Signal Processing Techniques for Reducing the Impact of Fiber Nonlinearities on System Performance

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OFC 2016

Outline

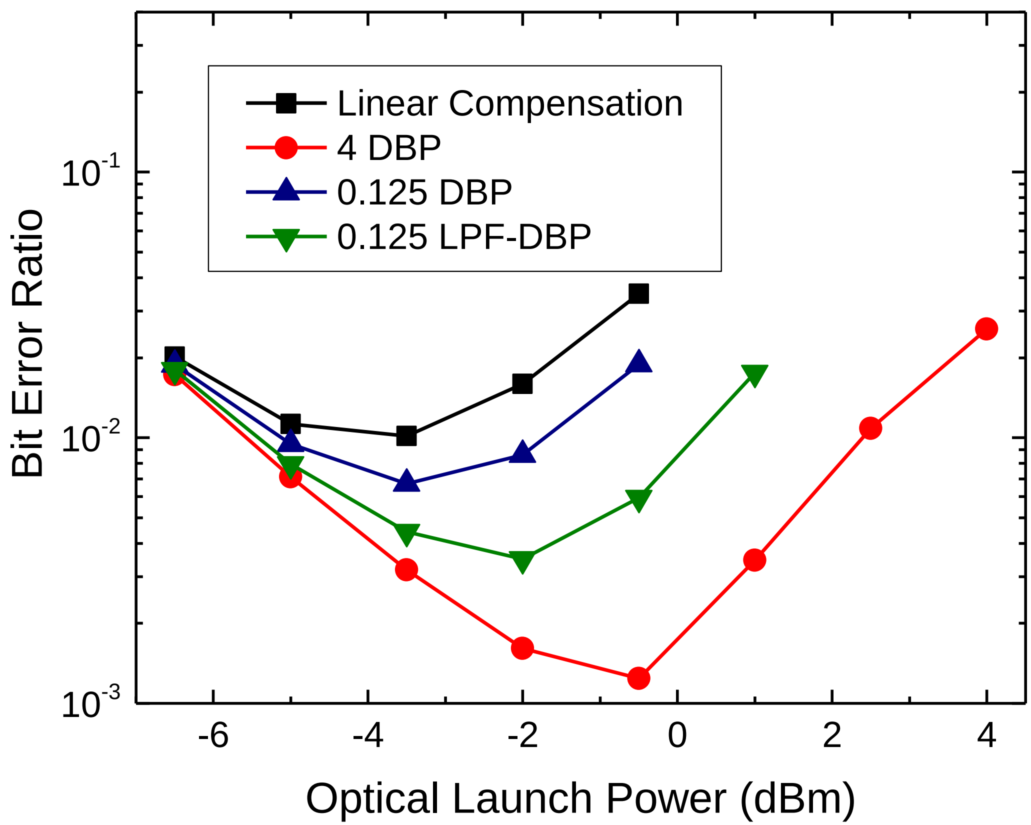
- “We are very interested in hearing about use of digital signal processing and optical signal processing for compensating nonlinear penalties.”
- Broad overview with some specific illustrative examples.
- Techniques that compensate for the nonlinearity-induced signal distortion.
- Techniques that make the signal propagation more tolerant of fiber nonlinearities.
- Apologies for those not mentioned – simply not enough time to cover everything.
- Selected references focus on recent contributions.

Digital Back Propagation (DBP)

- Signal distortion caused during propagation is inverted by using the received signal as the input to a back propagation calculation that determines the corresponding input signal.
- Both single-channel and multi-channel DBP have been investigated.
- Stochastic effects (ASE noise, PMD, PDL, carrier frequency fluctuations) impact the resultant performance.
- Modifications have been proposed to reduce the complexity, e.g., correlated DBP or low-pass filtered (LPF) DBP.
- One key parameter that affects the performance and complexity is the step size (or number of steps-per-span): maximum step size is inversely related to the total bandwidth of the signal(s).

- A. Napoli, et al., J. Lightw. Technol., vol. 32, 1351-1362, 2014.
- I. Sackey, et al., J. Lightw. Technol., vol. 33, 1821-1827, 2015.
- R. Maher, et al. Sci. Rep., vol. 5, 08214, 2015.
- R. Maher, et al. OFC, Th4D.5, 2015.

LPF Digital Back Propagation



- 112 Gb/s DP 16-QAM
- Fiber length = 2400 km
- Gaussian LPF
- LPF-DBP: a low-pass filter reduces the high frequency components of the back-calculated signal before estimating the nonlinear phase correction.
- Allows more flexibility in reducing the steps-per-span and implementation complexity.

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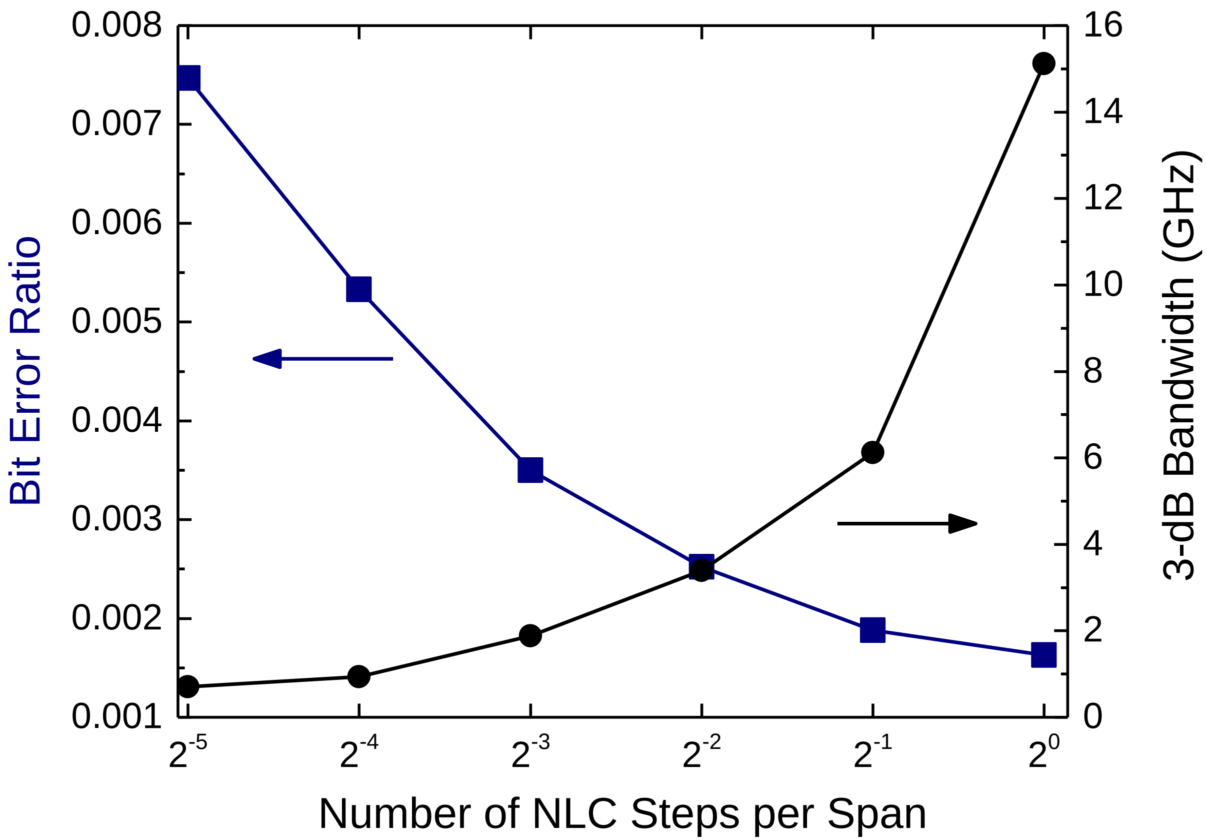
Digital Back Propagation



- 112 Gb/s DP 16-QAM
- 2400 km, P_l = -2 dBm
- Optimum values of the scaling factor and LPF bandwidth.
- Reducing the influence of the high frequency components, which change significantly with a large step size, allows an increase in the nonlinear phase compensation step size and potentially a reduction in the computational complexity

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DBP and Frequency Referenced Carriers

- Frequency referenced optical carriers (optical comb source) eliminate the uncertainties in the walk-offs among the channels.
- Allows a more accurate full-field inverse solution to the nonlinear Schrödinger equation.

