Spectrally Efficient Optical Communications based on Time-Frequency Packing

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Outline

1. Introduction
2. Time-Frequency Packing
3. Optical Links
   - Long-haul Communications
   - Optimization in Flexi-Grid Networks
   - Signal overlap for Elastic Networks
4. Conclusions

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Assumptions for the 1st part

- We consider a bandlimited AWGN channel
  - Long-haul optical channels in the absence of NL effects
- We assume a multichannel/multiuser scenario (WDM, we will use the terms “channels”, “carriers”, and “users” interchangeably)
  - Different users
  - Different subchannels to lower the processing speed or in case of technological constraints

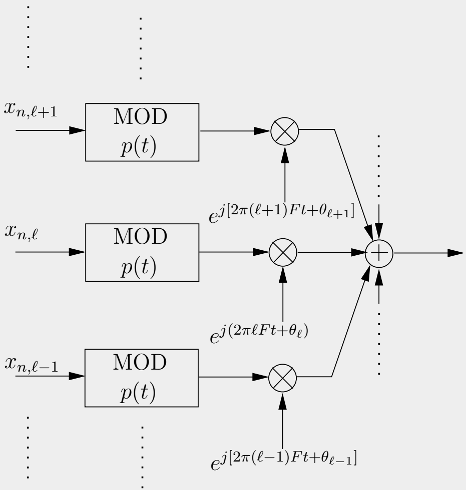
Signal model

Transmitted signal $s(t)$

$$s(t) = \sqrt{2E_s} \sum_n \sum_\ell x_{n,\ell} p(t - nT - \tau_\ell) e^{j(2\pi\ell F t + \theta_\ell)}$$

- E_s: symbol energy
- $x_{n,\ell}$: M-ary symbol transmitted over the ℓ-th channel during the n-th symbol interval
- T: symbol time (or time spacing)
- F: frequency spacing
- $p(t)$: shaping pulse
- θ_ℓ and τ_ℓ: phase and time shifts of the ℓ-th subcarrier

Signal model (cont'd)

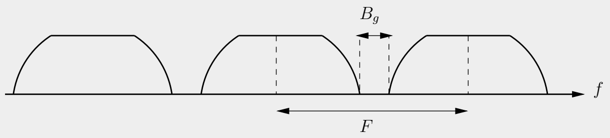


Orthogonal Signaling

- From Shannon theory, it is well known that orthogonal signaling with no excess bandwidth and Gaussian inputs achieves capacity on this channel
- Orthogonal signaling means no ISI in case of a single-carrier transmission, no ISI and no ICI in case of a multi-carrier transmission
- For many years, digital communication systems for quasi-static channels have been designed based on orthogonal signaling

FDM

- FDM with Nyquist signaling:
  e.g., $p(t)$ has RRC-shaped spectrum with roll-off factor α and $F \geq \frac{1+\alpha}{T}$ ($F = \frac{1}{T}$ in case of OQAM, OPSK [1])

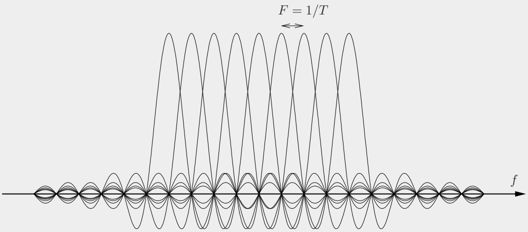


- Examples: DVB-S2, WDM

[1] B. R. Saltzberg, " Performance of an efficient parallel data transmission system", IEEE Transactions of Communication Technology, Dec. 1967

OFDM

- OFDM:
  $p(t)$ is rectangular of duration T and $F = 1/T$



  - No guard bandwidth
  - Efficient processing at Tx and Rx side
  - On a frequency-selective channel, capacity is achieved through waterfilling

Shaping and Faster-than-Nyquist

- When a high-order constellation is employed or shaping [2] is adopted, we can approach the condition of “Gaussian inputs”
- What is the best thing to do when low-order constellations are employed?
- Change of paradigm: faster-than Nyquist (FTN) [3,4]
  - The baud rate $R = 1/T$ is increased w.r.t. Nyquist rate, thus introducing controlled ISI (as in partial response signaling)
  - However, FTN does not modify the shape of the transmitted spectrum

[2] A. R. Calderbank and L. H. Ozarow, “Nonequiprobable signalling on the Gaussian channel,” IEEE Trans. Inform. Theory, July 1990

