and superchannels for EONs.*

Reconfigure modulation format provides signals with flexible optical bandwidths!

O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic optical networking: a new dawn for the optical layer?" *IEEE Communications Magazine*, vol. 50, no. 2, pp. s12-s20, February 2012.

Modulation Format Adaptable Transmitter

Generic Edge-Node Interface for network convergence

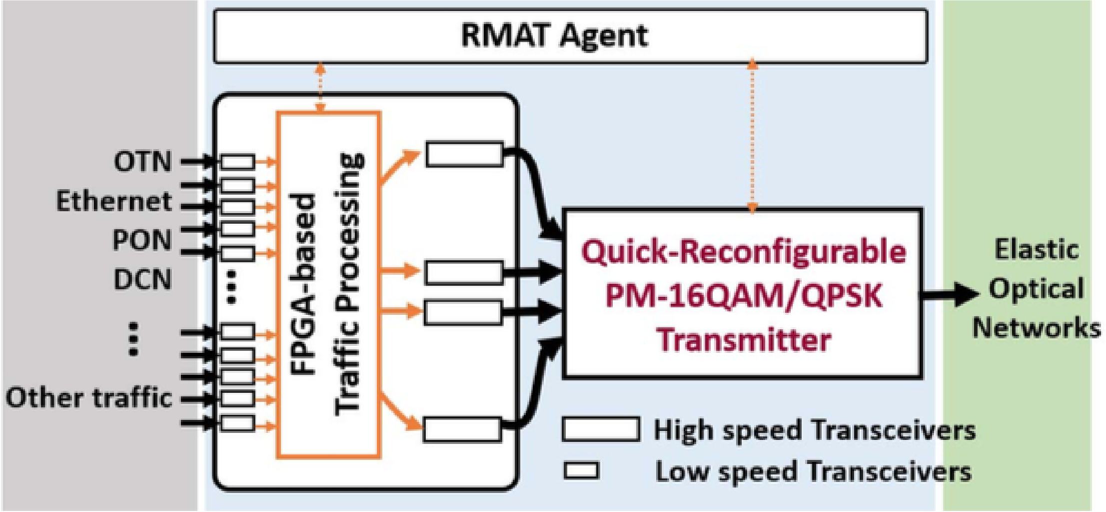


Fig. 1: Architecture of the generic edge-node interface

Real-time modulation-format adaptable transmitter (RMAT) based on a high-performance FPGA. Both the FPGA and the trasmitter are controlled by a local agent (RMAT agent) to adapt the optical signal modulation format.

S. Yan *et al*., "Demonstration of Real-Time Modulation-Adaptable Transmitter," *European Conference on Optical Communication (ECOC)*, Gothenburg, 2017.

