Analytical Approach to Account for ISRS when Planning Ultra-Wideband DWDM Optical Networks

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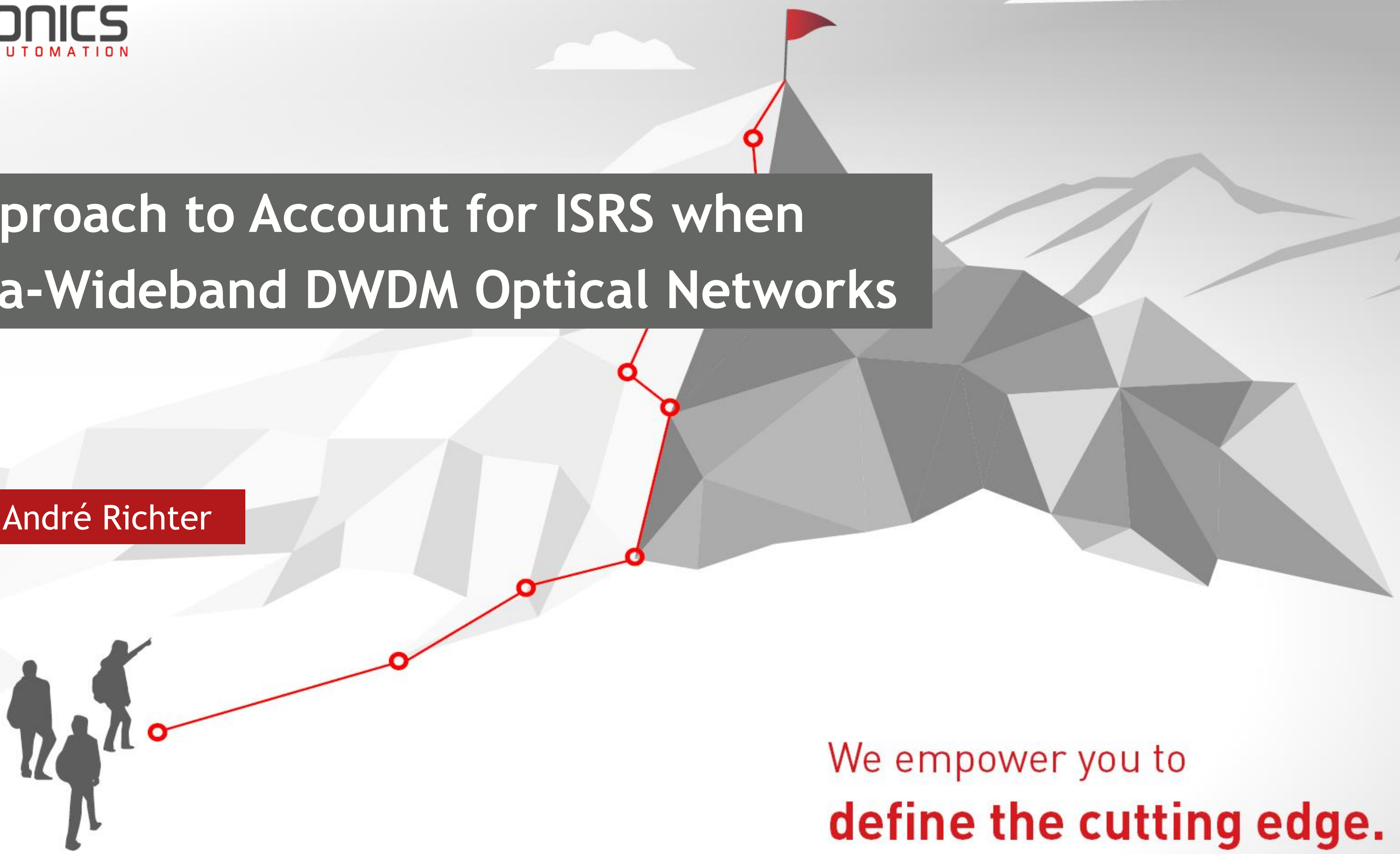

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Outline

- ✓ ISRS in Multi-band WDM Systems
- ✓ Analytical Approach to ISRS Modeling
- ✓ Investigated Use-cases
- ✓ Summary

