POLITECNICO DI TORINO

QUALITY OF TRANSMISSION ESTIMATOR ENABLING TRANSPARENCY PARADIGM IN LEGACY IMDD NETWORKS

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OPTCOM

OUTLINE

- Motivations
- Structure of a 10G Dispersion Managed Quality of Transmission Estimator (QoT-E)
- QoT-E Validation
- An example of QoT-E enabled performance estimation

MOTIVATIONS

PHYSICAL LAYER AWARE AUTOMATION ON 10G DM LINKS

WHY?

- Operators Interest in exploit possibilities of deployed fiber and infrastructure
- Ancient (but still deployed) pre-WDM technology would see substantial capacity gains by upgrading to cheap IMDD links on metro networks

↓

- QoT-E for legacy DM links enables:
  - Real-time management by physical layer aware SDN controller
  - Network design and disaggregation

TWO MAIN OPTIONS

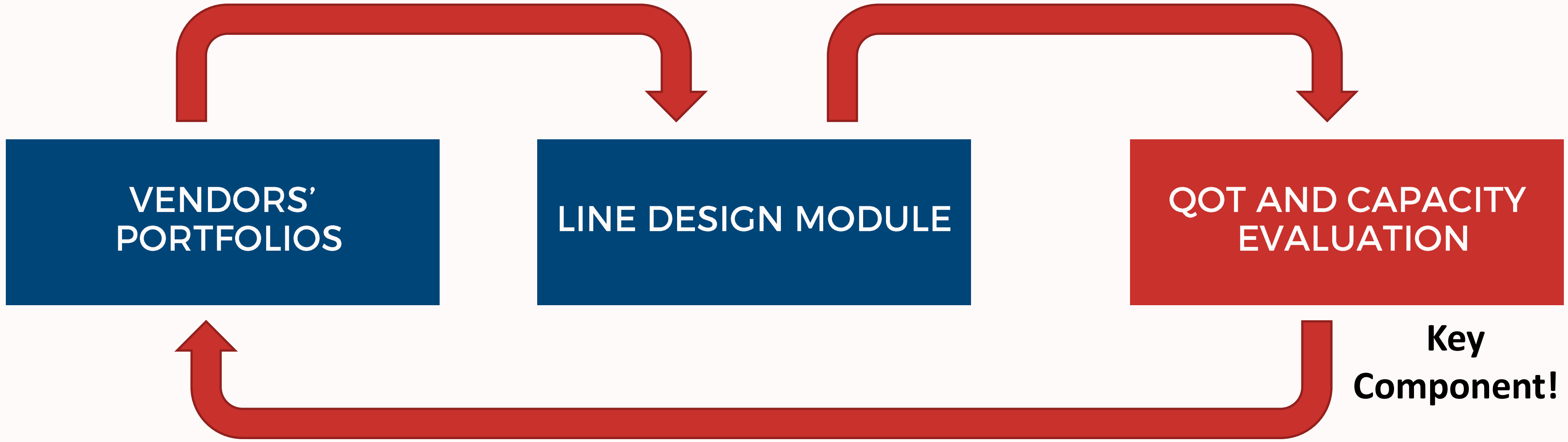
Network Design

- Selecting network elements from vendors' portfolios to optimize network performance