[3] J. E. Mazo, “Faster-than-Nyquist signaling,” Bell System Tech. J., Oct. 1975

[4] A. D. Liveris and C. N. Georghiades, “Exploiting faster-than-Nyquist signaling,” IEEE TCOMM, Sept. 2003

Shaping and Faster-than-Nyquist

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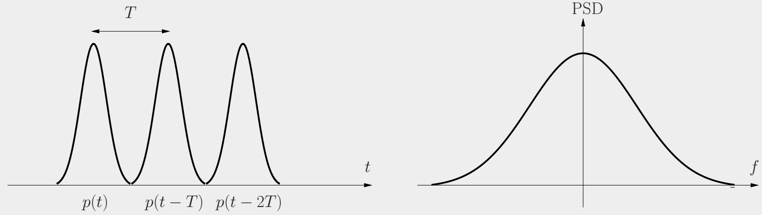

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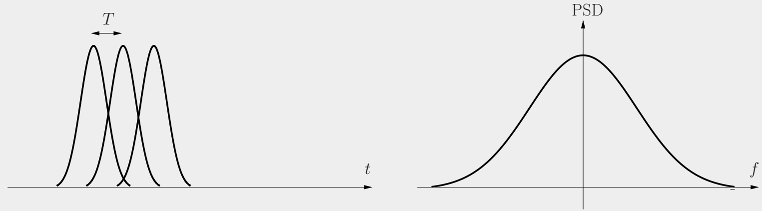

Faster-than-Nyquist

- In FTN, T is selected as the smallest value giving no reduction of the minimum Euclidean distance with respect to the Nyquist case $\Rightarrow$ asymptotically, the ISI-free BER performance is reached (with the optimal MAP sequence detector)
- Extended to both time and frequency by Rusek and Anderson [5]: both T and F are reduced $\Rightarrow$ both ISI and ICI arise
- Main drawback: the optimal MAP sequence detector must be used (high complexity)
- Is the BER the main performance measure? In other words: are we interested in the BER performance when keeping the same code?

[5] F. Rusek and J. B. Anderson, “The two dimensional Mazo limit,” in Proc. IEEE International Symp. Inform. Theory, Sept. 2005

CDMA

- By the way.....CDMA:

  $F = 0$ and a spreading code is assigned to each user. In a synchronous CDMA system ($\tau_\ell = \tau_m$), orthogonal codes can be used to implement orthogonal signaling

  But the main success of CDMA is related to the possibility to increment the spectral efficiency through overload (in asynchronous non-orthogonal systems), thus accepting interference...

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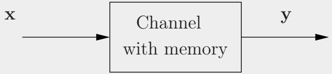
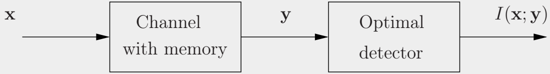
Information Theory Background



- Information rate or symmetric capacity or i.u.d. capacity: the mutual information $I(\mathbf{x};\mathbf{y})$ for i.u.d. symbols constrained to a finite constellation

Information Theory Background



- Information rate or symmetric capacity or i.u.d. capacity: the mutual information $I(\mathbf{x};\mathbf{y})$ for i.u.d. symbols constrained to a finite constellation
- For a channel with finite memory, $I(\mathbf{x};\mathbf{y})$ can be computed as in [6], employing an optimal MAP symbol detector

Spectral efficiency η is our performance measure

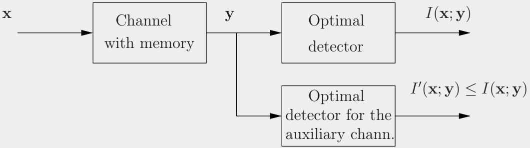
$$\eta = \frac{I(\mathbf{x};\mathbf{y})}{FT} \qquad \left[\frac{\mathrm{bit}}{\mathrm{s}\cdot\mathrm{Hz}}\right]$$

[6] D. M. Arnold, H.-A. Loeliger, P. O. Vontobel, A. Kavčić, and W. Zeng, "Simulation-based computation of information rates for channels with memory," IEEE Trans. Inform. Theory, Aug. 2006

Background (cont'd)

The receiver complexity can be taken into account by resorting to the concept of mismatched detection [7]:

if we use an optimal MAP symbol detector not for the real channel but for an auxiliary channel that approximates the original one, we obtain an achievable lower bound on $I(\mathbf{x};\mathbf{y})$ $\Rightarrow$ we will say that the spectral efficiency depends on the employed receiver