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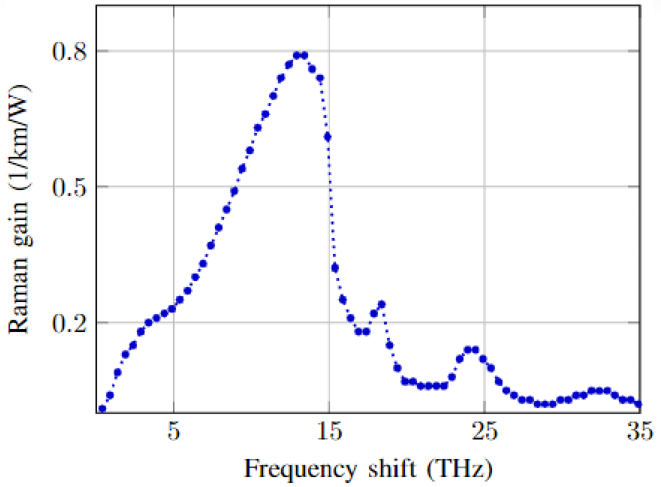
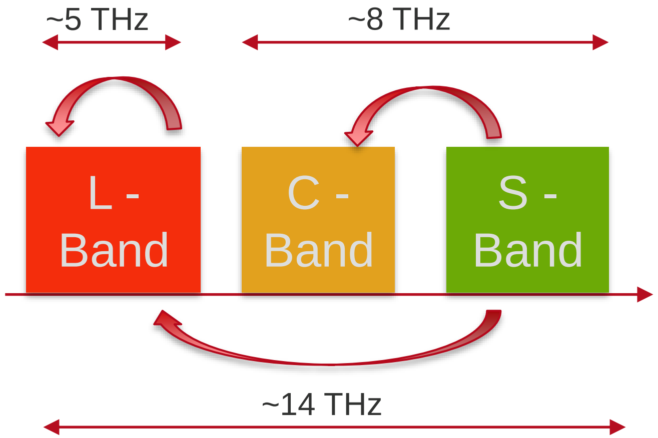
Inter-channel Stimulated Raman Scattering

Accounting for ISRS at Network Planning

Inter-Channel Stimulated Raman Scattering

- Power transfer due to Raman effect
  - Intra-band in DWDM signal
  - Inter-band in multi-band DWDM signal
- GNLS describes propagation of DWDM signal along a fiber*
- Numerical simulations
  - Accurate
  - Time-consuming





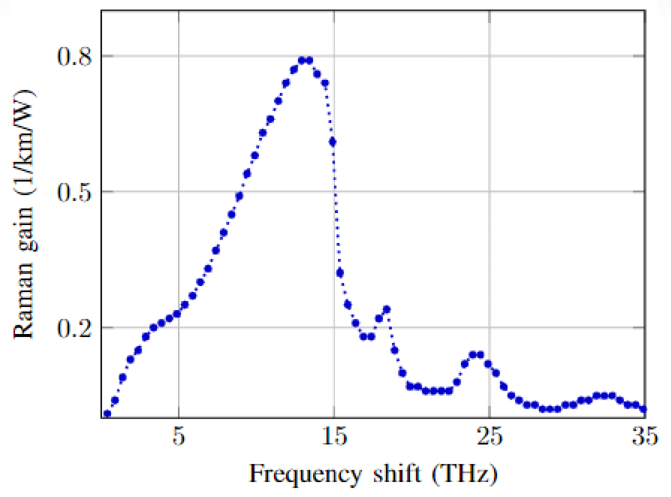
* A. Richter, G. Di Rosa and I. Koltchanov, "Challenges in Modeling Wideband Transmission Systems," in 2022 European Conference on Optical Communication (ECOC), December 2022.

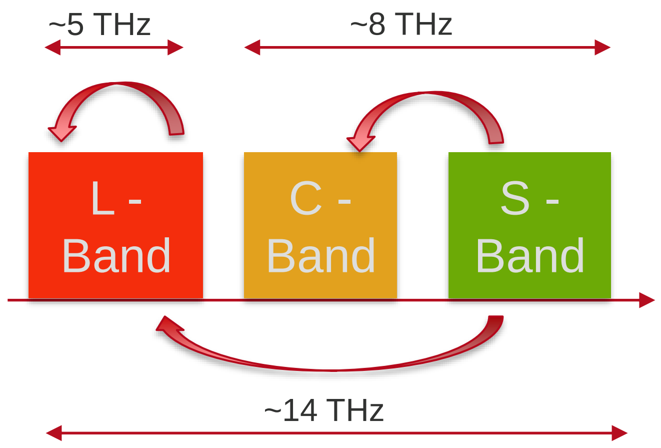
ISRS in Multi-band WDM Systems

- Simplified propagation equations describing inter-channel power transfer*
- Numerical calculations for a single 100 km span
  - ~0.5 dB tilt in output power of DWDM signal in C-band
  - up to 10 dB tilt when S, C, and L–bands are in use

TILT VALUE FOR DIFFERENT SPECTRAL UTILIZATION

Tilt (dB)				
C	C + L	S + C	S + L	S + C + L
0.9	3.5	4.5	7.1	10.1





- The effect is accumulated over several spans!

* S. Cani et al., "An Analytical Approximated Solution for the Gain of Broadband Raman Amplifiers With Multiple Counter-Pumps," Journal of Lightwave Technology, vol. 27, no. 7, pp. 944 - 951, October 2009.