- N. Alic, et al., J. Lightw. Technol., vol. 32, 2690-2698, 2014.
- E. Temprana et al., Science, vol. 348, 1445-1448, 2015.
- E. Temprana et al., Opt. Express, vol. 23, 20774-20783, 2015.
- N. Alic, OFC, Tu2E.1, 2016.

Perturbation-Based Pre- or Post-compensation

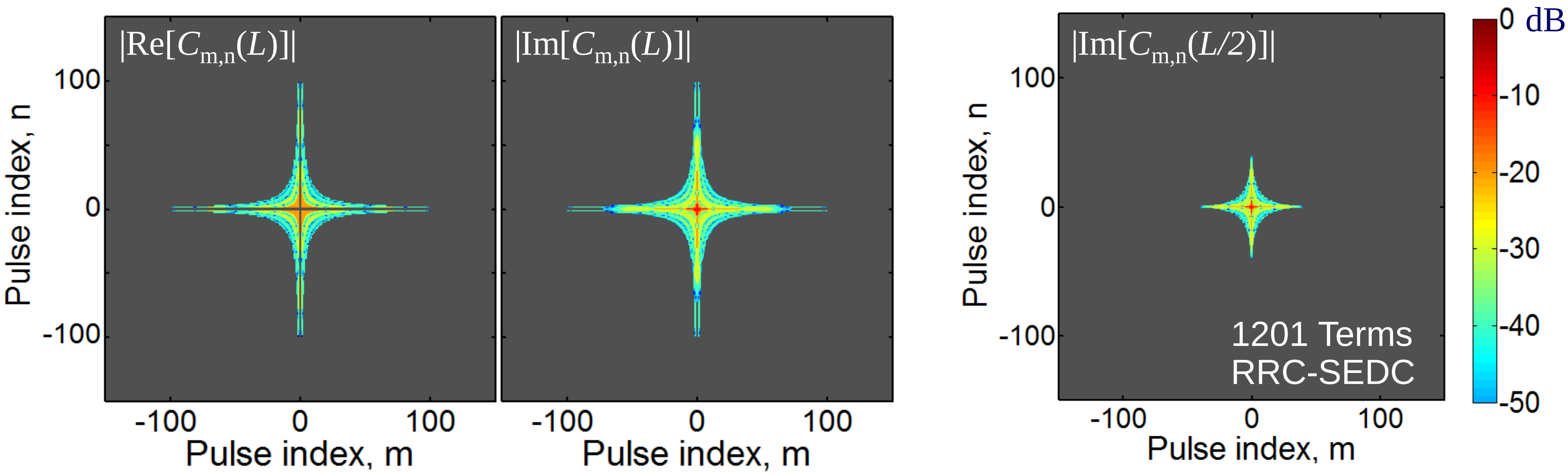
- Based on calculating nonlinearity induced perturbations for the received symbols and pre-distorting the transmitted sequence.
- Compensates accumulated nonlinearities with only one computation step and can be implemented with one sample per symbol
- Calculation of the nonlinear perturbation involves single and double summations that are functions of the transmitted symbol sequence and perturbation expansion coefficients $\{C_{m,n}\}$.
- Nonlinear perturbation includes SPM, IXPM, and IFWM; the complexity is dominated by the IFWM through a double summation.
- Can be implemented at the receiver; a recursive approach reduces the complexity.

- Z. Tao, et al., J. Lightw. Technol., vol. 29, 2570-2576, 2011.
- Y. Gao, et al., Opt. Express, vol. 22, 1209-1219, 2014.
- X. Liang and S. Kumar, Opt. Express, vol. 22, 29733-29745, 2014.

Perturbation-Based Pre-compensation

$$A_{x,0}^{IFWM} = P_0^{1.5} \sum_{m\neq 0, n\neq 0} C_{m,n}(L)\left(A_{x,n}A_{x,m+n}^{*}A_{x,m} + A_{y,n}A_{y,m+n}^{*}A_{x,m}\right)$$

- $A_{x,n}$ and $A_{y,n}$: symbol sequences, P_0: optical launch power, $C_{m,n}$: nonlinear coefficient, depends on the fiber length and pulse shape.
- Two simple modifications yield a significant reduction in the number of summation terms: the use of symmetric electronic dispersion compensation and a root-raised-cosine pulse shape.



Gaussian pulse
8193 terms

SEDC, RRC pulse
1201 terms

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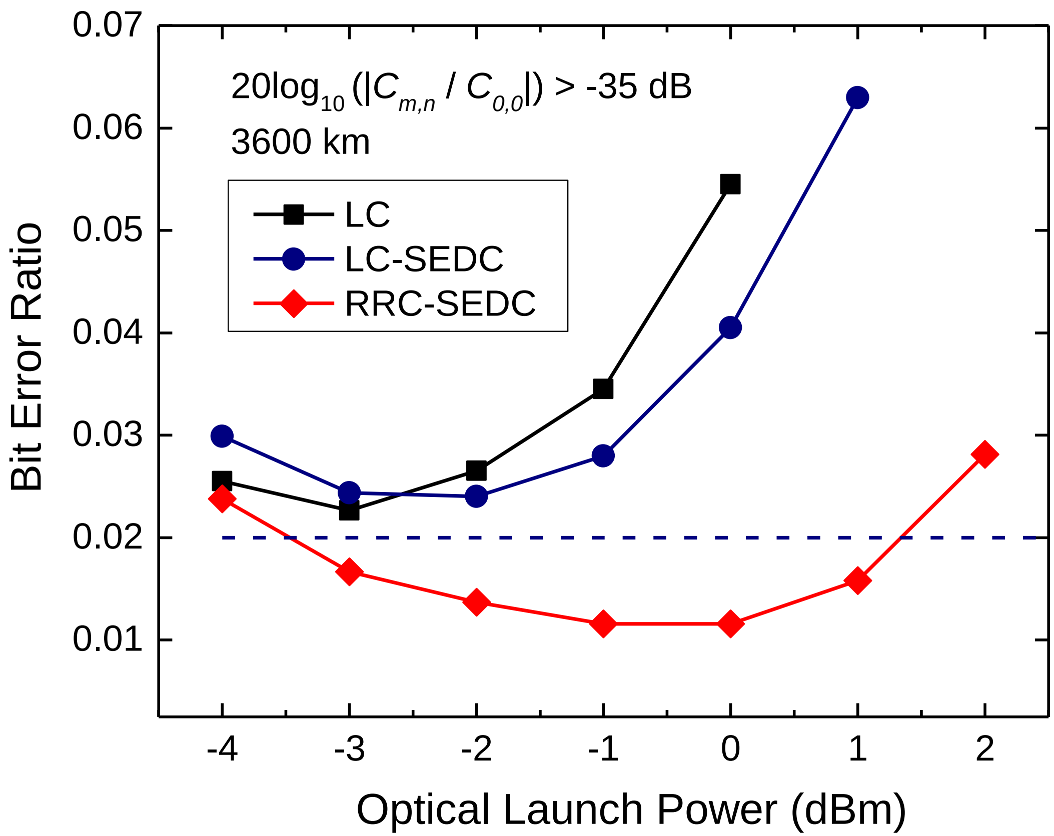
Perturbation-Based Pre-compensation



- 128 Gb/s DP 16-QAM
- Fiber length = 3600 km
- Pre-compensation yields a 3 dB increase in the optimal launch power relative to dispersion compensation.

