Achievable Information Rate in Optical Communications: From Time-Frequency Packing to Flexi-Grid Networks

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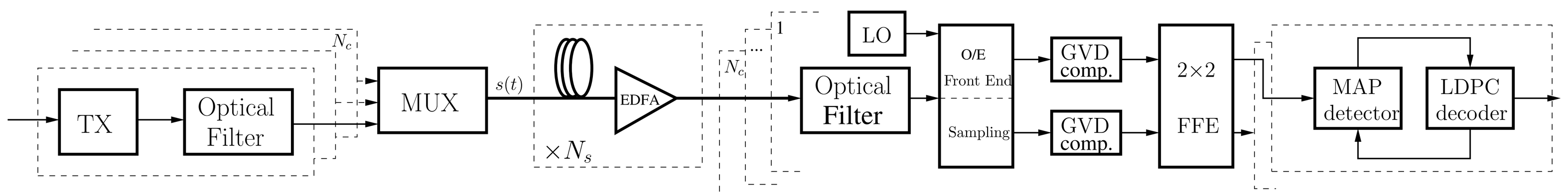
Synopsis

The increasing demand for higher spectral efficiency in long-haul optical communications paved the way to advanced transmission techniques like orthogonal frequency domain multiplexing (OFDM) and Nyquist-WDM, and to the use of high-order modulation formats. We introduced the Time-Frequency Packing (TFP) technique, which goes beyond the paradigm of Nyquist frequency spacing, and allows QPSK to outperform M-QAM in terms of spectral efficiency at equal complexity. The use of bounds on the achievable information rate (AIR), numerically evaluated according to the auxiliary channel and mismatched decoding principles, provides a useful, fast and reliable estimation of the system performance, without reference to any specific employed code. We applied such an approach in the analysis of modern flexi-grid scenarios where cascaded wavelength selective switches (WSS) severely impair signal propagation. Results on the performance of practical low-density parity check (LDPC) codes were provided, and we showed their good agreement with the AIR bound.

System Model



- Time-Frequency Packing: QPSK, RZ50, polarization multiplexing
- Other formats: 16/64/256-QAM, RZ50, polarization multiplexing
- Optimized optical filtering (4^{th}-order Gaussian) and frequency spacing
  - TFP: below Nyquist limit
  - Other formats: above Nyquist limit
- Multi-carrier scenario
- Fixed-tap GVD equalization (one per polarization)
- 2X2 adaptive-tap PMD equalization and polarization demultiplexing
  TFP: Linear filtering (CS) for complexity reduction (ISI compression)
- Iterative detection/decoding (single-user detector)
- BCJR: 2 to 16 states

Working Principle and SE computation [1]

- Receiver designed for an auxiliary channel, suboptimal for the actual channel, since the optimal receiver is unknown. This provides a lower bound on the SE, **achievable by that receiver**.
- Unwanted and intentionally introduced ISI is handled through MAP symbol detection (BCJR algorithm).

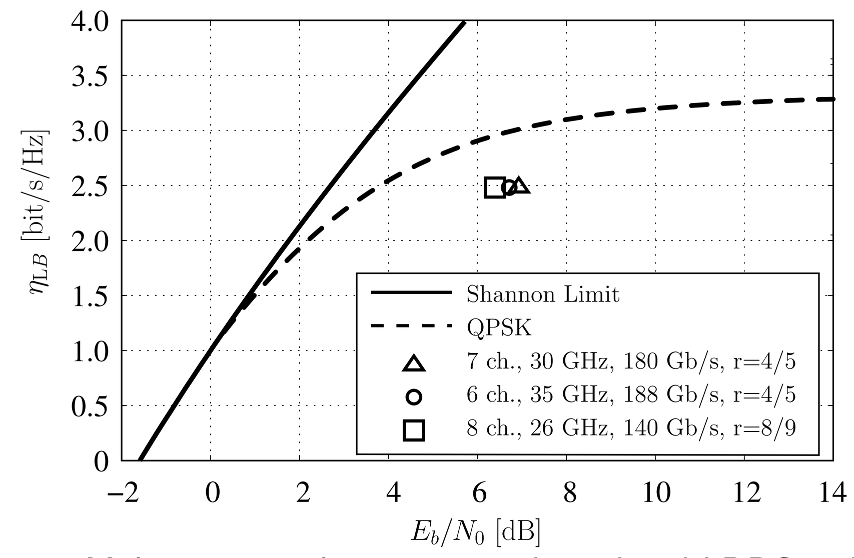


Figure : Multi-carrier in linear regime, bound and LDPC codes.