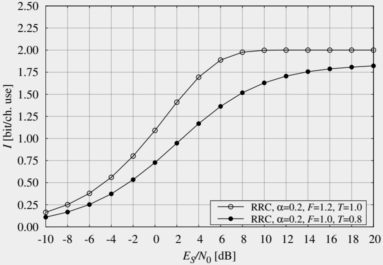
[7] N. Merhav, G. Kaplan, A. Lapidoth, and S. Shamai, "On information rates for mismatched decoders," IEEE Trans. Inform. Theory, Nov. 1994

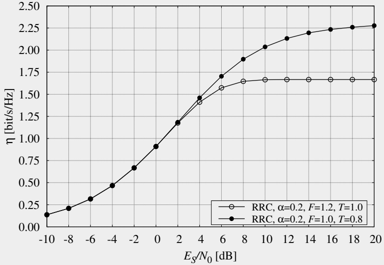
Time-Frequency Packing (cont'd)

SPADiC

- Given $p(t)$, we optimize F and T to maximize η assuming different receivers
- In fact, when F and T are reduced interference increases $\Rightarrow I(\mathbf{x};\mathbf{y})$ degrades but η can improve

Example





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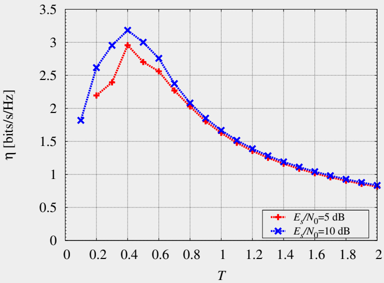

- QPSK, RRC $\alpha = 0.2$, $F = 1.2$

Time-Frequency Packing (cont'd)

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Differences with FTN:

- We use low-complexity receivers
- We accept a degradation of the information provided the spectral efficiency is increased $\Rightarrow$ a proper code ensuring an error-free transmission in those conditions can be found
- In other words, if we keep the same code, the performance degrades but an improvement is obtained by using a code with lower rate (higher overhead)

Time-Frequency Packing (cont'd)

Receivers with different complexity can be considered

Single-user symbol-by-symbol detector after a proper linear front-end

Auxiliary channel:

$$y_{k,0} = x_{k,0} h(0,0,k) + \underbrace{\sum_{(n,\ell)\neq(0,0)} x_{k-n,\ell} h(n,\ell,k) + z_k}_{v_k}$$

ISI and ICI are assumed to be additive noise whose distribution must be optimized to improve the lower bound

$h(\cdot,\cdot,\cdot)$ depends on the employed front-end (to be optimized)

Time-Frequency Packing (cont'd)

Single-user receivers with complexity $O(M^L)$

L interfering symbols are taken into account in the auxiliary channel model. The remaining ISI and ICI are assumed to be additive noise. The corresponding optimal MAP symbol detector has M^L states

Multi-user receivers with complexity $O(M^{LU})$

L interfering symbols of the considered user and of U side users are taken into account in the auxiliary channel. The remaining ISI and ICI are assumed to be additive noise. The corresponding optimal MAP symbol detector has M^{LU} states

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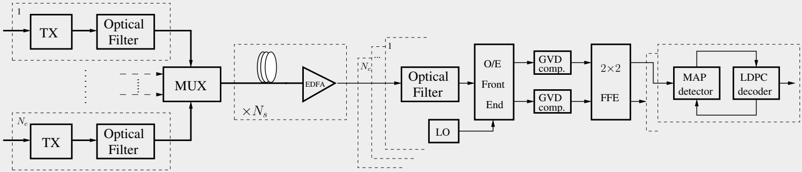
System Model

- Next generation channels at 1 Tb/s will hardly be reached with single-channel transmissions (for technological and practical issues of processing high data rates on a single channel)
- Many different solutions have been proposed all based on multicarrier transmissions or so called superchannels (not to be confused with classical WDM systems)
- In other words, the goal capacity is reached by binding up as many single channels together as necessary, in an efficient way



Schemes in the Literature

- Orthogonal signaling is the main paradigm also in optical communications and ISI or ICI are seen as side effects. Examples:
  - Nyquist WDM [11]: carriers are packed as much as possible trying to limit ICI (spacing larger than $1/T$)
  - OFDM
  - Receiver-side duobinary shaping [12]: signals are filtered to limit ICI and properly shaping ISI (coped with a MLSD receiver)

[11] G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, “On the performance of nyquist-WDM terabit superchannels based on PMQPSK, PM-8PSK or PM-16QAM subcarriers,” JLT, January 2011.
[12] J. Li, E. Tipsuwannakul, T. Eriksson, M. Karlsson, and P. A. Andrekson, “Approaching Nyquist limit in WDM systems by low-complexity receiver-side duobinary shaping,” JLT, June 1 2012.