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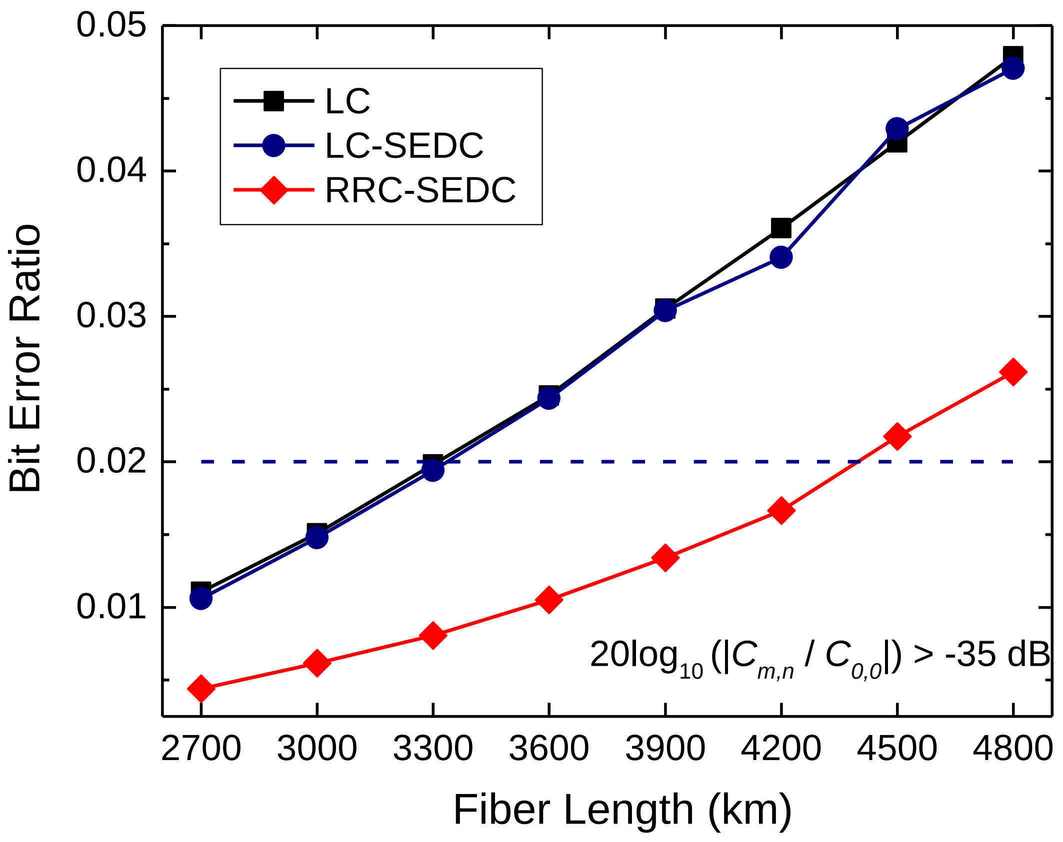
Perturbation-Based Pre-compensation



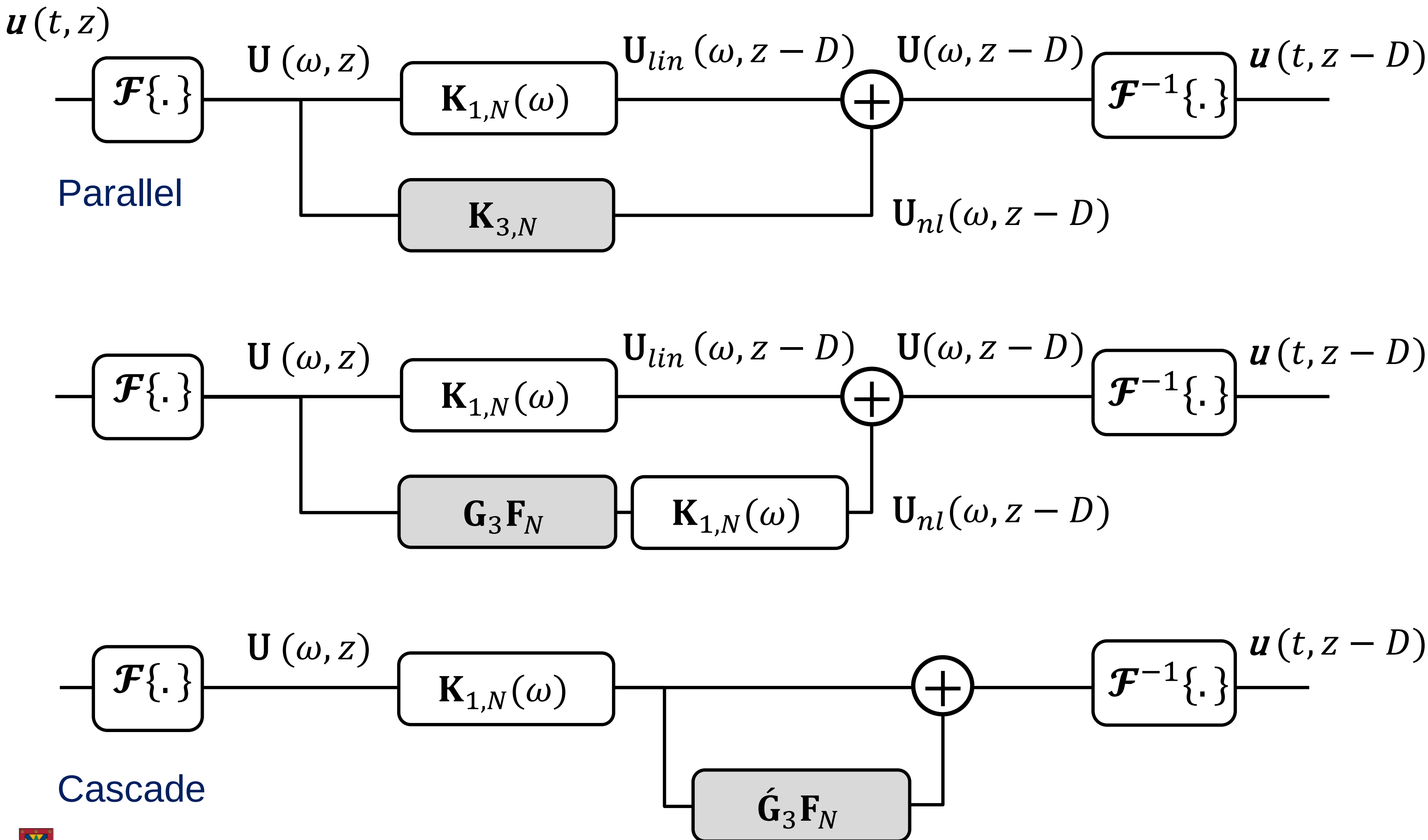
- 128 Gb/s DP 16-QAM
- Transmission over 4200 km, an increase of 900 km relative to linear compensation.

Volterra Nonlinear Equalizer (VNLE)

- Nonlinear equalization based on a frequency domain Volterra series expansion of the Schrödinger equation.
- Compensates for accumulated dispersion and Kerr nonlinear distortion.
- VNLE with a cascade structure offers an improved performance-complexity trade-off compared to the conventional parallel structure

- L. Liu, et al., J. Lightw. Technol., vol. 30, 310-316, 2012.
- F. P. Guiomar, et al., J. Lightw. Technol., vol. 31, 879-3891, 2013.
- F. P. Guiomar, et al., J. Lightw. Technol., vol. 33, 3170-3181, 2015.
- A. Bakhshali, et al., J. Lightw. Technol., vol. 34, 1770-1771, 2016.

Volterra Nonlinear Equalizer



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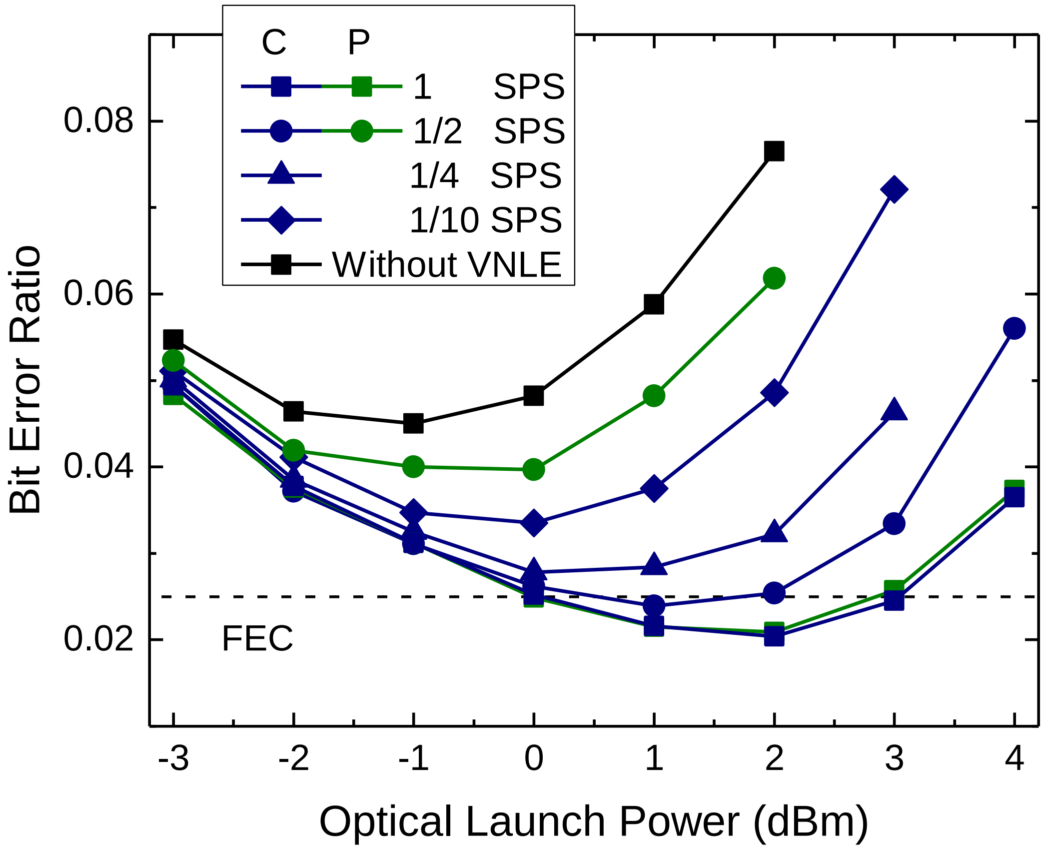
P-VNLE and C-VNLE Implementations