Transparent Reach for Coherent Optical Transmission

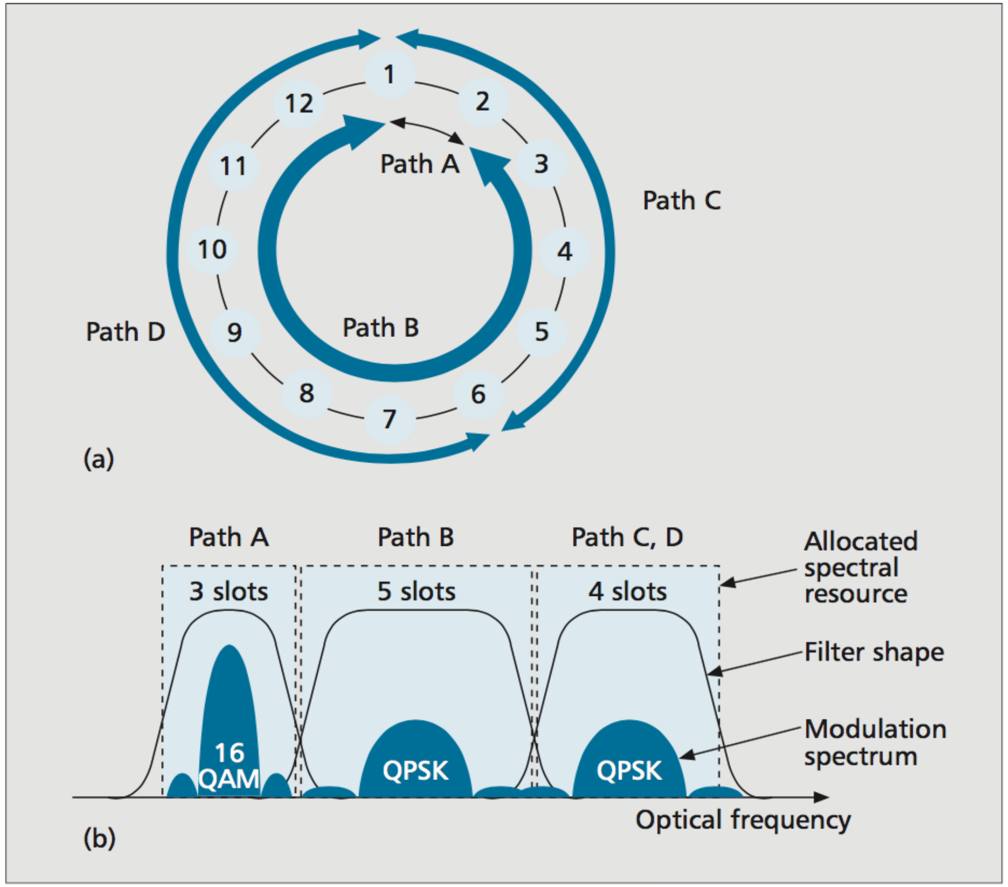


Figure 1. *Spectrum resource allocation in distance-adaptive SLICE: a) allocated spectrum resources for various optical paths; b) signal and filter passband arrangement.*

Shortest path, A: smallest optical SNR degradation & filter narrowing effect, 16-QAM & filter width of 37.5 GHz is selected.

Path C or D: larger number of node hops, more robust set of parameters (e.g., QPSK and 50 GHz) is utilized.

Longest path, B: highest filter narrowing effect, broadest filter bandwidth (e.g., 62.5 GHz) assigned to ensure an acceptable passband at the egress optical node.

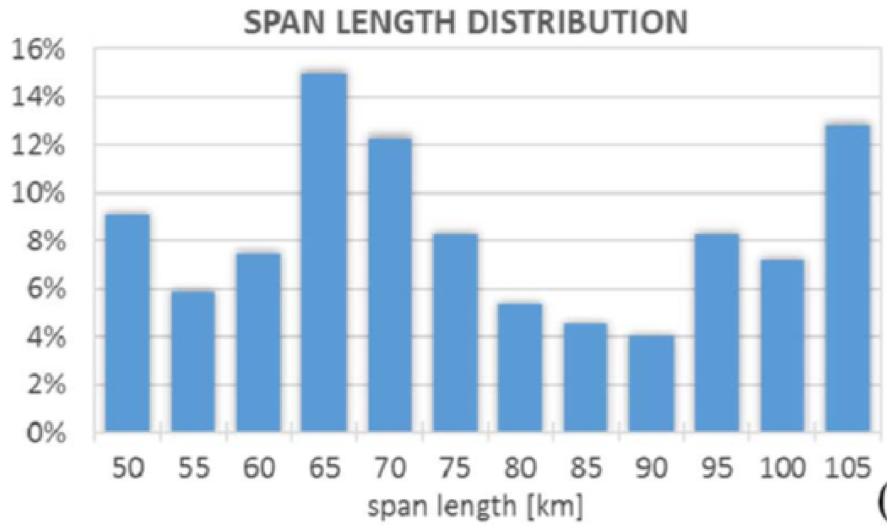
M. Jinno *et al.*, "Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network [Topics in Optical Communications]," *IEEE Communications Magazine*, vol. 48, no. 8, pp. 138-145, August 2010.