Inter-channel Stimulated Raman Scattering

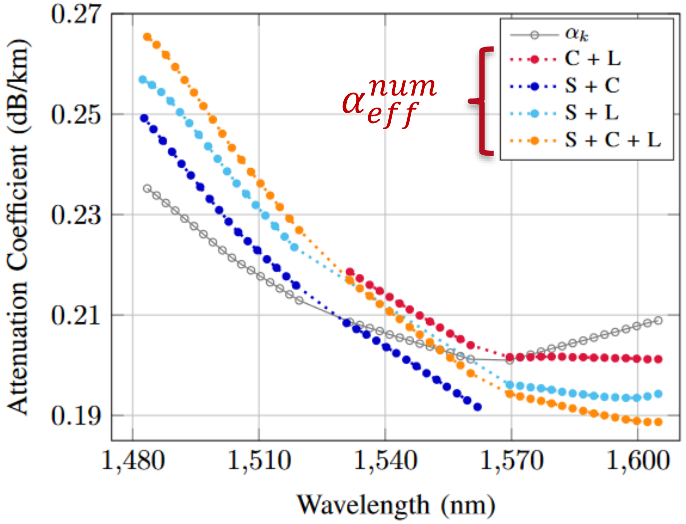
Accounting for ISRS at Network Planning

Accounting for ISRS at Network Planning

- Solve propagation equations* numerically
  - Good to estimate quality of signal for a given transmission line (TL)
  - Time-consuming - not efficient at network planning
- Define effective attenuation coefficient

$$\alpha_{eff}^{num} = \ln[P(0)/P(L)]L$$

  - $P(0)$ – per channel power at the fiber input
  - $P(L)$ – per channel power at the fiber output
  - L – fiber length
- Estimate quality of TL via α_{eff}^{num} : $P(L) = P(0)e^{-\alpha_{eff}^{num} L}$

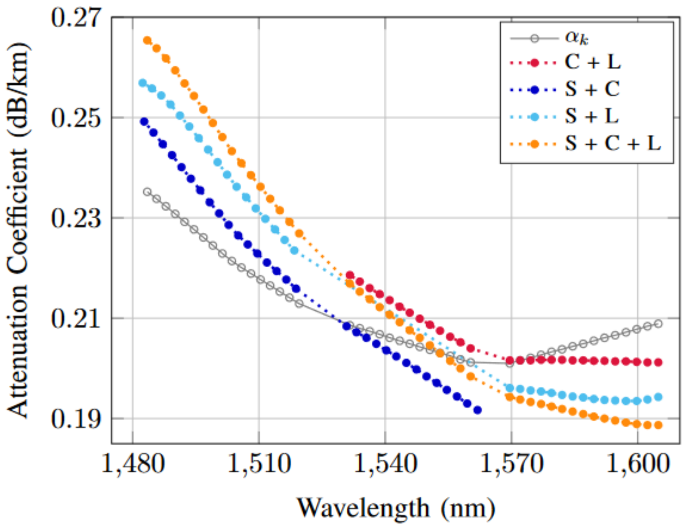


α_k: fiber attenuation coefficient at frequency f_k and α_{eff}^{num} for different spectral utilization (0 dBm/channel @ fiber input, 100 km span)

* S. Cani et al., "An Analytical Approximated Solution for the Gain of Broadband Raman Amplifiers With Multiple Counter-Pumps," Journal of Lightwave Technology, vol. 27, no. 7, pp. 944 - 951, October 2009.

Effective Attenuation Coefficient

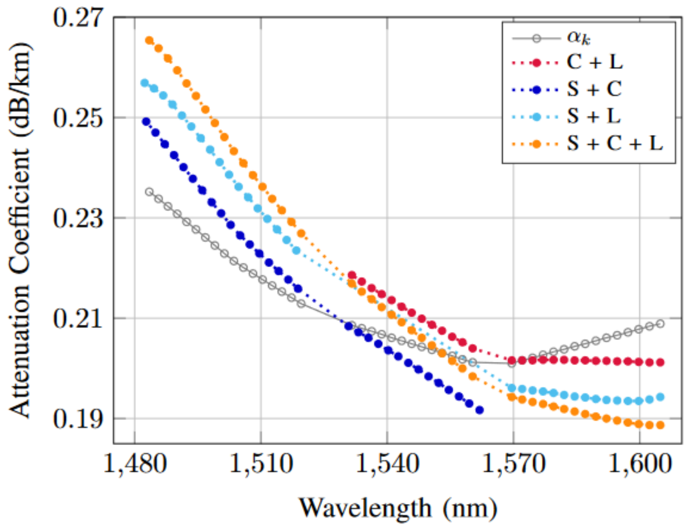
- α_{eff}^{num} depends on many parameters
  - DWDM signal parameters
    - Per channel power
    - Channel frequencies and spacing