- 256 Gb/s DP 16-QAM
- Fiber length = 4500 km
- VNLE yields a 3 dB increase in the optimal launch power relative to dispersion compensation.
- Performance of C-VNLE and P-VNLE are comparable for 1 step-per-span (SPS).
- Better performance for C-VNLE for smaller values of SPS and reduced complexity.
- Shorter discrete Fourier transform lengths for third order kernel.

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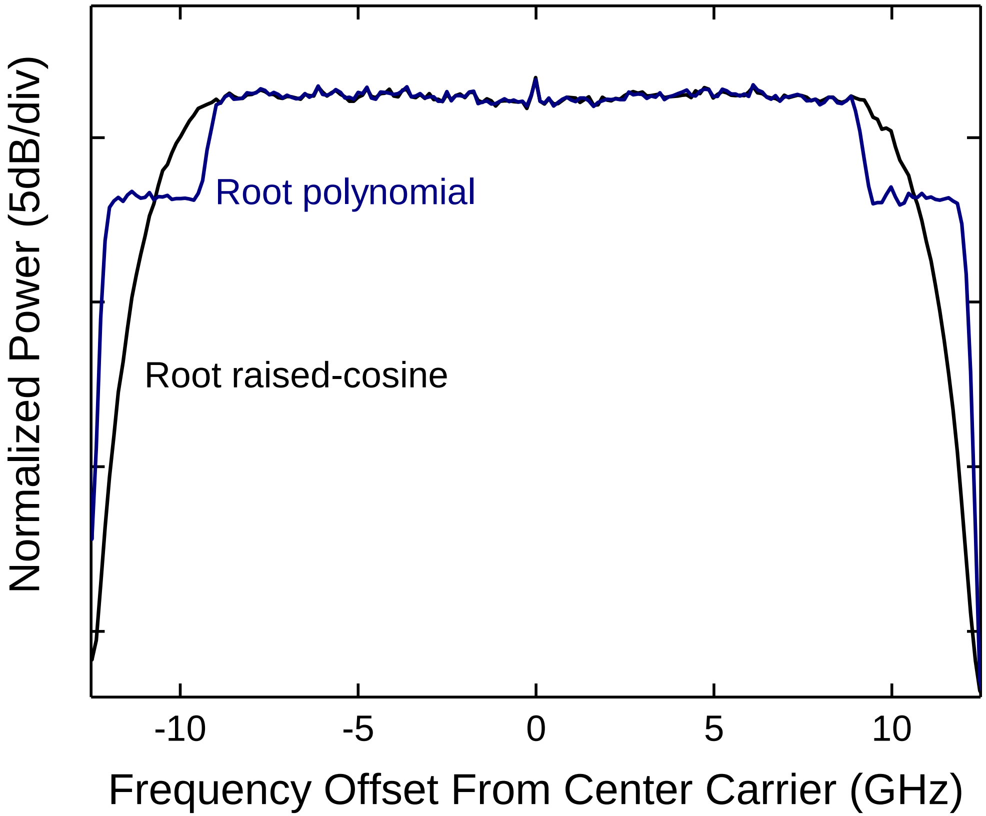
Pulse Shaping

- Pulse shapes can exhibit an increased tolerance to fiber nonlinearities: optimized Nyquist pulses, M-shaped pulses, intersymbol interference free polynomial pulses.
- Nonlinearity-tolerant pulse shaping generally requires an increase in the bandwidth compared to Nyquist pulses (raised-cosine with a roll-off factor of 0).
- Need to consider the performance of alternatives (format and pulse shape) with the same spectral efficiency.

- B. Châtelain, et al., Opt. Exp., vol. 20, 8397-8416, 2012.
- X. Xu, et al., OFC, W1G.3, 2014.
- O. V. Sinkin, et al., OFC, Tu3J.3, 2014.
- A. Karar, et al., Photon. Technol. Lett., vol. 27, 1653-1655, 2015.

Polynomial and Raised-Cosine Pulse Shapes



- Polynomial pulses have step function like power spectral densities with an analytical expression that facilitates optimization with respect to two parameter values for a given null-to-null optical bandwidth.
- Symbol rate = $2W$, α is the roll-off factor, f_s is the shape frequency
- 128 Gb/s DP 8-QAM
- 25 GHz channel spacing

$$\alpha = 0.0172, \quad f_s = 1.65 \text{ GHz}$$

$$p(t) = 3\cos(2\pi f_s t)\,\text{sinc}(2Wt)\,\frac{\text{sinc}^2(\alpha Wt) - \text{sinc}(2\alpha Wt)}{(\pi\alpha Wt)^2}$$

$$BW = 2(1+\alpha)W + 2f_s$$

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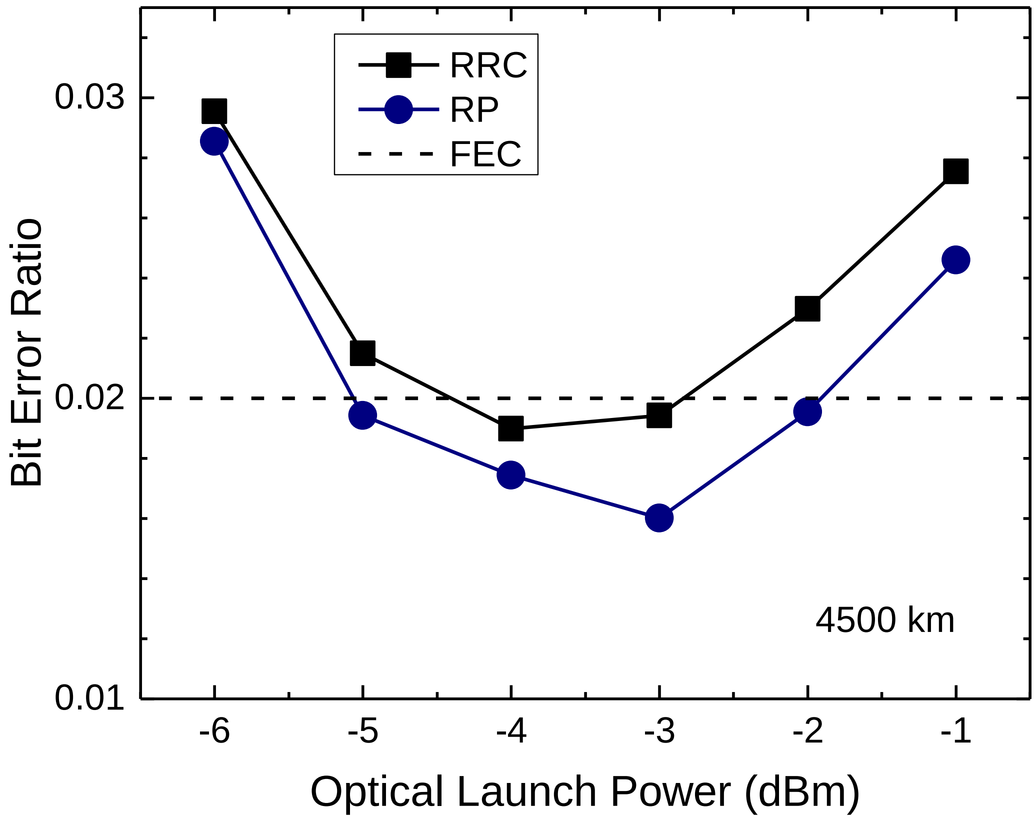
Pulse Shaping



- 9-channel 128 Gb/s DP 8-QAM
- spectral efficiency of 4 b/s/Hz
- 25 GHz channel spacing
- Fiber length = 4500 km
- Both pulse shapes yield essentially the same measured back-to-back BER performance. Root-polynomial (RP) pulse shape offers a 0.26 dB improvement in the signal-to-noise ratio relative to the root-raised-cosine (RRC, roll-off factor = 0.17) pulse shape.