Proposed Solution

- Time packing cannot be implemented “as is” due to the NL Mach-Zehnder (MZ) modulator: instead of packing the pulses in time, we “stretch” the pulses through a proper optical filter
- The comparison has been performed taking into account NL effects

Considered receivers

- Optional digital backpropagator
- Two-dimensional MMSE equalizer to cope with GVD and PMD (perfect compensation in the absence of NL effects)
- BCJR detector to cope with ISI intentionally or accidentally introduced in the system
  - In case of Nyquist-WDM and receiver-side duobinary shaping the relevant memory is completely taken into account
  - For receiver-side duobinary shaping, a proper digital filter is also required as specified in [12]
  - For TF-packing, a lower memory is taken into account to limit the receiver complexity (but a CS is also adopted)

Aim of the investigation

- We are computing the SE achievable on the optical channel when two possible receiver designs are adopted
  - In the first one, nonlinear effects are neglected at the receiver (i.e., the receiver is designed for the linear regime). This is obviously a worst case
  - The second case is when we adopt the best available technique for the compensation of nonlinear effects

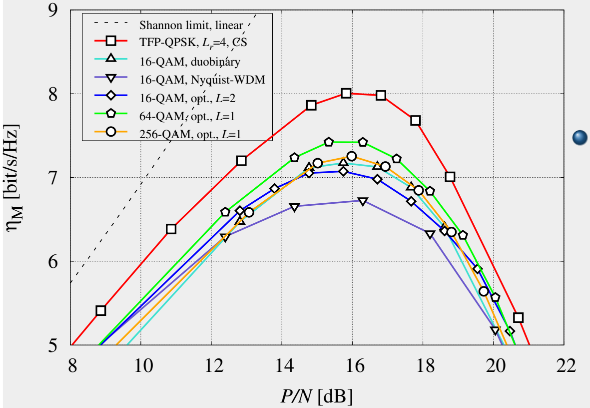
Numerical results

- We consider polarization-multiplexed systems
- The employed shaping pulses are those resulting from the use of RZ pulses with duty cycle 50%, a MZ modulator, and a 4th-order Gaussian optical transmit filter with 3-dB optical filter bandwidth B
- For Nyquist-WDM, it is $F \geq 1/T$ (F properly optimized) to avoid falling into the TF-packing domain
- All systems with 50-Gbaud/s sub-channels for a total band occupation of approximately 200 GHz
- The considered link is described in [13] without inline dispersion compensation

[13] G. Colavolpe, T. Foggi, "High spectral efficiency for long-haul optical links: time-frequency packing vs high-order constellations," ECOC 2013, September 2013.

Numerical Results (cont'd)

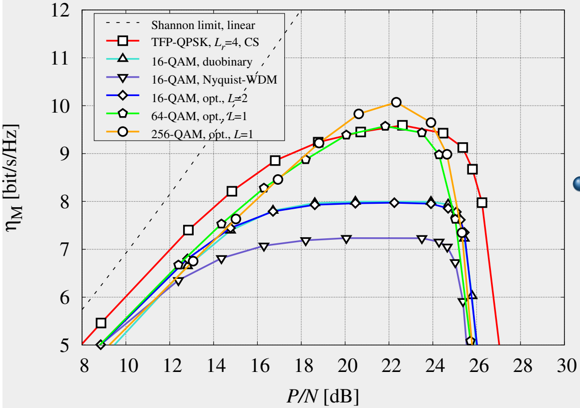
No backpropagation



- 16 states for TFP (one BCJR for each SOP and each component)

Numerical Results (cont'd)

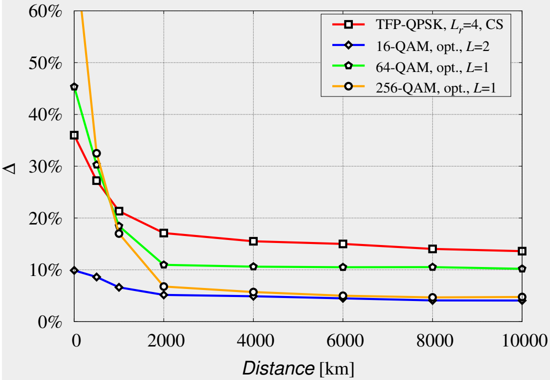
Ideal backpropagation



- Same as before

Numerical Results (cont'd)