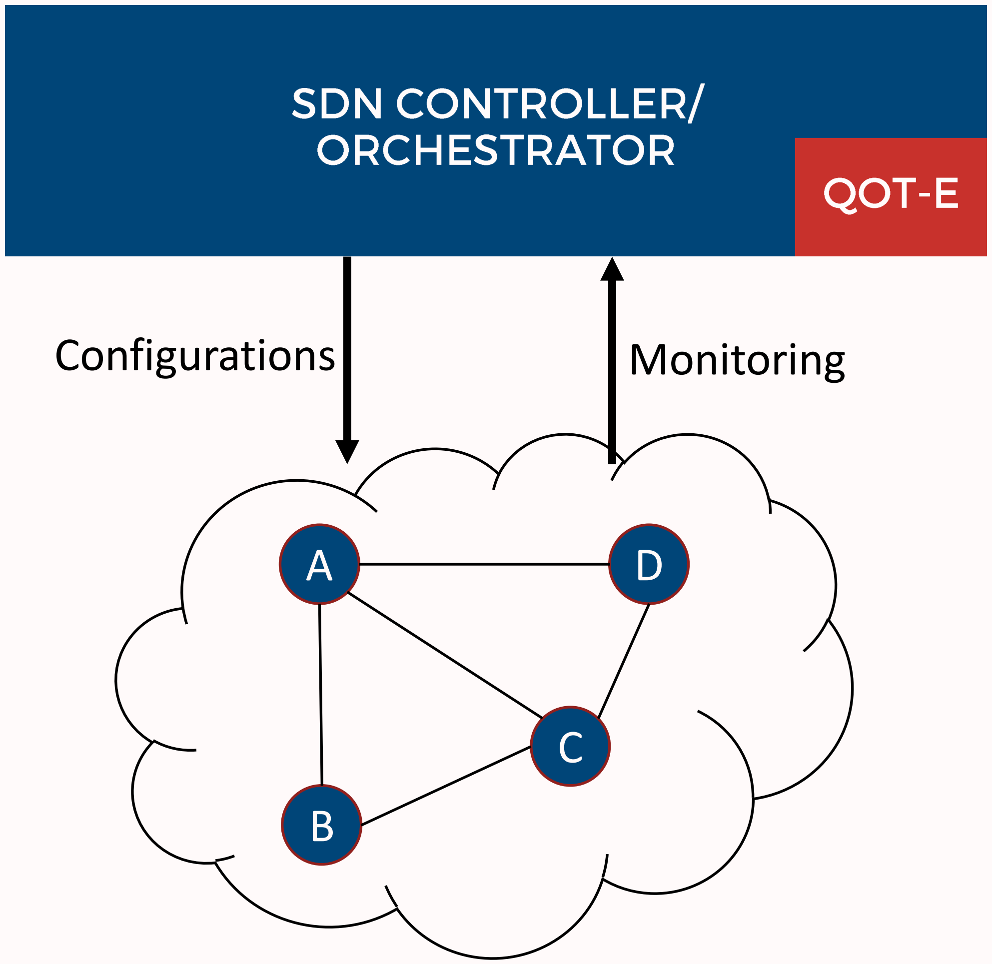
Network Management & Orchestration

- Make optical feasibility evaluation and select hardware working points to optimize capacity, flexibility and resiliency of the optical network infrastructure
  - Network element setup for lightpath turn up
  - Fast rerouting against failures