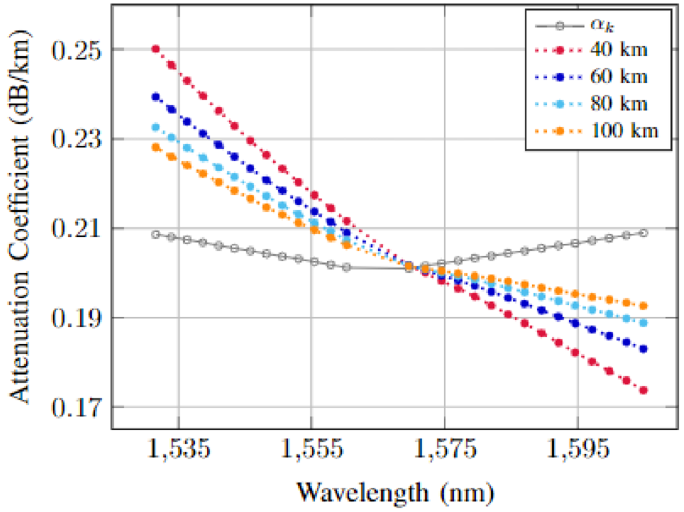


α_k: fiber attenuation coefficient at frequency f_k and α_{eff}^{num} for different spectral utilization
(0 dBm/channel @ fiber input, 100 km span)

Effective Attenuation Coefficient

- α_{eff}^{num} depends on many parameters
  - DWDM signal parameters
    - Per channel power
    - Channel frequencies and spacing
  - Fiber type and length
- Look-up table – clumsy approach
- Can α_{eff} be calculated analytically?





Propagation Equations

Iterative Approximation to Analytical Solution

Propagation Equations

- Equations accounting for stimulated and spontaneous Raman scattering*

- Signal-to-Signal interaction only**
  - No spontaneous scattering
  - No Signal-to-Noise interaction

$$\frac{dP_\nu^\pm}{dz} = \mp \alpha_\nu P_\nu^\pm \pm P_\nu^\pm \sum_{\mu>\nu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-)$$

$$\mp P_\nu^\pm \sum_{\mu<\nu} \frac{\nu}{\mu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-)$$

$$\pm 2N_{E,\nu} \sum_{\mu>\nu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-) \cdot T_N$$

$$\mp P_\nu^\pm \sum_{\mu<\nu} \frac{\nu}{\mu} \frac{C_{R,\mu\nu}}{\Gamma} 4N_{E,\mu} \cdot T_N$$

** Justification is given later

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Propagation Equations

- Equations accounting for stimulated Raman Scattering
- Copropagating only

$$\frac{dP_k(z)}{dz} = -\alpha_k P_k(z) + P_k(z) \sum_{i \neq k} g_{ik} P_i(z) \quad (1)$$

$$\frac{dP_\nu^\pm}{dz} = \mp \alpha_\nu P_\nu^\pm \pm P_\nu^\pm \sum_{\mu>\nu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-) \mp P_\nu^\pm \sum_{\mu<\nu} \frac{\nu}{\mu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-)$$

where

$$g_{ik} = \begin{cases} -\frac{f_i}{f_k}\frac{C_{ik}}{\Gamma}, f_i < f_k \\ \frac{C_{ik}}{\Gamma}, f_i > f_k \end{cases}$$

$P_k(z)$ – power of DWDM channel at frequency f_k
α_k – fiber attenuation coefficient
C_{ik} – Raman gain efficiency
Γ – polarization factor

- Numerical calculations
- Analytics ?

Propagation Equations

Iterative Approximation to Analytical Solution

Iterative Approximation to Analytical Solution

- Signal-to-Signal interaction is negligible $\Longrightarrow$ zero order approximation

$$\frac{dP_k(z)}{dz} = -\alpha_k P_k(z) + \cancel{P_k(z) \sum_{i \neq k} g_{ik} P_i(z)} \quad (1) \quad \Longrightarrow \quad P_k^{(0)}(z) = P_k(0) e^{-\alpha_k z} \quad (2)$$

- First order approximation, after substituting (2) into the right side of (1)

$$P_k^{(1)}(z) = P_k(0) e^{-\alpha_k z} \boxed{\exp\left[\sum_{i \neq k} g_{ik} P_i(0) \frac{1 - e^{-\alpha_i z}}{\alpha_i}\right]}$$

Correction due to interfering channels

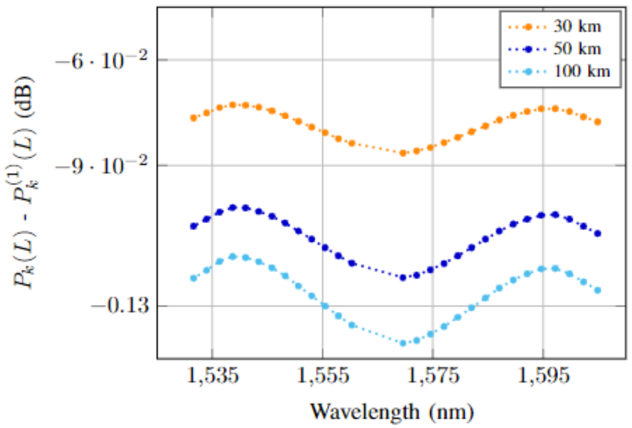
- Effective attenuation coefficient in the 1st approximation

$$\alpha_k^{eff(1)} = \alpha_k + \sum_{i \neq k} A_{ik} \frac{L_i^{eff}}{L} \,, \qquad A_{ik} = -g_{ik} P_i(0) \,, \qquad L_i^{eff} = (1 - e^{-\alpha_i L})/\alpha_i \qquad (3)$$