No Backpropagation



- 8 channels, 140 Gbit/s each
- $\Delta = \frac{\eta_{\mathrm{M}} - \eta_{\mathrm{M}}^{REF}}{\eta_{\mathrm{M}}^{REF}}$
- η_{M}^{REF} is the maximum SE at each distance of 16-QAM Nyquist WDM as in [14]

[14] G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, "On the performance of nyquist-WDM terabit superchannels based on PMQPSK, PM-8PSK or PM-16QAM subcarriers," J. Lightwave Tech., vol. 29, no. 1, 2011.

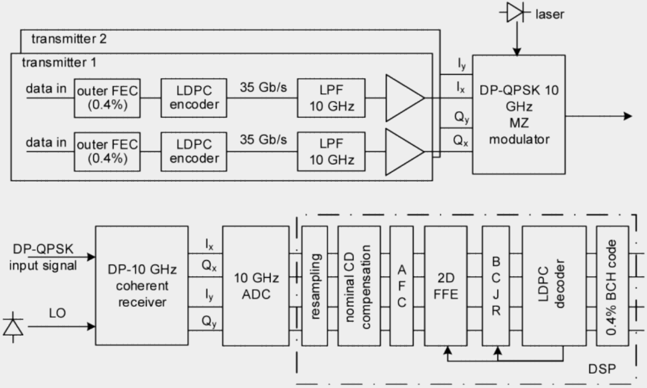
The Australian field trial [5]

- Long-haul Telstra link between Sydney and Melbourne, 995 km of uncompensated SMF.
- 40 and 100 Gb/s copropagating channels in a 50 GHz grid + our superchannel (four 50 GHz WSS $\rightarrow$ 200 GHz)
- Superchannel: 8 subchannels with PM-QPSK, 975 Gb/s overall.
- Offline processing by means of our MATLAB demonstrator (receiver algorithms presented in [6])
- Maximum measured spectral efficiency: 5.58 b/s/Hz

[5] L. Potì, G. Meloni, G. Berrettini, F. Fresi, T. Foggi, M. Secondini, L. Giorgi, F. Cavaliere, S. Hackett, A. Petronio, P. Nibbs, R. Forgan, A .Leong, R. Masciulli, C. Pfander, "Sub- Nyquist Field Trial Using Time Frequency Packed DP-QPSK Super-Channel Within Fixed ITU-T Grid", *Optics Express*, vol. 23, no. 12, pp. 16196-16208, Jun. 2015.
[6] 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.

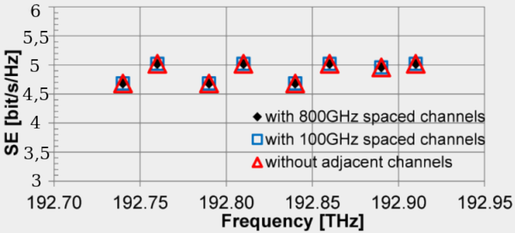
Australian field trial TX + RX

Transmitter + Receiver



Australian field trial results

Measured spectral efficiency



- Results on the 995-km link, optimization performed on the central channel
- Impact of adjacent channels measured at different channel spacings
- Average SE: 4.87 b/s/Hz $\rightarrow$ 975 Gb/s

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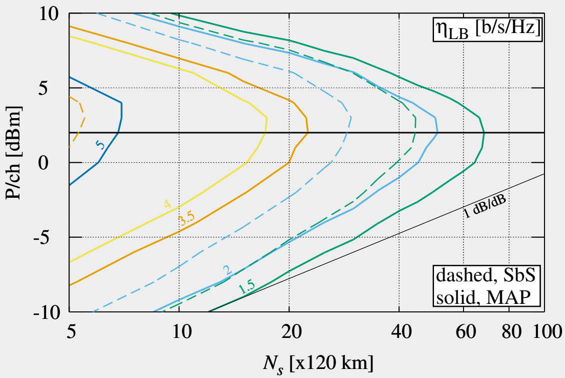
Scenario