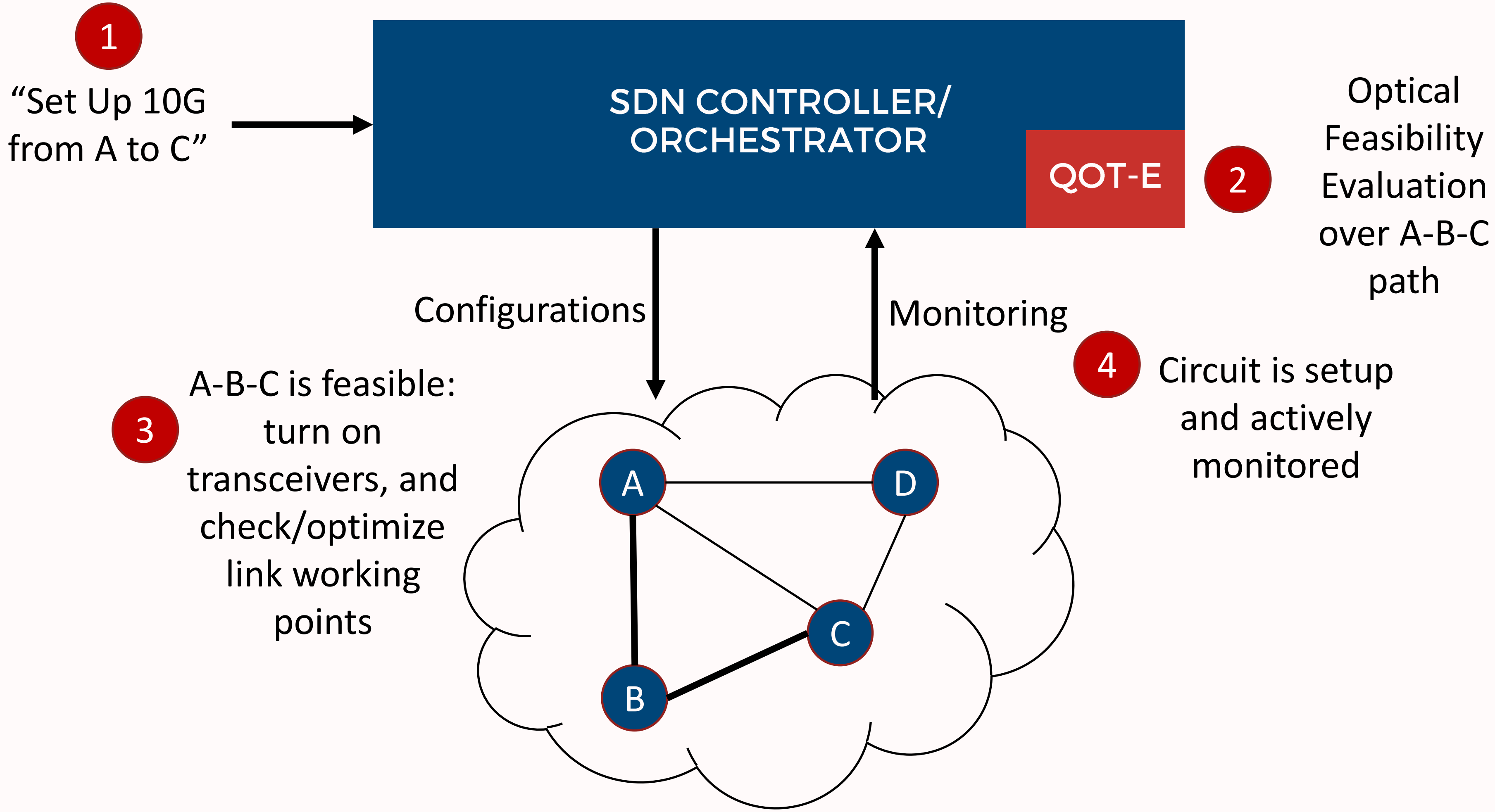
NETWORK DESIGN



NETWORK CONTROL AND ORCHESTRATION

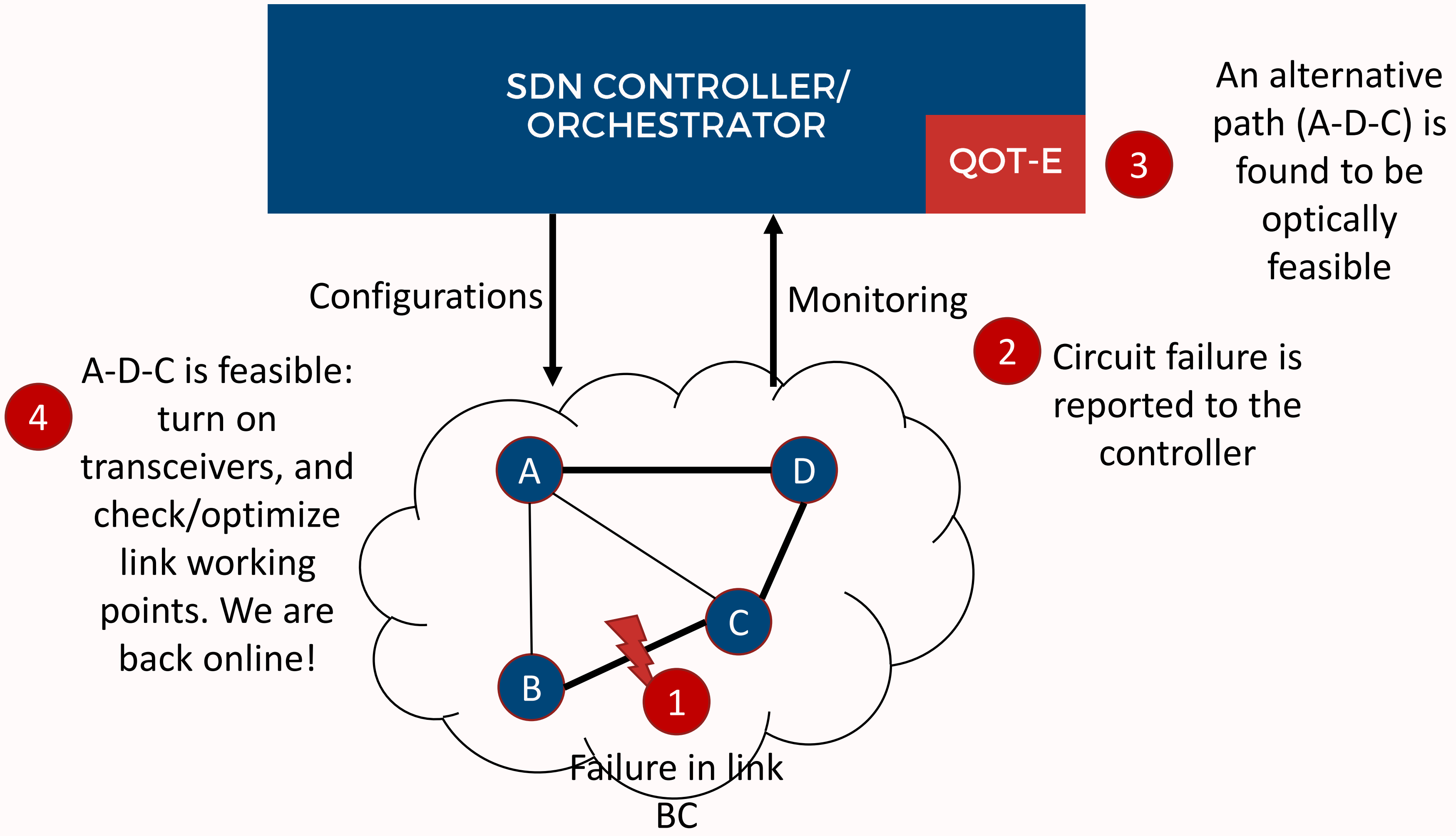


NETWORK CONTROL – CIRCUIT SETUP



OPTCOM

NETWORK CONTROL – CIRCUIT RESTORATION