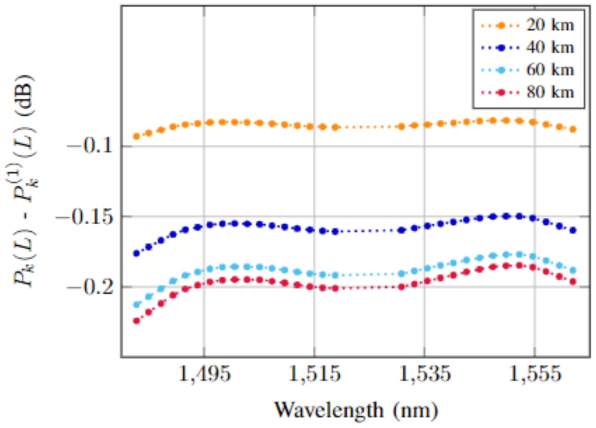
Numerical Calculations vs. 1^{st} order Approximation

- Zero order approximation
  - Applicable to short fiber spans or to a few channels
- First order approximation
  - Applicable for a single band or adjacent bands, short spans, or quite low input power

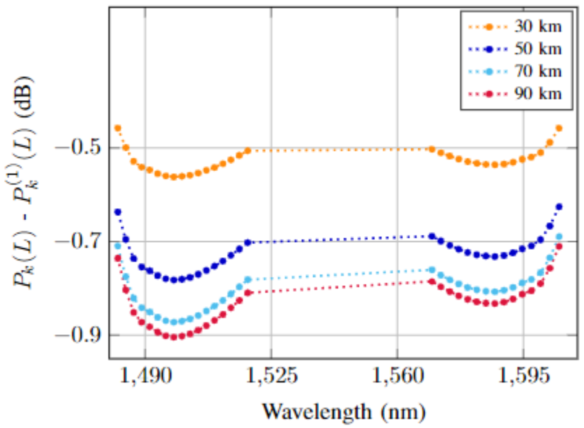
C+L



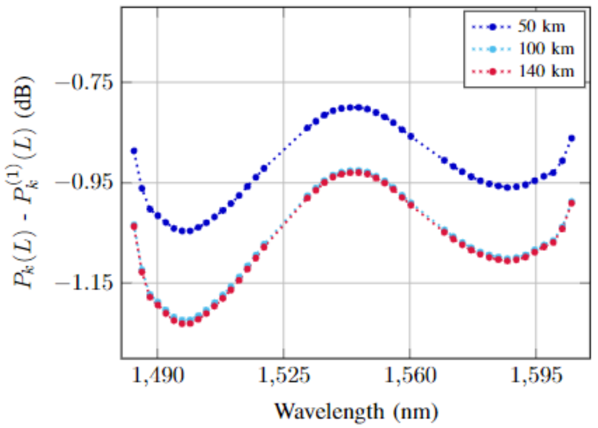
S+C



S+L



S+C+L



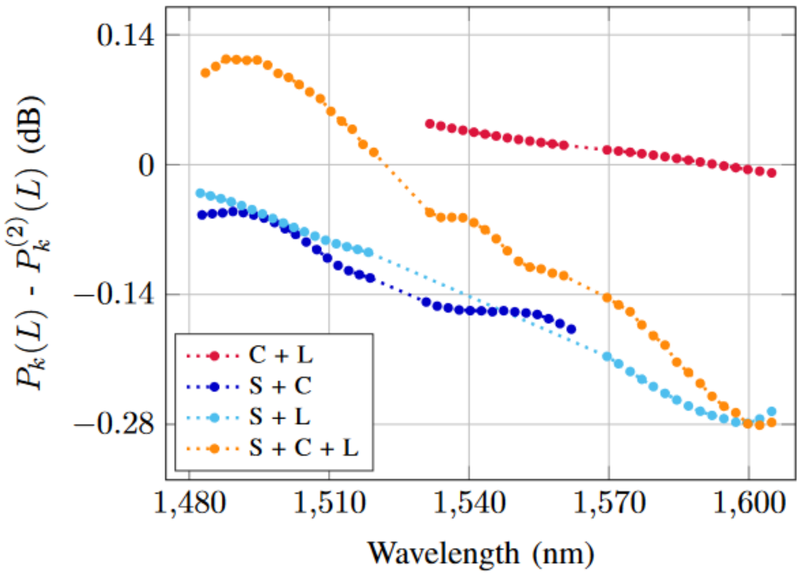
- The higher the fiber length or spectral utilization,
  the higher the discrepancy with numerical calculations!