Evaluation of Elastic Modulation Gains in Microsoft’s Optical Backbone in North America

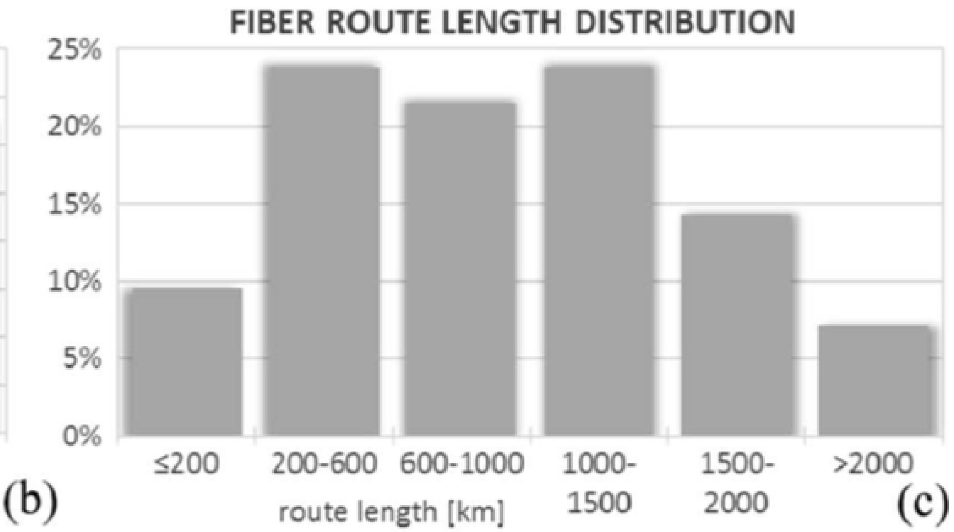
M. Ghobadi, J. Gaudette, R. Mahajan, A. Phanishayee, B. Klinkers, and D. Kilper, "Evaluation of elastic modulation gains in Microsoft's optical backbone in North America,” *Optical Fiber Communications Conference and Exhibition (OFC)*, March 2016.

- ✓ Study Q-factor and its variation in Microsoft’s backbone network carrying live traffic and simulation.
- ✓Found that a capacity gain of at least 70% is achievable via elastic modulation.

Microsoft N.A. Backbone Fiber Summary


SPAN LENGTH DISTRIBUTION

(b)


FIBER ROUTE LENGTH DISTRIBUTION

(c)

Relatively high concentration of fiber spans longer than 90 km.

Routes carrying DWDM traffic between data center regions range from sub-100-km to more than 2500 km.

Capacity Gain with Elastic Modulation Format

- Polling of Q-factor from Microsoft's existing N.A. backbone network was performed over a period of 3 months (February-April 2015), for 100G QPSK linecards.
- Simulated performance of 8-QAM & 16-QAM modulations to determine propagation penalties associated with the fiber nonlinear response.
- Observed Q-factor measurements are converted to SNR in and plotted cumulative distribution function (CDF) of the samples over the three-month period.
- SNR is defined as $\frac{E_S}{N_0}$, where E_S is the average symbol energy, and N_0 is noise .

Capacity Gain With Elastic Modulation Format

- To determine potential capacity gain of PM-8QAM and PM-16QAM, calculated the electrical SNR limits of these modulation formats.