- We consider a multichannel transmission with ℓ identical subcarriers
- The signal propagates over reconfigurable optical add-drop multiplexer (ROADM)-based optical networks
- Every ROADM envisages the presence of wavelength selective switches (WSS)
  - Three WSS if the ROADM is an add/drop node for the observed subcarrier
  - Two WSS if the ROADM is simply crossed by the observed subcarrier
- New generation WSS have pros and cons
  - The 12.5 GHz granularity can be exploited to increase the network spectral effiency
  - Crossing cascaded ROADMs induce an increasing tight filtering effect on the signal, that can be detrimental

# WSS	1	2	5	10	20	50	100
Power loss	8%	14%	24%	32%	39%	47%	53%

Numerical Results (cont'd)

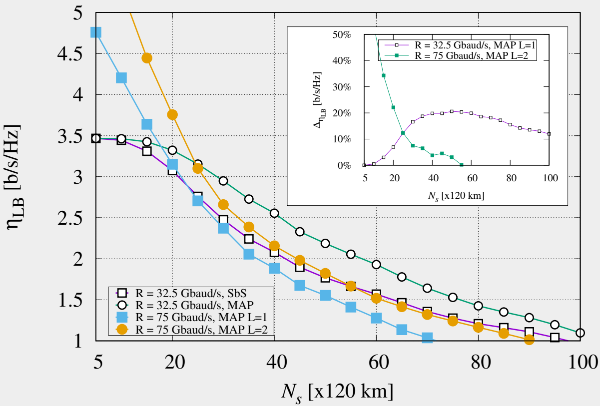
Contour plots of SE as a function of launch power and distance



- R=50 Gbaud/s
- Conventional symbol-by-symbol (SbS) detector
- MAP symbol detector

Numerical Results (cont'd)

SE as a function of distance @ P/ch=2 dBm



- R32.5 Gbaud/s and R=75 Gbaud/s
- Conventional symbol-by-symbol (SbS) detector
- MAP symbol detector
- Achievable SE and LDPC simulations
- Relative MAP detectors gain w.r.t. 32.5 Gbaud/s SbS

$$\Delta\eta_{LB} = \frac{\eta_{LB} - \eta_{LB,REF}}{\eta_{LB,REF}}$$

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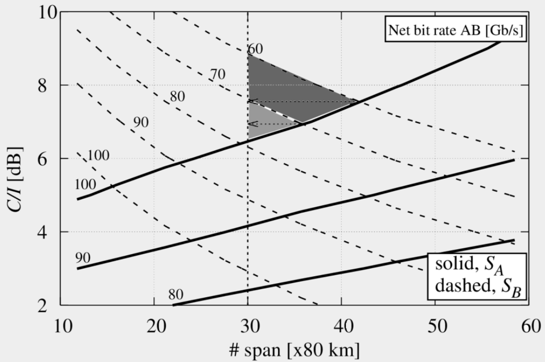
Scenario

- Elastic Optical Networks supporting flexi-grid technology are nowadays popular
- Optical signals occupy dedicated frequency slots
- Signal overlap can be exploited, based on a few basic concepts
  - No synchronization (unlike O-CDMA)
  - Successive interference cancellation (SIC)
- Less spectrally efficient and more complex than higher-cardinality constellations
- But enables advantages in terms of protection schemes and network reconfiguration capabilities

Numerical Results

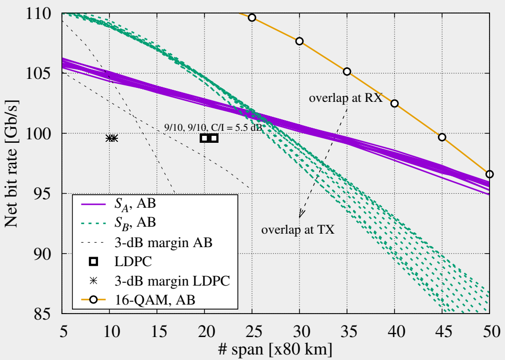
Contour plots of net bit rate as a function of C/I and distance



- Reach obtained by OSNR given the link
- PM-QPSK @ 112 Gbit/s
- Conventional symbol-by-symbol (SbS) detector
- The gray-shaded regions gives information on the required code rates for $S_A \sim 100$ Gb/s

Numerical Results (cont'd)

Net bit rate and LDPC simulations for different overlap nodes



- Dispersion unmanaged link
- Non-linear effects
- Varying overlap node from 0 to 50th span
- $C/I = 5.5$ dB
- 16QAM @ same overall rate

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Conclusions

- Spectral efficiency can be considerably improved by introducing controlled interference
- This technique promises to provide significant advantages in many applications (not only those considered here)
- The combination of TFP with other techniques such as probabilistic shaping can be a interesting field of research