Improving Analytical Solution

- Second order approximation, after substituting (3) into the right side of (1)

$$\alpha_k^{eff(2)} = \alpha_k + \sum_{i \neq k} A_{ik} \frac{L_i^{eff^*}}{L}, \qquad L_i^{eff^*} = \frac{1 - exp\left[\sum_{j \neq i} A_{ji} L_j^{eff}\right]}{\sum_{j \neq i} A_{ji}} \qquad (4)$$

$$P_k^{(2)}(L) = P_k(0) e^{-\alpha_k^{eff(2)} L}$$



Power difference vs. λ @ fiber output
(0 dBm/channel @ fiber input)

- Assumption:
  - $\alpha_i = \alpha_j$, i.e., fiber attenuation coefficients for interfering channels are identical

Investigated Use-cases

1 x 100 km Transmission Line

6 x 100 km Transmission line

9 span Transmission Line from 17 node network

Validation of Simplified Propagation Equations

- Propagation equations without signal-to-noise interaction, because
  - ISRS tilt is high when wide spectral range is in use
  - Output DWDM signal needs equalizing
  - Extra loss due to equalization
  - Raman noise negligible,
    compared to preamplifier ASE

$$\frac{dP_k(z)}{dz} = -\alpha_k P_k(z) + P_k(z) \sum_{i \neq k} g_{ik} P_i(z)$$

VS.

$$\frac{dP_\nu^\pm}{dz} = \mp \alpha_\nu P_\nu^\pm \pm P_\nu^\pm \sum_{\mu > \nu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-)$$

$$\mp P_\nu^\pm \sum_{\mu < \nu} \frac{\nu}{\mu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-)$$

$$\pm 2N_{E,\nu} \sum_{\mu > \nu} \frac{C_{R,\mu\nu}}{\Gamma} \cdot (P_\mu^+ + P_\mu^-) \cdot T_N$$

$$\mp P_\nu^\pm \sum_{\mu < \nu} \frac{\nu}{\mu} \frac{C_{R,\mu\nu}}{\Gamma} 4N_{E,\mu} \cdot T_N$$

- Numerical solution extended to account for Raman noise and its amplification gives < 0.01 dB difference in OSNR values.

Single span transmission line

- The difference in dB between per channel power @ fiber output calculated numerically and via $\alpha_k^{eff(2)}$
  - < 0.05 dB when C and L bands are in use
  - < 0.3 dB when S, C, and L bands are in use
    - Underestimation of channel power at blue side of S-band (0.15 dB)
    - Overestimation of channel power at red side of L-band (0.3 dB)

MAXIMAL ERROR FOR DIFFERENT SPECTRAL UTILIZATION

Approx. No.	$P_k(L)$ - $P_k^{(1,2)}(L)$ (dB)			
	$C+L$	$S+C$	$S+L$	$S+C+L$
1	-0.1	-0.2	-0.9	-1.2
2	0.05	-0.15	-0.3	-0.3

0 dBm / channel @ fiber input

- The accuracy is lower at higher spectral utilization due to the assumption about equal attenuation of interfering channels.

Single span transmission line

- Different power levels at fiber input with S, C, and L bands in use
  - Same per channel power
    - Per channel power varies in range [-3;3] dBm
    - Maximal error

MAXIMAL ERROR WITH S, C, AND L BANDS IN USE

Input per Channel Power (dBm)	-3	0	1	3
$P_k(L)$ - $P_k^{(2)}(L)$ (dB)	-0.15	-0.3	-0.6	5

  - Non-flat input signal
    - Lower powers at lower frequencies and higher powers at higher frequencies, i.e., “inverse” ISRS tilt
    - Power range at lower frequencies is [-10;-3] dBm
    - Power range at higher frequencies is [-3;3] dBm
    - Maximal error is below 0.5 dB

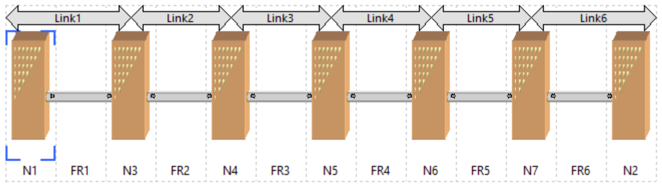
1 x 100 km Transmission Line

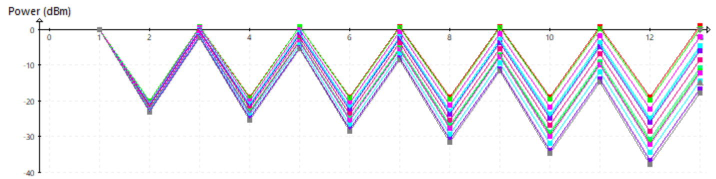
6 x 100 km Transmission line

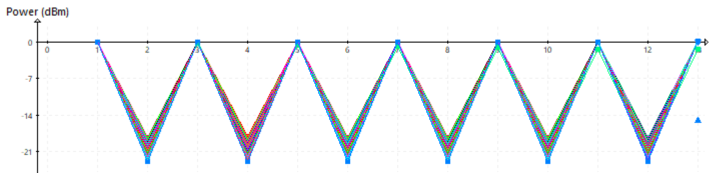
9 span Transmission Line from 17 node network