- For the employed suboptimal receiver, achievable lower bounds on the information rate $\mathcal{I}_{LB}$ are computed, according to mismatched detection, using a simulation-based method.
- Maximum spectral efficiency η_{LB} is computed optimizing the frequency spacing among sub-channels and transmit and receive filter bandwidths.

$$\eta = \frac{\mathcal{I}_{LB}}{FT} \text{ [b/s/Hz]} \qquad \eta_{LB} = \max_{F,B>0} \eta(F,B)$$

Numerical Results [2]

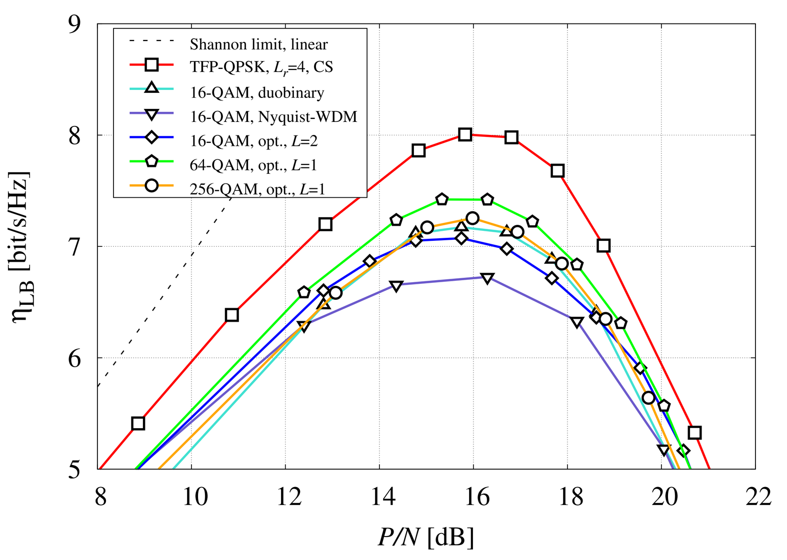
Uncompensated fixed-length link

D	PMD	α	γ	Amp. NF
16 ps/nm/km	0.1 ps/$\sqrt{\text{km}}$	0.23 dB/km	1.3 $W^{-1}km^{-1}$	6 dB

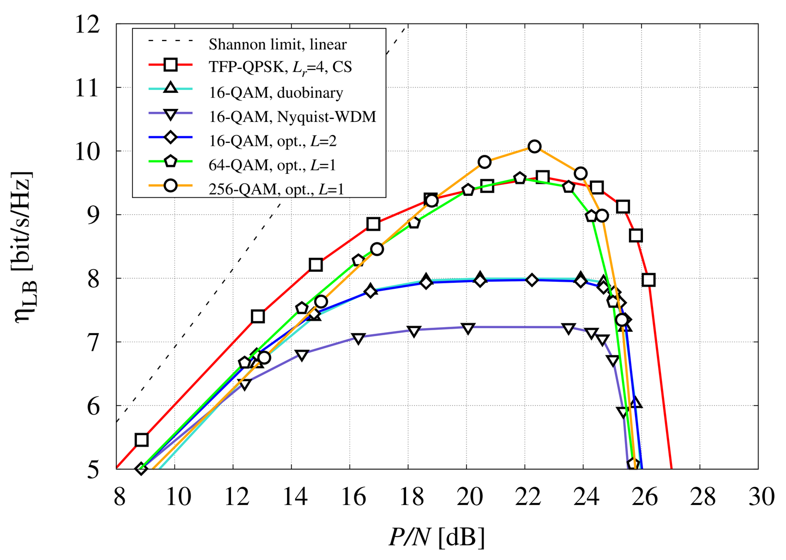
span #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SMF (km)	70.8	75.5	55.1	52.1	40.1	67.	53.2	50	80.3	79.1	53.6	75.1	90.3	54.2	99.4