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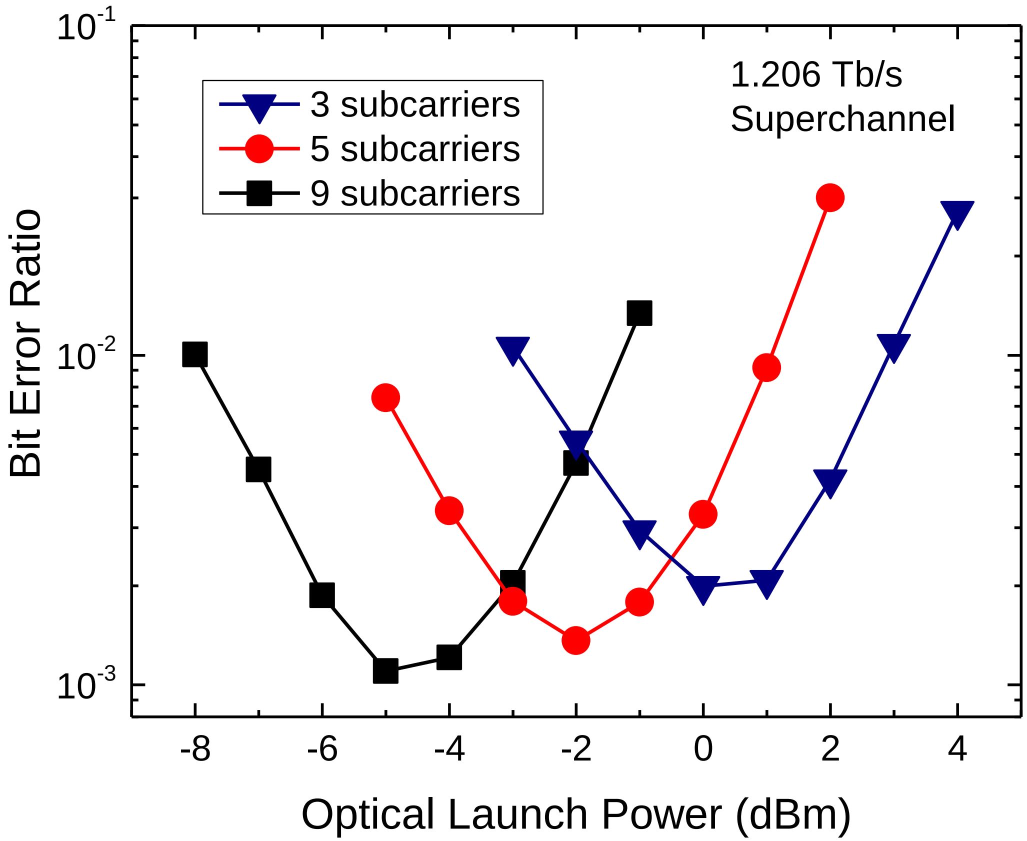
Subcarrier Modulation

- Using multi low-baud-rate subcarriers instead of single carrier the nonlinearity tolerance can be improved.
- Also applies to a superchannel which is comprised of several optical subcarriers but considered as a single entity as it is routed through a network.

- P. Poggiolini, et al., OFC, Th3D.6, 2015.
- P. Poggiolini, et al., ECOC, We.4.6.2, 2015.
- P. Poggiolini, et al., J. Lightw. Technol., vol. 34,1872-1885, 2016.
- A. C. Meseguer, et al., OFC, Tu3A.6, 2015.
- W. Idler, et al., OFC, Th3A.7, 2016.
- A. Nespola, et al., OFC, Th3D.2, 2016.

1.206 Tbit/s Superchannel



- Simulated transmission over 1500 km of SMF
- 20% FEC overhead
- 3 subcarriers (50.25 Gbaud per subcarrier), 5 subcarriers (30.15 Gbaud per subcarrier) and 9 subcarriers (16.75 Gbaud per subcarrier).
- All configurations have a bandwidth occupancy of 162.5 GHz, spectral efficiency of 7.4 bits/s/Hz
- Optimum launch powers of 0, -2 and -5 dBm, respectively.

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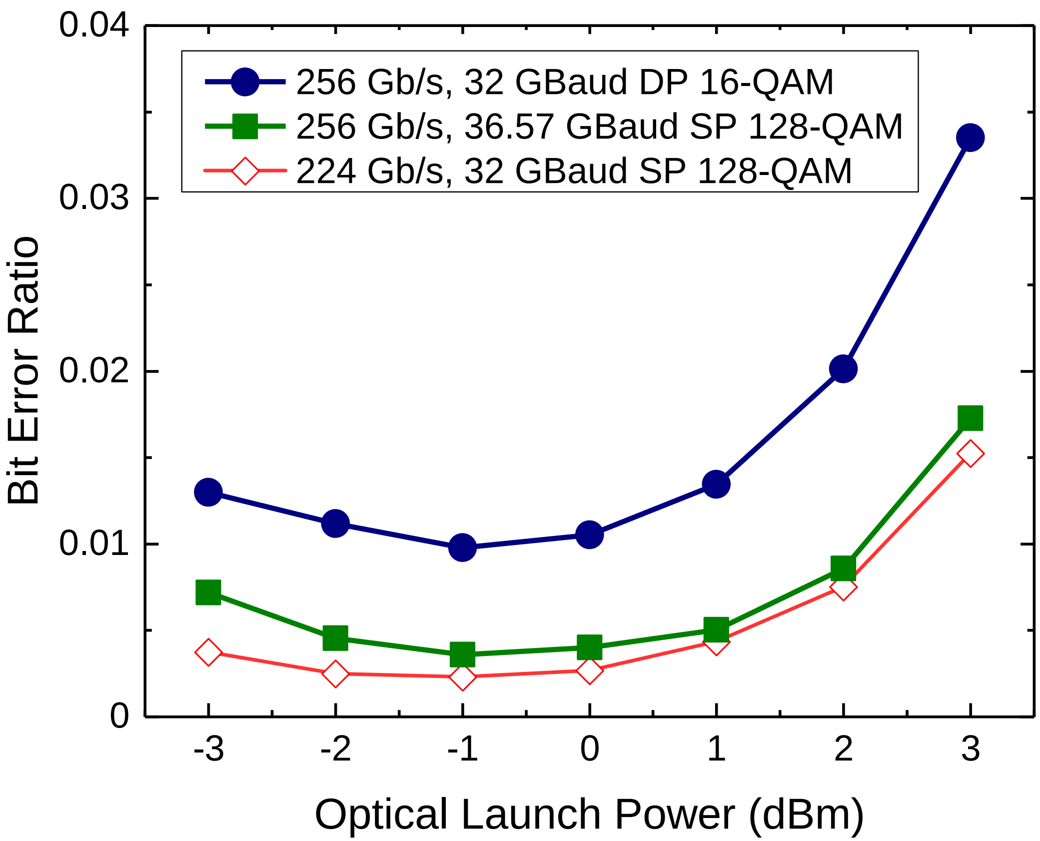
Set-Partitioning

- The simultaneous in-phase and quadrature modulation of two orthogonally polarized carriers is referred to as four-dimensional (4D) modulation.
- By applying set-partitioning (SP) to DP 16-QAM constellations, 4D SP QAM formats can be obtained with a small increase in transceiver complexity.
- SP introduces parity bits that reduce the information rate for the same symbol rate compared to conventional DP modulation. This reduces the number of bits per 4D symbol and increases the robustness to noise (i.e., minimum Euclidean distance).
- SP 128-QAM format selects 128 constellation symbols out of the 256 possible 4D constellation symbols corresponding to DP 16-QAM.

- M. Sjödin, et al., Opt. Express, vol. 20, 8356-8366, 2012.
- T. A. Eriksson, et al., Opt. Express, vol. 21, 19269-19279, 2013.
- A. S. Kashi, et al., ECOC, Mo.3.6.6, 2015.
- OFC 2016, sessions M2A, M3A, Th1D

Set-Partitioning



- DP 16-QAM and SP 128-QAM at the same bit rate (different symbol rates).
- DP 16-QAM and SP 128-QAM at the same symbol rate (different bit rates) for completeness.
- Fiber length = 2100 km
- Optimum launch powers are similar for DP 16-QAM and SP 128-QAM at the same bit rate.
- SP 128-QAM outperforms DP 16-QAM.