Six Span Transmission Line

- Propagation of multi-band DWDM signal along 600 km transmission line
  - Different combinations of fully loaded frequency bands
  - Accumulated tilt is higher after several spans
  - Power equalization
  - Exact compensation of fiber and equalization losses after each span
    - 0 dBm channel power at the input of each span
    - 5 dB amplifier noise figure







Six Span Transmission Line

- Propagation of multi-band DWDM signal along 600 km transmission line
  - Different combinations of fully loaded frequency bands
  - Accumulated tilt is higher after several spans
  - Power equalization
  - Exact compensation of fiber and equalization losses after each span
    - 0 dBm channel power at the input of each span
    - 5 dB amplifier noise figure
- Significant difference between zero approx. and numerical calculations

OSNR DIFFERENCE

Distance (km)	$OSNR^{(0)}$ - $OSNR^{(n)}$ (dB)			
	C + L	S + C	S + L	S + C + L
1x100	1.9	2.1	3.9	5.7
2x100	1.9	2.1	3.9	5.7
6x100	1.9	2.1	3.9	5.6

- Reduced cumulative error $(OSNR^{(n)} - OSNR^{(2)})$
  - 0.1dB - C and L bands are in use
  - 0.6dB - S,C, and L bands are in use

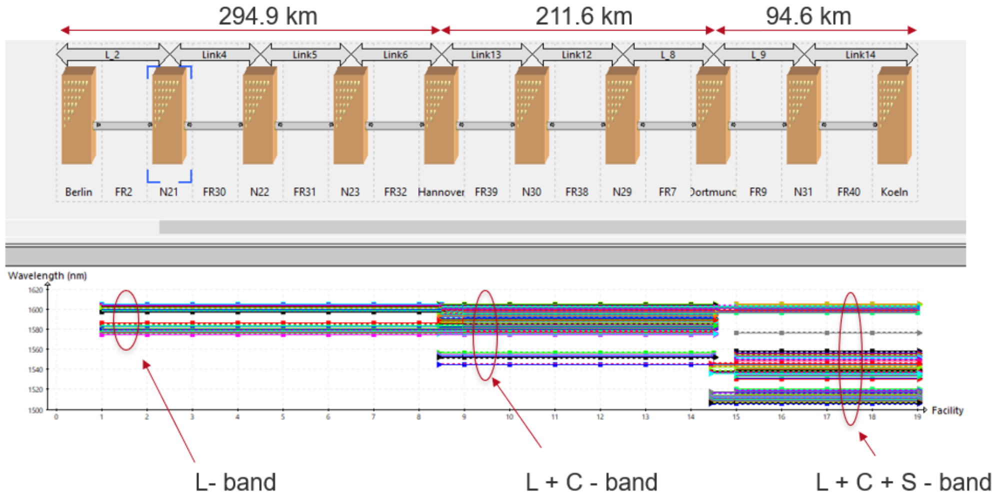
1 x 100 km Transmission Line

6 x 100 km Transmission line

9 span Transmission Line from 17 node network

9 Span Transmission Line

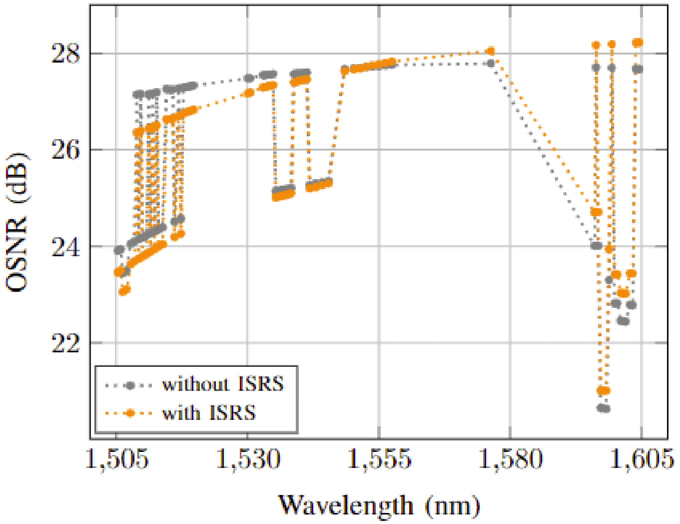
- Transmission line from Nobel Germany Network* with 17 add/drop nodes
- Traffic matrix corresponds to 2030 year planning period**
- The shortest route between Berlin & Cologne
  - Four add/drop nodes
  - 6 repeater huts
  - 9 fiber spans of different lengths
- Exact loss compensation at add/drop nodes and repeater huts
- Equalization at add/drop nodes only