Uncompensated variable-length link

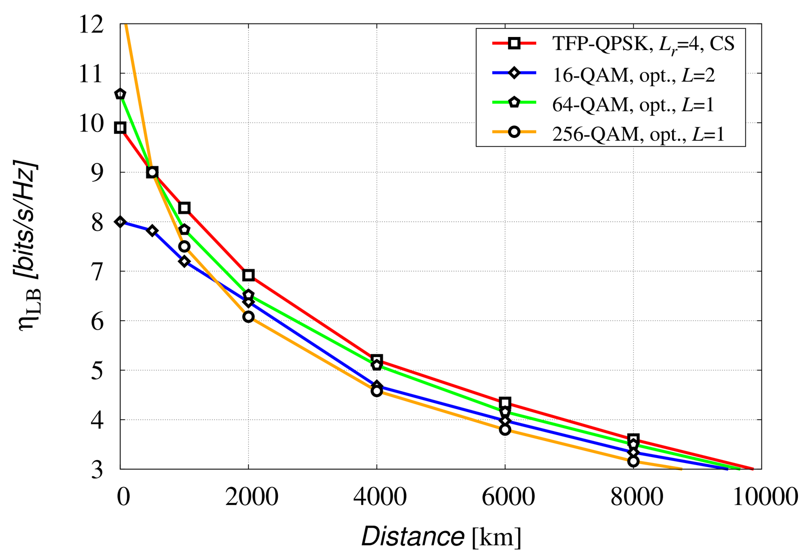
D	PMD	α	γ	Amp. NF	span length
16 ps/nm/km	0.1 ps/$\sqrt{\text{km}}$	0.23 dB/km	1.3 $W^{-1}km^{-1}$	6 dB	100 km



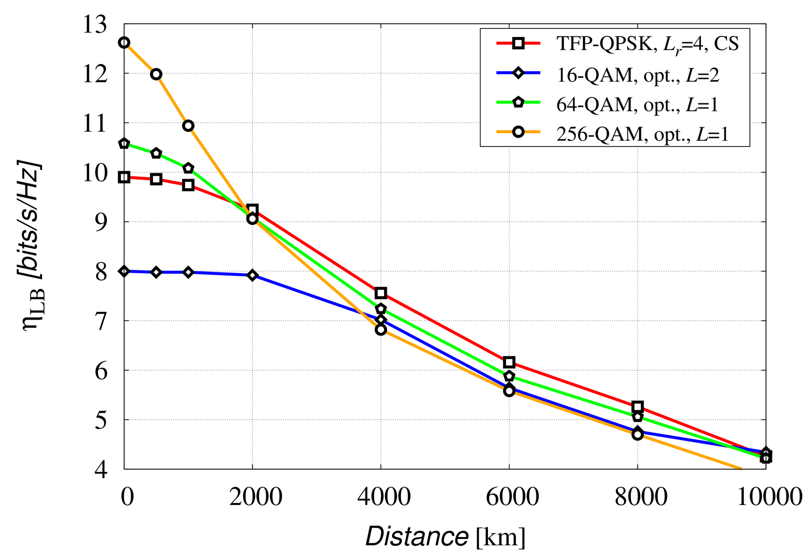
- $\frac{P}{N} = \lim_{N_c \to \infty} \frac{N_c P_c}{B_0 2 N_0} \simeq \frac{P_c}{2N_0F}$, with c channels.
- Equal detector complexities.
- 50 Gbaud channels, 200 GHz total bandwidth.
- Similar results at equal bit rate or equal baud rate.
- A properly designed LDPC code, length 64800 bits, rate 4/5, was simulated (@BER=10^{-7}), reaching almost 7.5 b/s/Hz, less than 0.5 b/s/Hz below the computed bound.



- Equal detector complexities.
- 50 Gbaud channels, 200 GHz total bandwidth.
- Comparative performance is similar also in presence of ideal digital backpropagation, i.e., full complexity on the overall transmission bandwidth.
- No significant advantage is envisaged by using higher-order modulation formats in this case as well.