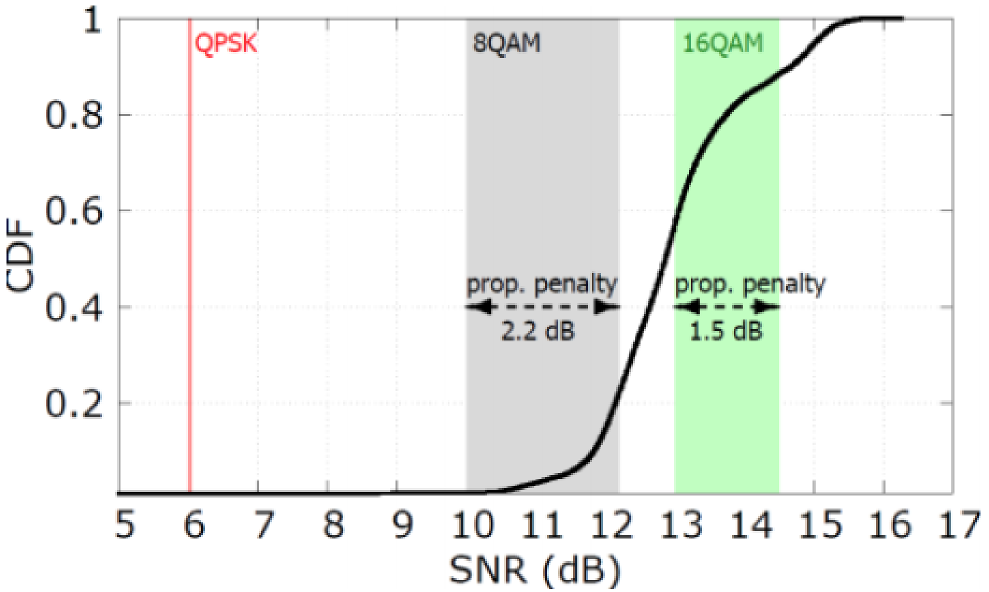


Fig. 1. CDF of converted electrical SNRs from measured Q-factors across Microsoft backbone. The vertical lines are modulation SNR limits.

Capacity Gain with Elastic Modulation Format

8QAM is applicable to 78% - 99% samples

16QAM is applicable to 12% - 43% of the samples,

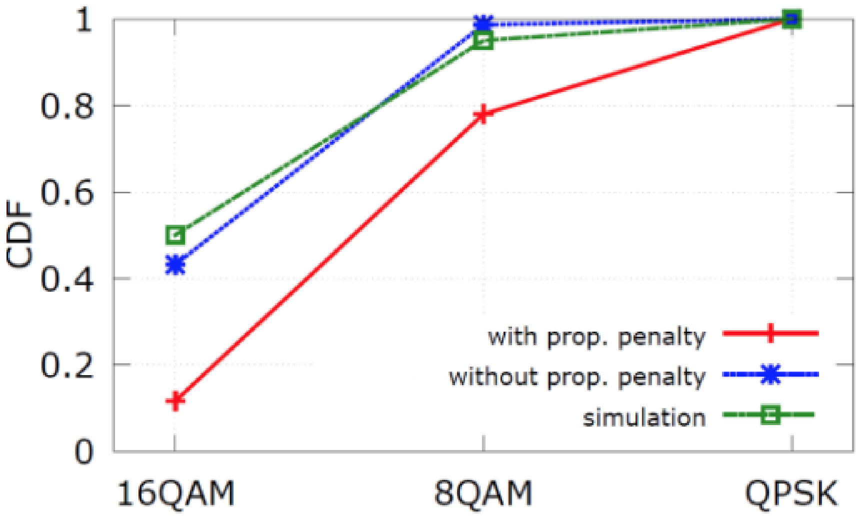


Fig. 2. Cumilative percentage of channels that can be upgraded to 8QAM/16QAM based on SNR estimation with and without propagation penalty (shown in Fig. 1). We also included simulation results for comparison.

Total capacity gain amounts to between 45% and 70% by using PM-8QAM and PM-16QAM where possible

Capacity Gain with Line-Rate Granularity

Analyzed benefits of a BVT with 25 Gb/s resolution operating between 100 Gb/s-250 Gb/s. The vertical lines are SNR limits.