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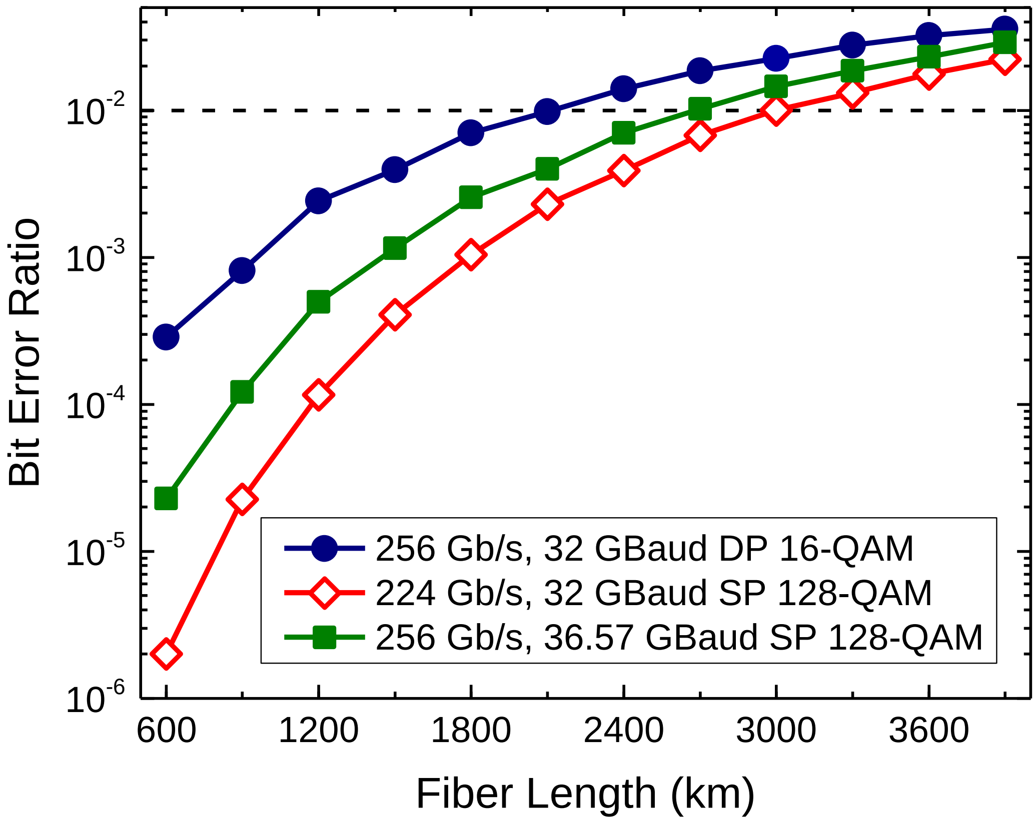
Set-Partitioning



- For BER = 10^{-2}, DP 16-QAM achieves 1800 km, SP 128-QAM achieves 2400 km.
- The additional overhead could be used for FEC coding (N. Swenson and D. Morero, OFC, W4A.1, 2016).

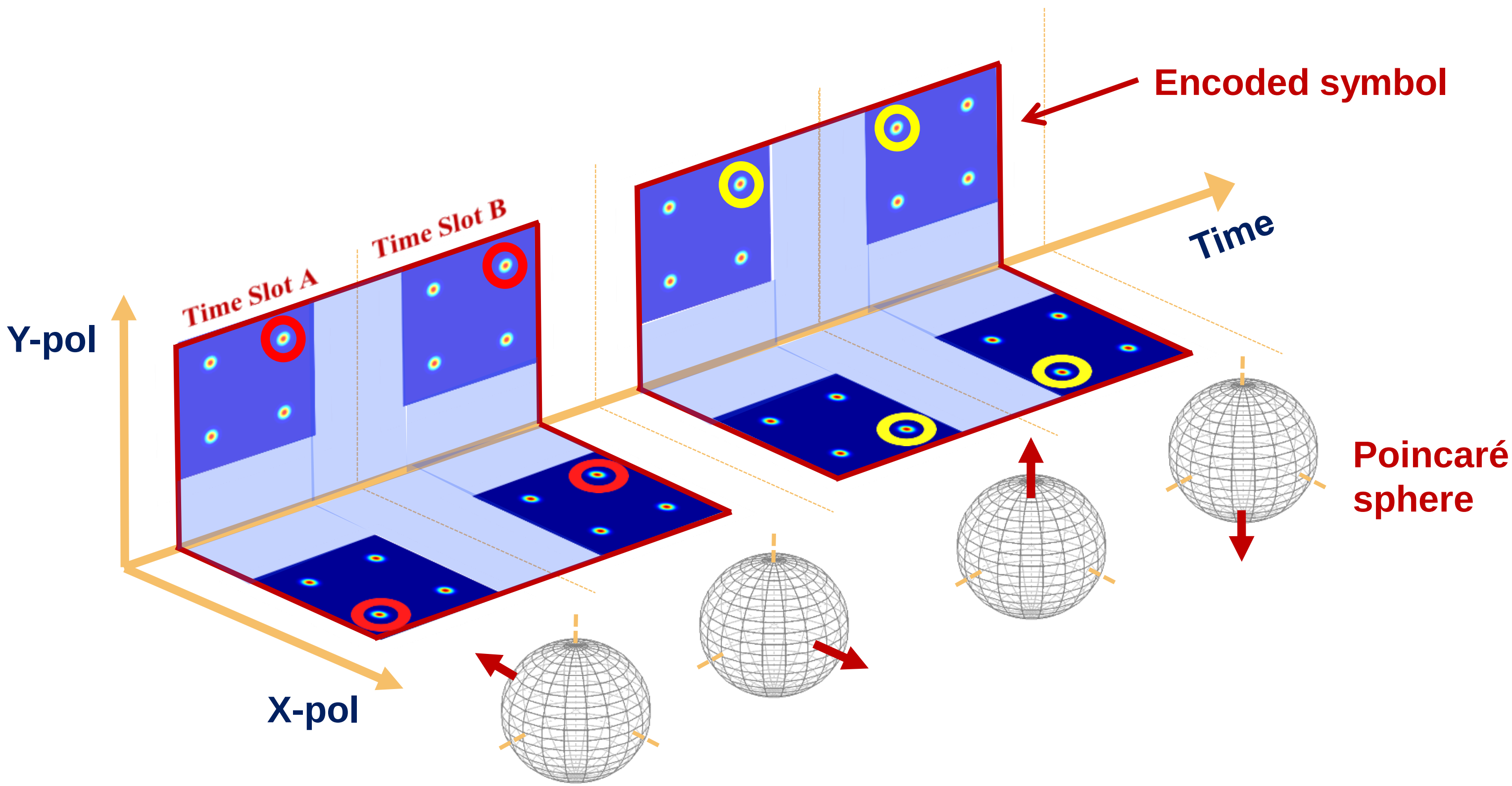
Constellation Design

- By defining constellation symbols based on 4D modulation of two adjacent symbol periods, eight-dimensional (8D) modulation is obtained.
- An 8D power and polarization balanced modulation format (denoted the X-constellation) is related to the biorthogonal format by a real-valued 8D rotation which preserves Euclidian distance and is designed to provide a constant power and zero degree of polarization in all 8D symbol periods.

- D. Millar, et al., Opt. Exp., vol. 22, 8798-8812, 2014.
- A. Shiner, et al., Opt. Exp., vol. 22, 20366-20374, 2014.
- A. Alvarado and E. Agrell, J. Lightw. Technol., vol. 33, 1993-2003, 2015.
- M. Reimer, et al., OFC, M3A.4, 2016.