- Equal detector complexities.
- 50 Gbaud channels, 200 GHz total bandwidth.
- Maximum achievable spectral efficiency as a function of distance.
- Better performance of higher-order QAM formats only for distance < 500 km.



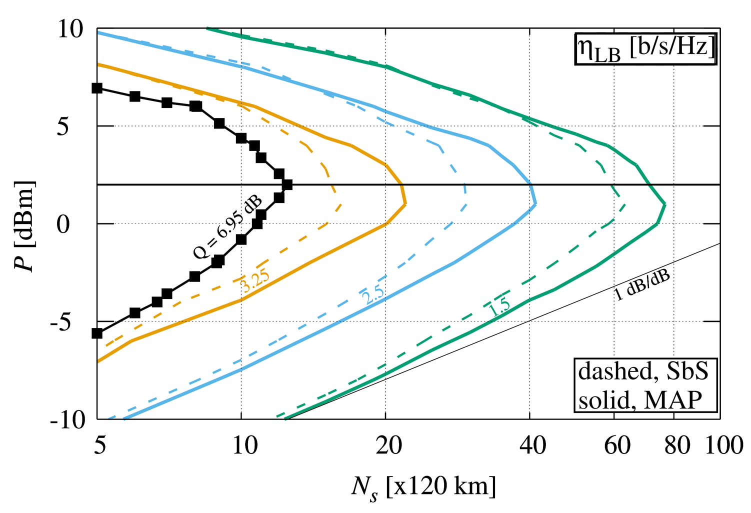
- Equal detector complexities.
- 50 Gbaud channels, 200 GHz total bandwidth.
- Maximum achievable spectral efficiency as a function of distance in presence of ideal backpropagation.
- Better performance of higher-order QAM formats only for distance < 2000 km.

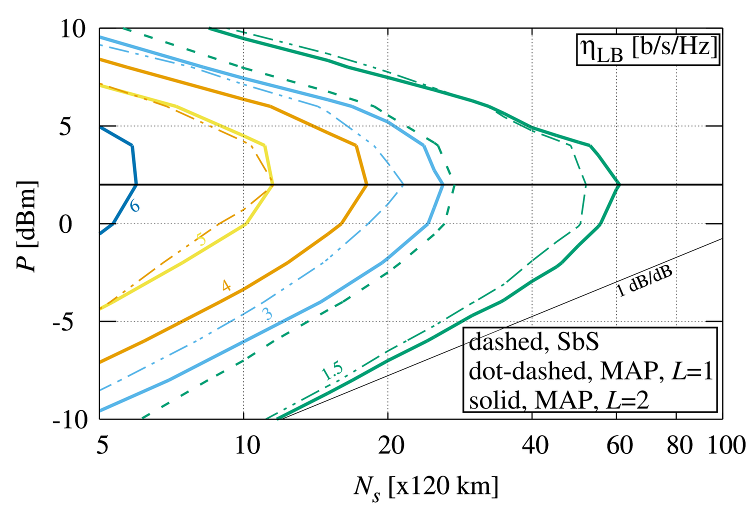
Numerical results [3]

# WSS	2	4	8	12	16	32	64
3-dB CBW [GHz]	31.85	28.4	25.2	23.6	22.5	20	17.8

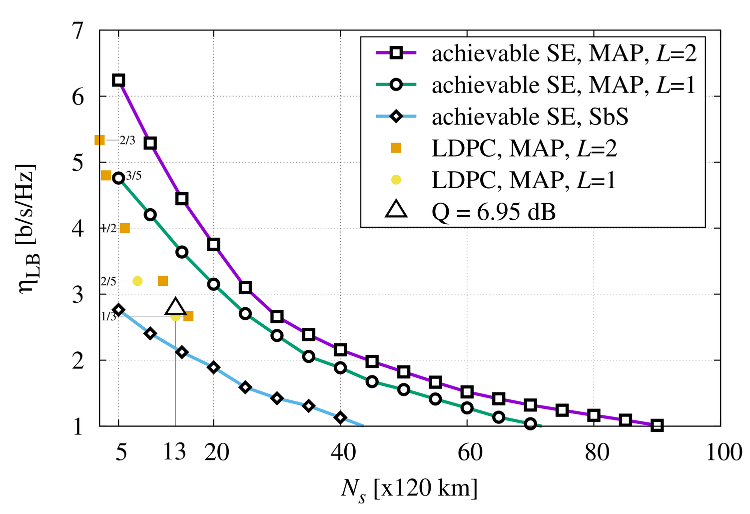
Table : Bandwidth reduction due to cascaded WSS.