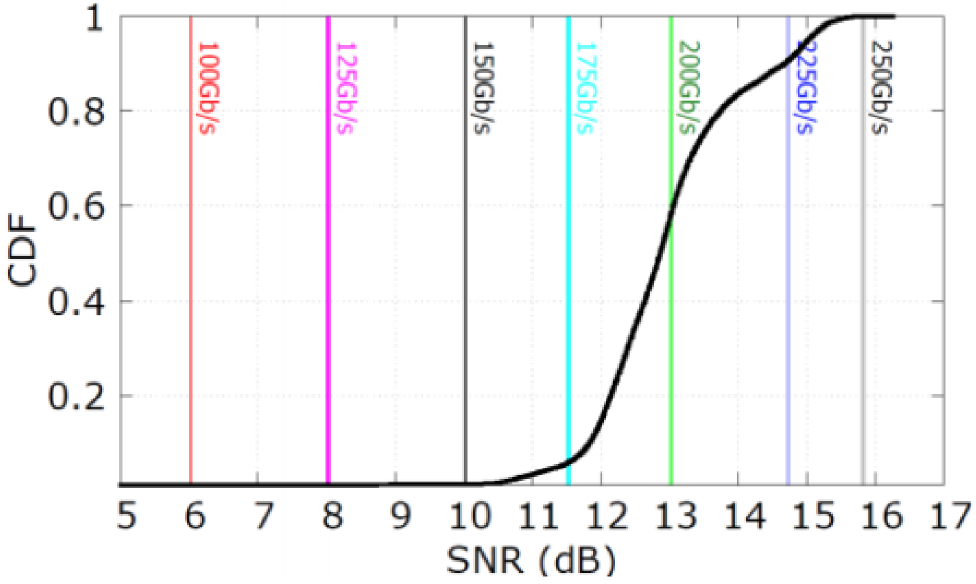


Fig. 3. CDF of converted electrical SNRs from measured Q-factors. The vertical lines are modulation SNR limits with 25 Gb/s resolution.

Capacity Gain with Line-Rate Granularity

- By applying SNR limits of 100 Gb/s up to 250 Gb/s with 25 Gb/s steps, more than 90% of samples can increase capacity to 175 Gb/s or higher. The average capacity gain is 86%.
- 25 Gb/s resolution on optical modulation offers 16% additional capacity gain than a QPSK/8QAM/16QAM transponder.

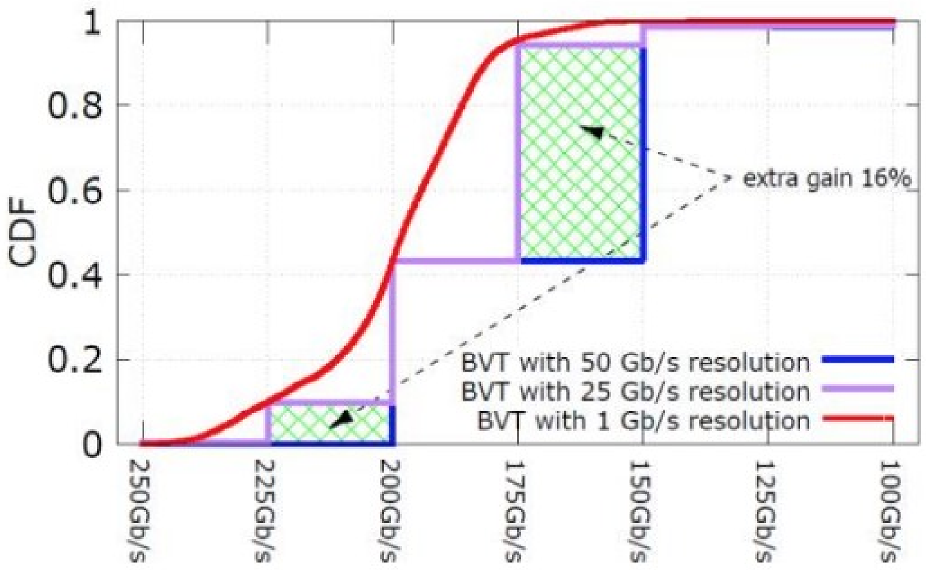


Fig. 4. Cumilative percentage of channels that can be upgraded to faster modulations using 50, 25, and 1 Gb/s resolution.

Q-factor Across Wavelength

SNR of wavelengths within a light path can differ significantly. Different wavelengths might benefit from different modulation formats even though the path is shared.