Polarization Balanced 8D Constellation

- Polarization balanced 8D biorthogonal constellation
- Equalizes symbol modulus between time slots (reduced XPM)
- Achieves zero DOP in each symbol (reduced XpolM)



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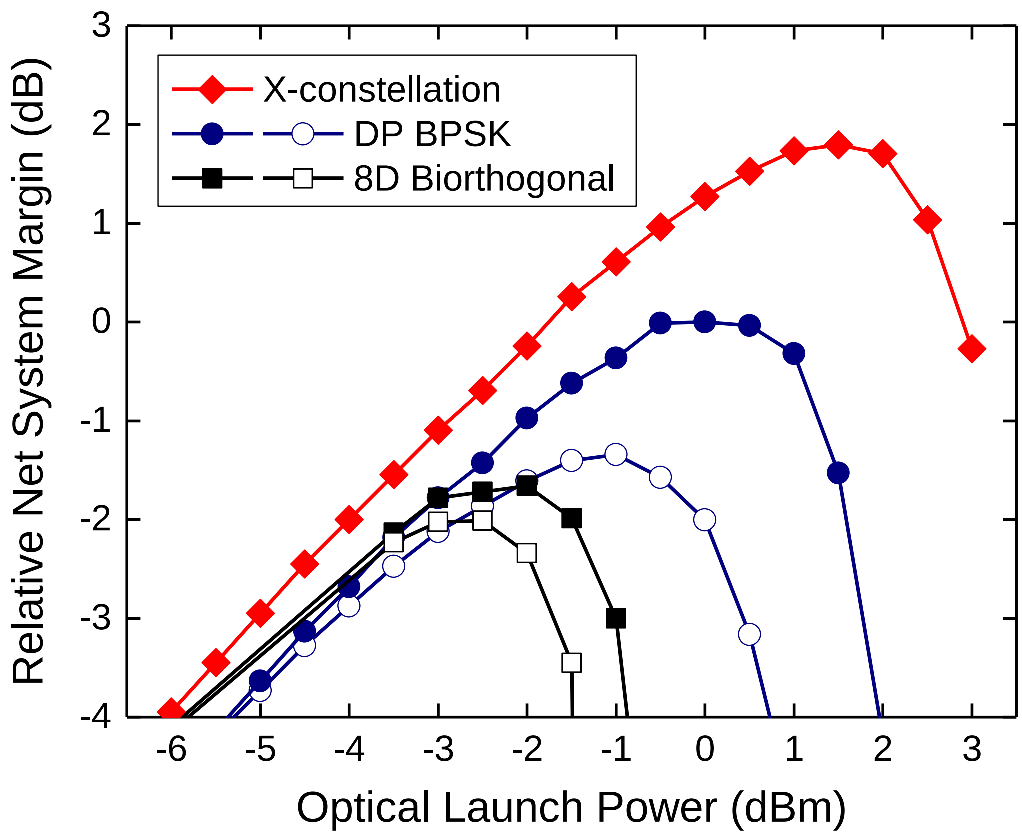
Constellation Design



- Simulated results for the center channel of a 9 channel 35 Gbaud system.
- 50×80 km spans of E-LEAF fiber with 90% inline compensation.
- Closed and open symbols show the largest and smallest relative margins as the polarization states of the interfering channels are varied at the system input with respect to the center channel.
- The performance of the power- and polarization-balanced X-constellation is virtually independent of the polarization states of the interfering channels

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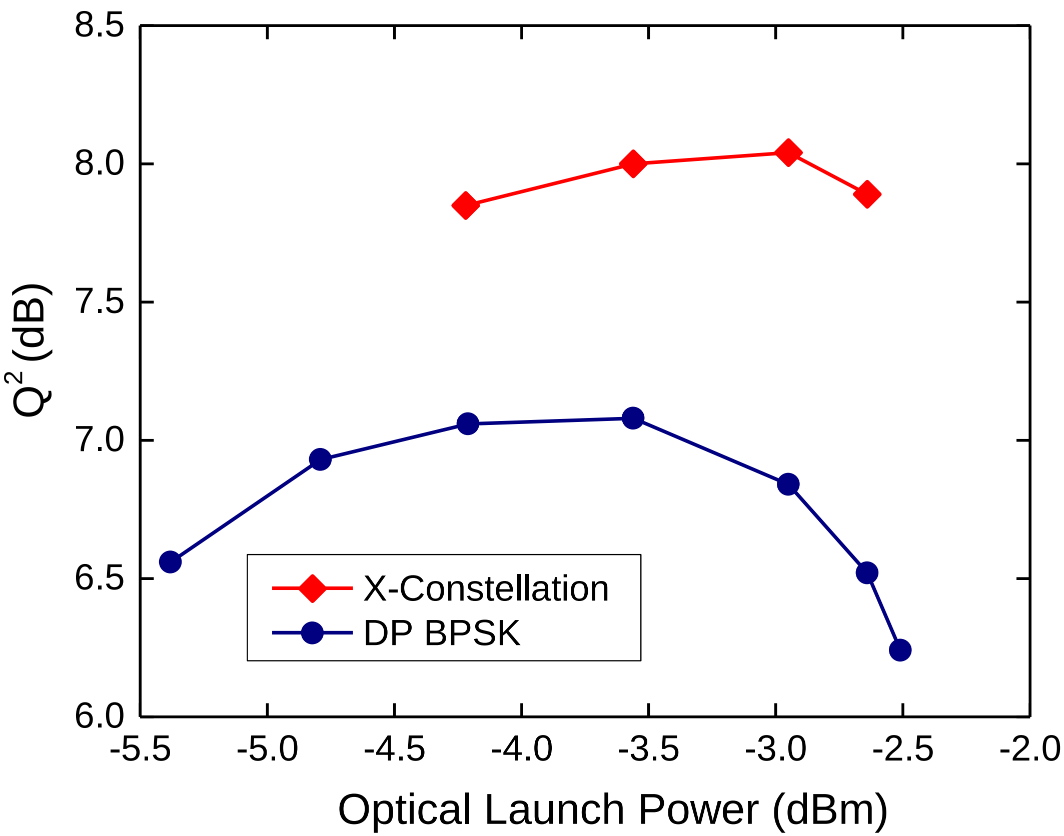
Constellation Design



- 35 Gbaud
- 10,000 km submarine test bed
- ~1 dB increase in Q^2
- Reduced polarization induced fluctuations in Q^2 by a factor of ~10

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And …

- Nonlinear Fourier transform
- Machine learning
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All-Optical Regeneration

- All-optical phase-preserving amplitude regeneration to reduce amplitude fluctuations which are the source of nonlinear phase noise.
- All-optical phase regeneration based on phase sensitive amplification.
- Hybrid optical phase squeezer; separately performs the steps for quantizing the phase.
- Single- and multi-channel operation, challenge is to isolate the signals being regenerated from each other.
- Requires optical dispersion compensation.

- T. Roethlingshoefer, et al., Photon. Technol. Lett., 556-559, 2014.
- F. Parmigiani, et al., J. Lightw. Technol., 1166-1174, 2015.
- T. Kurosu, et al., Opt. Express, vol. 23, 27920-27930, 2015.
- O. Pottiez, et al., Photon. Technol. Lett., 2272-2275, 2015.
- F. Parmigiani, et al., Photon. Technol. Lett., 845-848, 2016.
- K. R. H. Bottrill, et al., Photon. Technol. Lett., 205-208, 2016.
- N.-K. Kjøller, et al., J. Lightw. Technol., 643-652, 2016.
- OFC, 2016, session W4D.

Phase-Conjugated Twin Waves (PCTW)

- Nonlinear distortions of a pair of phase-conjugated twin waves co-propagating on two orthogonal polarizations are anti-correlated.
- Signal-to-signal nonlinear interactions can be cancelled by coherent superposition of the twin waves in the receiver DSP after coherent detection.
- Optimized digital electronic dispersion pre-compensation is used to meet a required condition.
- Mitigates intra- and inter-channel nonlinearities.
- Techniques to improve the spectral efficiency have been reported.

- X. Liu, et al., Nature Photon., vol. 7, 560-568, 2013.
- X. Liu, et al., J. Lightw. Technol., vol. 32, 766-775, 2014.
- T. Yoshida, et al., OFC, M3C.6, 2014.
- X. Liu, et al., J. Lightw. Technol., vol. 33, 1037-1043, 2015.
- Y. Yu, et al., Opt. Express, vol. 23, 30399-30413, 2015.

Variants of PCTW

- The conjugated copy of a signal can be transmitted in the different cores of a multi-core fiber, on different wavelengths, or in different time slots (conjugate data repetition).
- X. Liu, et al., Opt. Express, vol. 20, B595-B600, 2012.
- X. Liu, et al., Opt. Express, vol. 20, 19088-19095, 2012.
- Y. Tian, et al., Opt. Express, vol. 21, 5099-5106, 2013.
- H. Eliasson, et al., Opt. Express, vol. 23, 2392-2402, 2015.
- Z. Zheng, et al., J. Lightw. Technol., to appear.