QOT-E STRUCTURE

STRUCTURE OF THE QOT-E FOR 10G DISPERSION MANAGED LINKS

RELEVANT IMPAIRMENTS

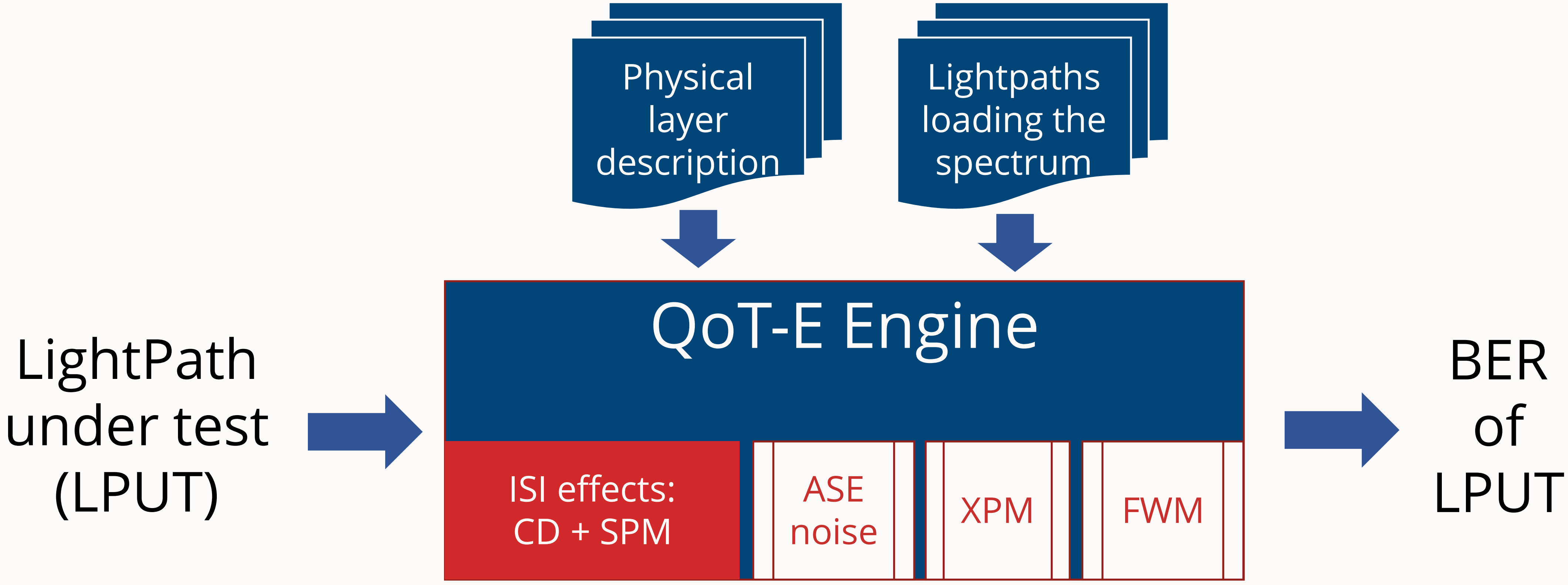
Relevant effects in ***single channel*** propagation:

- **Chromatic dispersion**: linear filter → Eye distortion (ISI)
- **SPM**: nonlinear effect → Eye distortion (ISI)
- **ASE noise**: AWGN → OSNR degradation

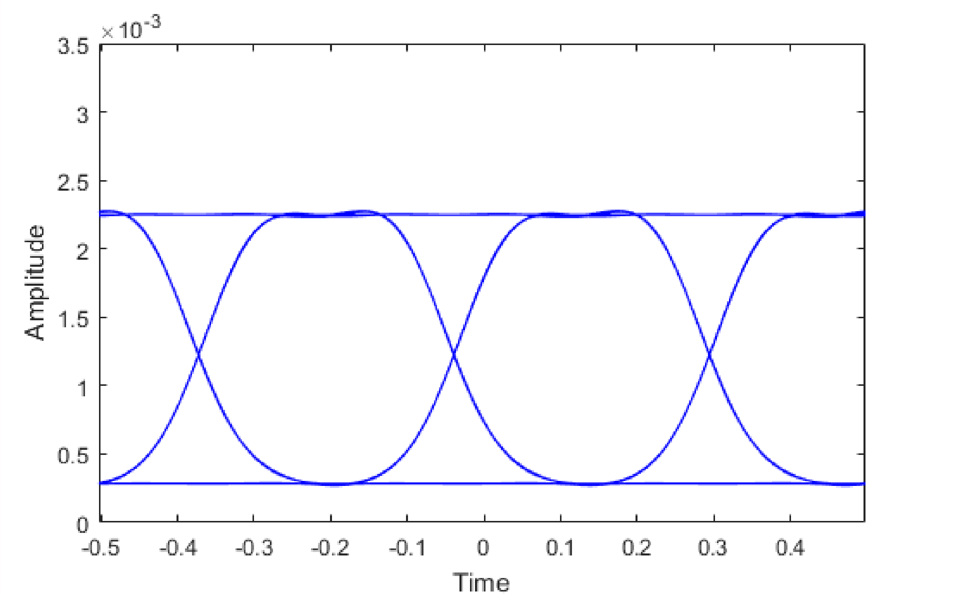
Relevant effects in ***multichannel*** propagation:

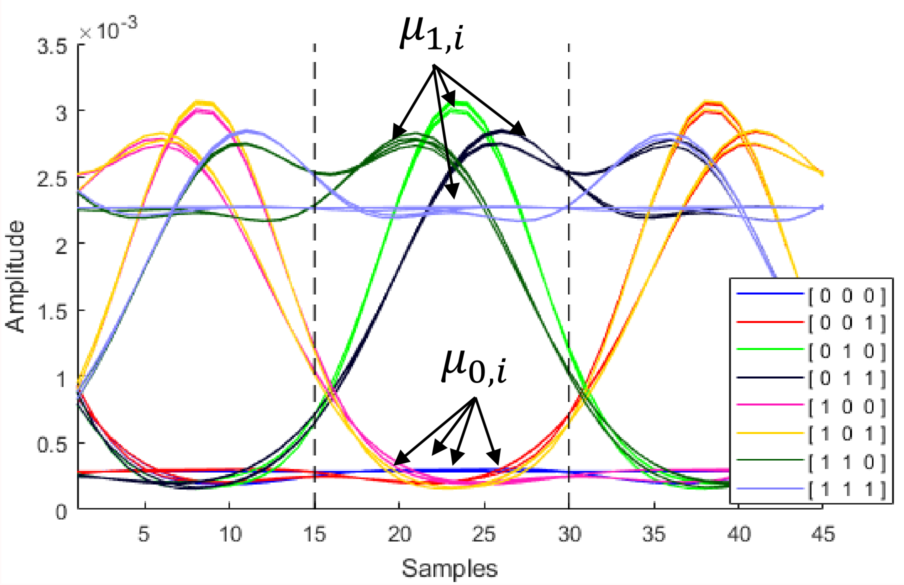
- **XPM**: nonlinear effect → OSNR degradation
  - Additive Gaussian Noise-like
- **FWM**: nonlinear effect → OSNR degradation
  - Additive Gaussian Noise-like

THE QOT-E TOOL



- **ISI**: introduces a memory of M bit.
- Assuming $M = 3$, the 0 and 1 levels $[\mu_{0,i}, \mu_{1,i}]$ of the received bit depend on the preceding and following bit