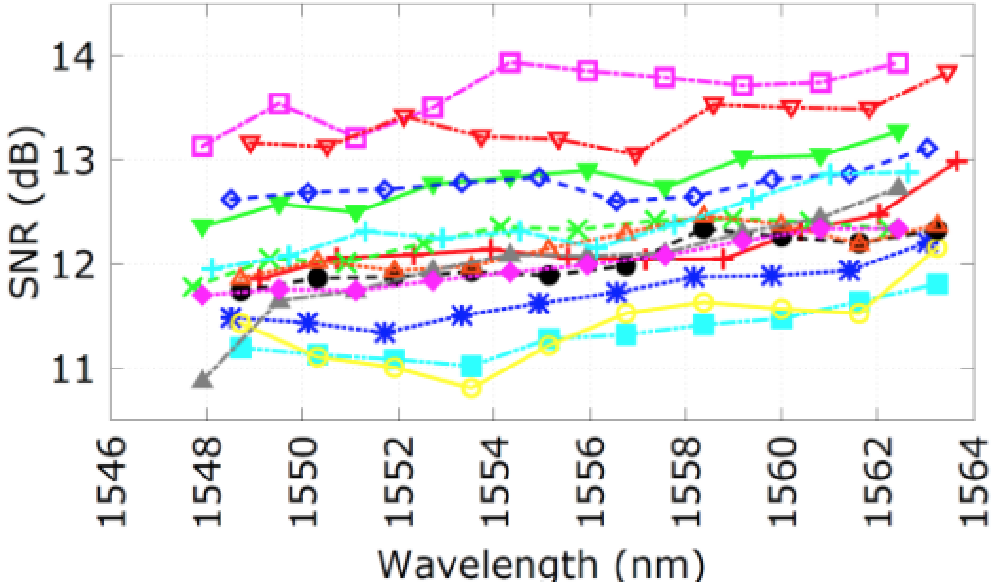


Fig. 5. SNR variation across wavelengths and segments. Each line represents a segment. Each point is a wavelength.

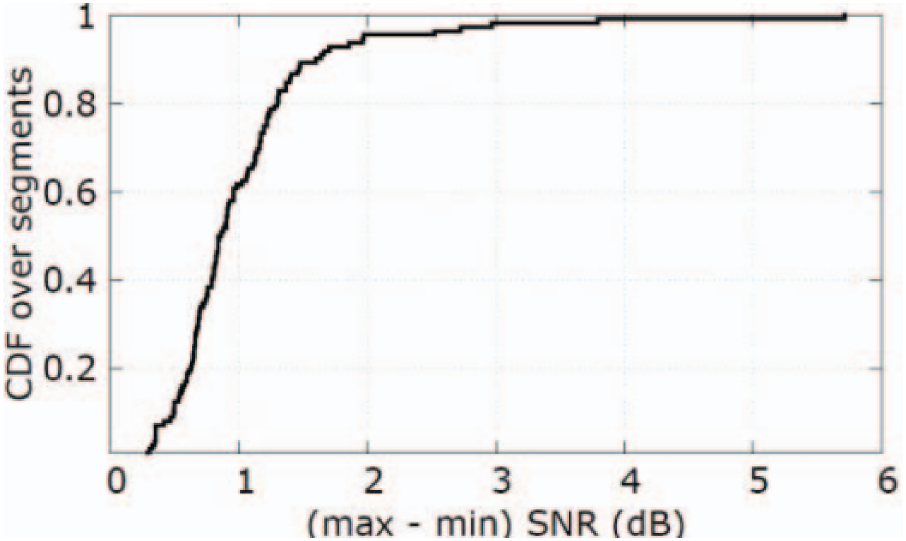


Fig. 6. Cumulative percentage of segments and their SNR variation across all wavelengths traversing the same segment.

Q-factor Over Time

Fig. 7 illustrates SNR over time at mid-band (~1550nm) across a channel. As shown, for each channel (each line) SNR remains mostly stationary over time.