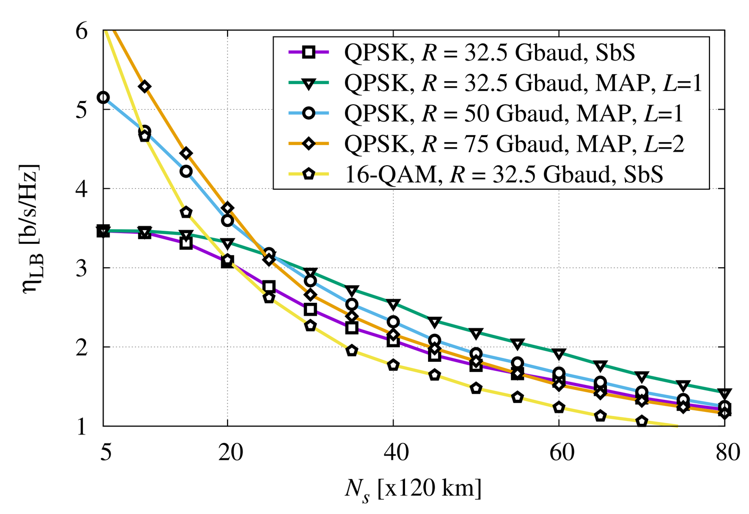
- Fiber impairments:
  - Group Velocity Dispersion (GVD)
  - Nonlinear effects
- Symbol rate from 32.5 Gbaud up to 75 Gbaud, with fixed filter bandwidths.
- Perfect synchronization assumed.
- Achievable spectral efficiency bounds as a function of link length and launch power ⇒ contour plots.





- 2 dBm launch power.
- MAP symbol detection, memory L=1,2.
- Memoryless detector performance as baseline.
- LDPC code rates from 1/3 up to 9/10, threshold at BER= 10^{-4}.
- *Ad hoc* design of codes would provide even better matching.
- TFP entails a spectral efficiency gain for distances up to 3000 km with respect to Nyquist spacing.





Remarks

The computation of mutual information achievable lower bounds is a powerful tool that allows a fast and reliable evaluation of receiver performance. If proper auxiliary channels are employed, as well as the resulting optimal detectors, this method assists in the design of effective codes that, by closely approaching the achievable bounds, improve the overall system performance. In this way it was possible to demonstrate the effectiveness of Time-Frequency Packing, which allows to exploit the QPSK format to obtain even better performance than higher-order modulation formats at equal complexity, and to evaluate the benefits of trellis processing in flexi-grid optical networks, where the presence of cascaded WSS impairs the signal propagation with increasing intersymbol interference, ultimately affecting the performance of conventional symbol-by-symbol detectors.

References

[1] G. Colavolpe, T. Foggi, A. Modenini, A. Piemontese, "Faster-than-Nyquist and beyond: how to improve spectral efficiency by accepting interference", *Optics Express*, Vol. 19 Issue 27, pp.26600-26609, Dec. **2011**.

[2] G. Colavolpe, T. Foggi, "Time-Frequency Packing for High-Capacity Coherent Optical Links", *IEEE Transactions on Communications*, vol. 62, no. 8, pp.2986-2995, Aug. **2014**.

[3] T. Foggi, G. Colavolpe, A. Bononi, P. Serena, "Spectral Efficiency Optimization in Flexi-Grid Long-Haul Optical Systems", *IEEE Journal of Lightwave Technology*, vol. 33, no. 13, pp. 2735-2742, Mar. **2015**.