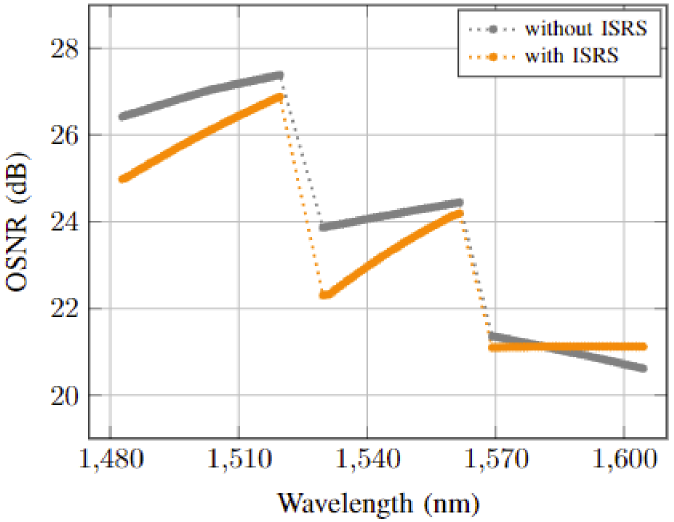


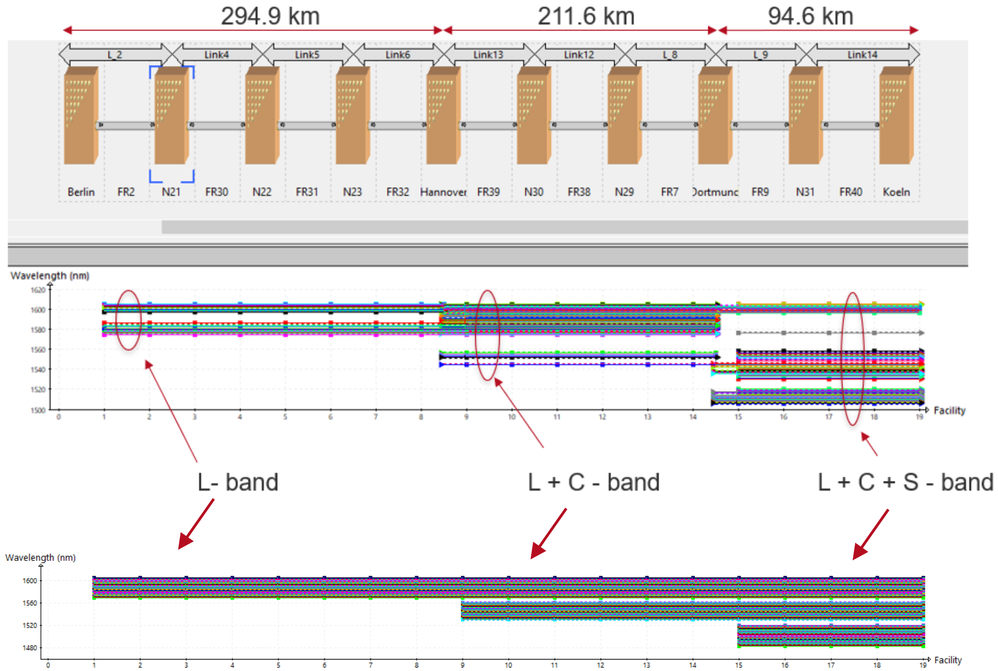
* Zuse Institute Berlin, “SNDLib”. [Online]. Available: sndlib.zib.de. Accessed: 2023-05-05.
** D.Khomchenko; S.K. Patri; A. Autenrieth; C. Mas-Machuca; A. Richter, ”Transmission-Aware Bandwidth Variable Transceiver Allocation in DWDM Optical Networks,” in 2021 International conference on Optical Network Design and Modeling (ONDM), July 2021.

9 Span Transmission Line

- Transmission line from Nobel Germany Network* with 17 add/drop nodes
- OSNR overestimation (if ISRS is ignored)
  - < 1 dB for actual traffic matrix
  - < 2 dB for full loading







* Zuse Institute Berlin, “SNDLib”. [Online]. Available: sndlib.zib.de. Accessed: 2023-05-05.

Summary

- Analytic approach to ISRS modeling has been presented
  - Quick assessment of cross-channel interference when planning ultra–wideband DWDM optical networks
  - Applicable to different configurations, including
    - Fiber spans of different lengths
    - Different bitrates, modulation formats and power levels at each lightpath
  - Analytical approach provides sufficiently accurate results for reasonable channel input powers

Thank you for your attention!

- ➲ Questions?
- ➲ Comments?

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