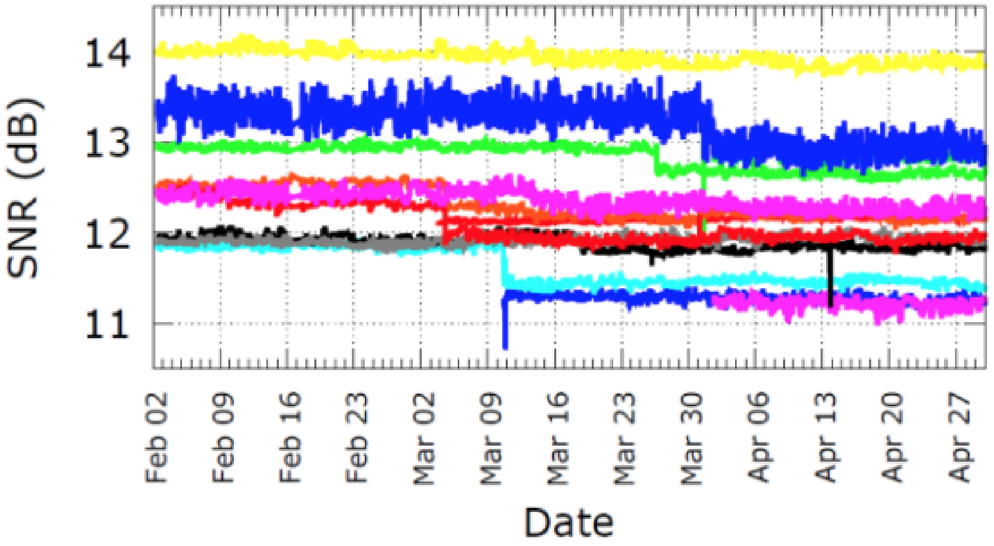


Fig. 7. SNR vs. time for some 100Gb/s PM-QPSK channels.

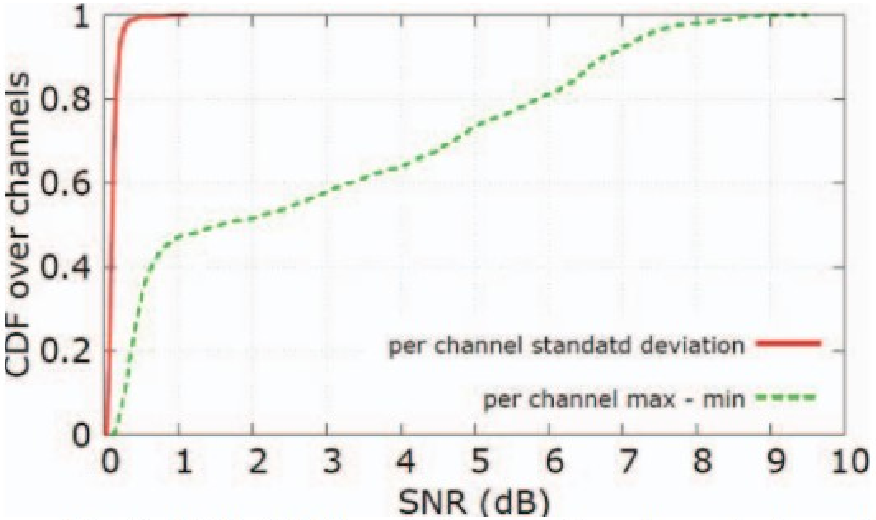


Fig. 8. CDF of SNR variation over time for each channel.

BVTs should have the ability to tune bandwidth on a channel-by-channel basis to optimize for wavelength-dependent performance.

Conclusion

- A substantial gain achieved using a BVT capable of elastic bit-rate and modulation.
- BVTs should have the ability to tune bandwidth on a channel-by-channel basis to optimize for wavelength-dependent performance.
- They can be relatively static in nature, commissioned at start-of-life or after major maintenances, and do not need the ability to tune bandwidth in real-time.