Phase Sensitive Amplifiers (PSAs)

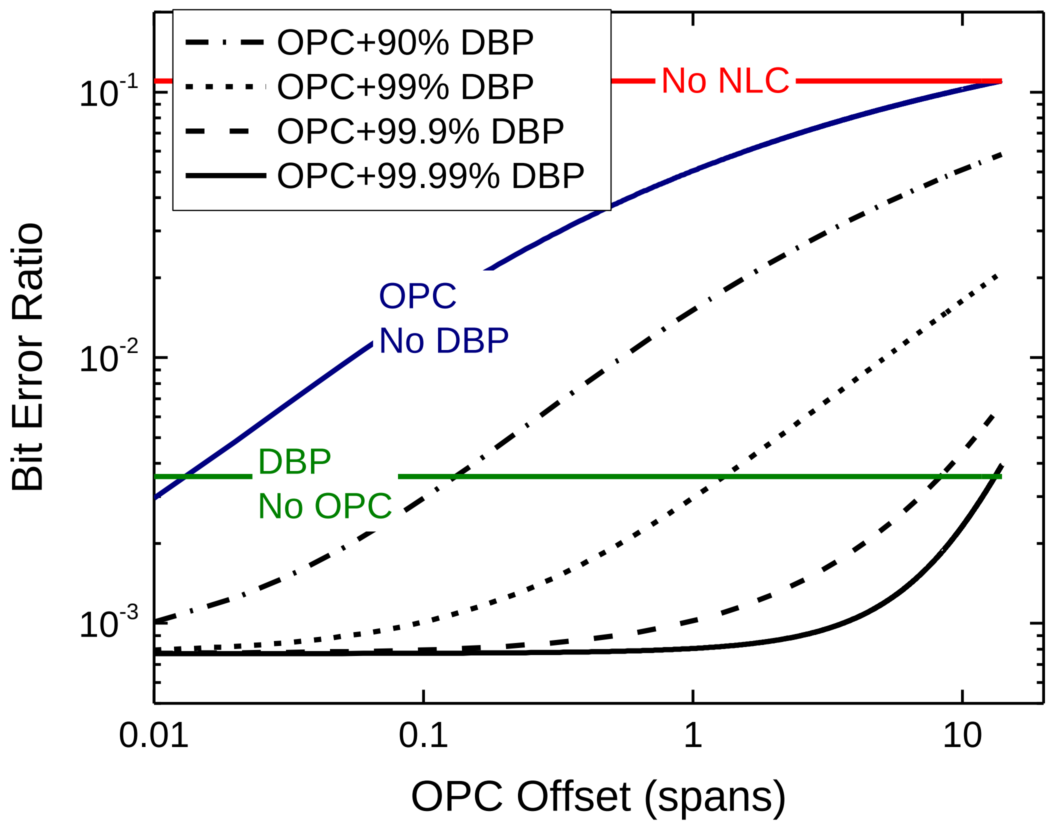
- A signal and its conjugate copy (idler) are transmitted on different wavelengths.
- All-optical coherent superposition of the signal and its copy is performed in each in-line amplifier; anti-correlated signal distortion is cancelled.
- Dispersion map (dispersion compensation is required) and symmetry of the power map are important: distributed Raman amplification is used to achieve a high degree of symmetry around the link center point.
- S. L. I. Olsson, et al., J. Lightw. Technol., vol. 33, 710-721, 2015
- H. Eliasson, et al., Opt. Express, vol. 24, 888-900, 2016.
- OFC 2016, Session W4D.

Optical Phase Conjugation (OPC)

- Conjugates of the propagating signals are created in the middle of the transmission link (or each span).
- Propagating the conjugated signals over the second half of the link (span) cancels out the distortion due to dispersion and fiber nonlinearities in the first half of the link (span).
- Mitigates intra- and inter-channel nonlinearities, supports multi-channel operation, disrupts the growth of parametrically amplified noise.
- Symmetry of the dispersion and power map (distributed Raman amplification).
- Multiple OPCs allow for a reduction in the excess noise and a greater tolerance to PMD.

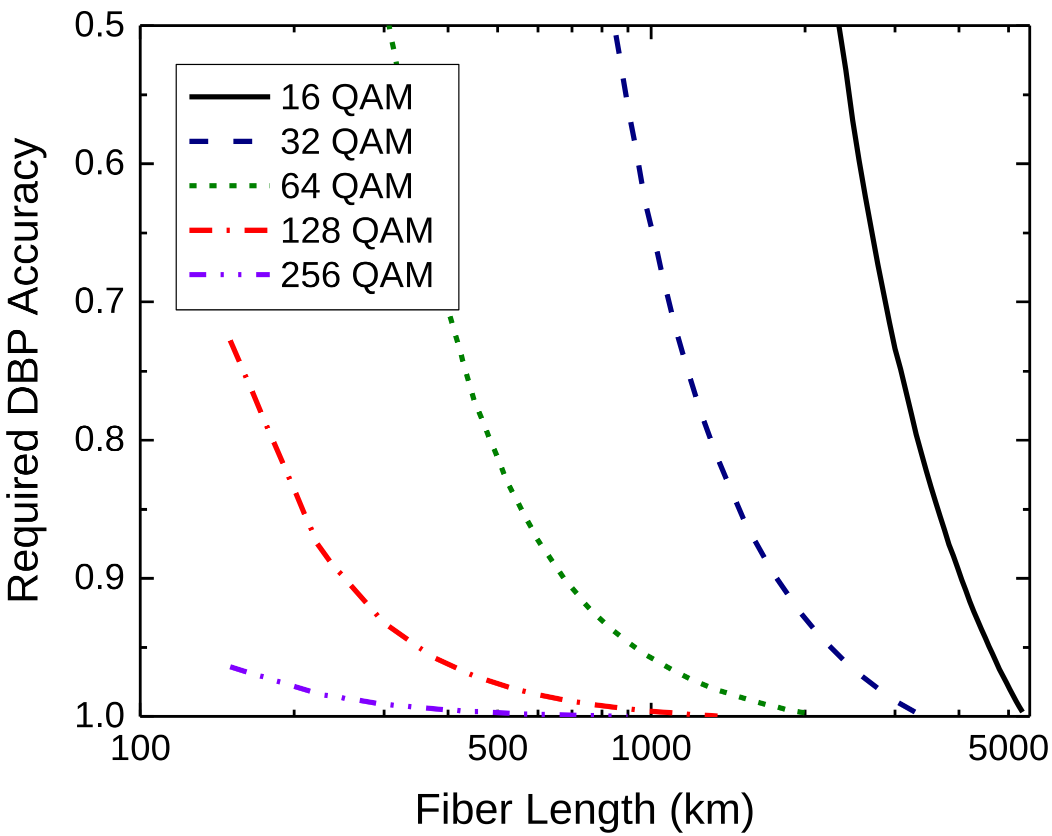
- I. Sackey, et al., J. Lightw. Technol., vol. 33, 1821-1827, 2015.
- A. D. Ellis, et al., Opt. Express, vol. 23, 20381-20393, 2015.
- K. Solis-Trapala, et al., ECOC, Mo.3.6.2, 2015.
- K. Solis-Trapala, et al., J. Lightw. Technol., vol. 34, 431-440, 2016.
- A. D. Ellis, et al., J. Lightw. Technol., vol. 34, 1717-1723, 2016.
- M. McCarthy, et al., Opt. Express, vol. 24, 3385-3392, 2016.

Mid-Point Offset OPC and DBP



- Difficult to locate the OPC at the exact mid-point of a link.
- DBP can be used to compensate the residual nonlinearity.
- DP 64-QAM system, 75 km spans, fiber length of 2100 km.
- Without DBP exact OPC mid-point placement is essential.
- 99.99% accurate DBP allows a displacement of 350 km from the mid-point.

Mid-Point Offset OPC and DBP



- Required DBP accuracy to accommodate an OPC offset from the mid-point by one span (BER = 10^{-3}).
- Substantial benefit is retained provided the DBP accuracy exceeds 90%.

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Summary

- Various degrees of readiness, ranging from near-term (implemented today, e.g., constellation design) to further-term.
- Is the computational and/or implementation complexity manageable?
- What is the *real* benefit? (R. Dar, OFC, W3I.1, 2016)
- If near-term solutions are implemented, what are the *additional* benefits of a future "upgrade" based on further-term solutions?
- How much link "knowledge" is needed for implementation? Can this knowledge be extracted autonomously? Is link engineering needed?
- Can a technique easily be included when needed and excluded when not needed?
- Does a technique require optical dispersion compensation?
- Is a technique applicable to systems with a variety of modulation formats?
- Is a technique applicable to reconfigurable networks?
- Is a technique applicable to a flexible grid and elastic networks?