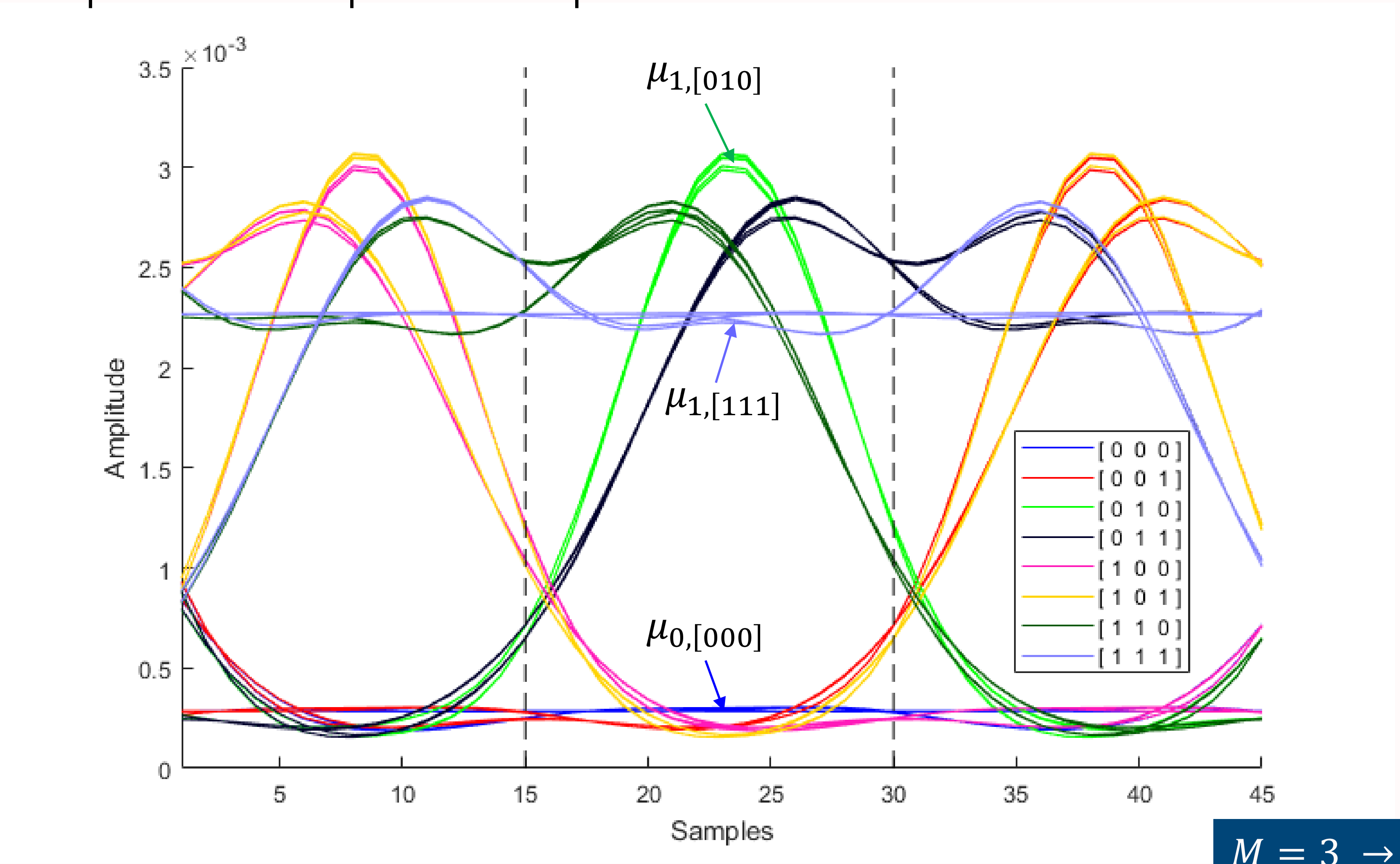




- **Key idea**: look at symbols of $M = 3$ bits to estimate the correct $\mu_{0,i}$ and $\mu_{1,i}$ levels

HOW TO DEAL WITH ISI

Transition diagram plots all the 8 possible bit patterns



$M = 3 \rightarrow 2^3 = 8$ symbols

BER = Sum of the 8 symbols BER contributions:

- $BER = \frac{1}{8}\{P_e(0_{Rx}|1_{Tx})|_{010} + P_e(0_{Rx}|1_{Tx})|_{011} + P_e(0_{Rx}|1_{Tx})|_{110} + P_e(0_{Rx}|1_{Tx})|_{111} + P_e(1_{Rx}|0_{Tx})|_{000} + P_e(1_{Rx}|0_{Tx})|_{001} + P_e(1_{Rx}|0_{Tx})|_{100} + P_e(1_{Rx}|0_{Tx})|_{101}\}$

$$\frac{1}{2} erfc\left(\frac{\boldsymbol{\mu_{1,[010]}} - V_{th}}{\sqrt{2}\cdot \boldsymbol{\sigma_{1,[010]}}}\right)$$

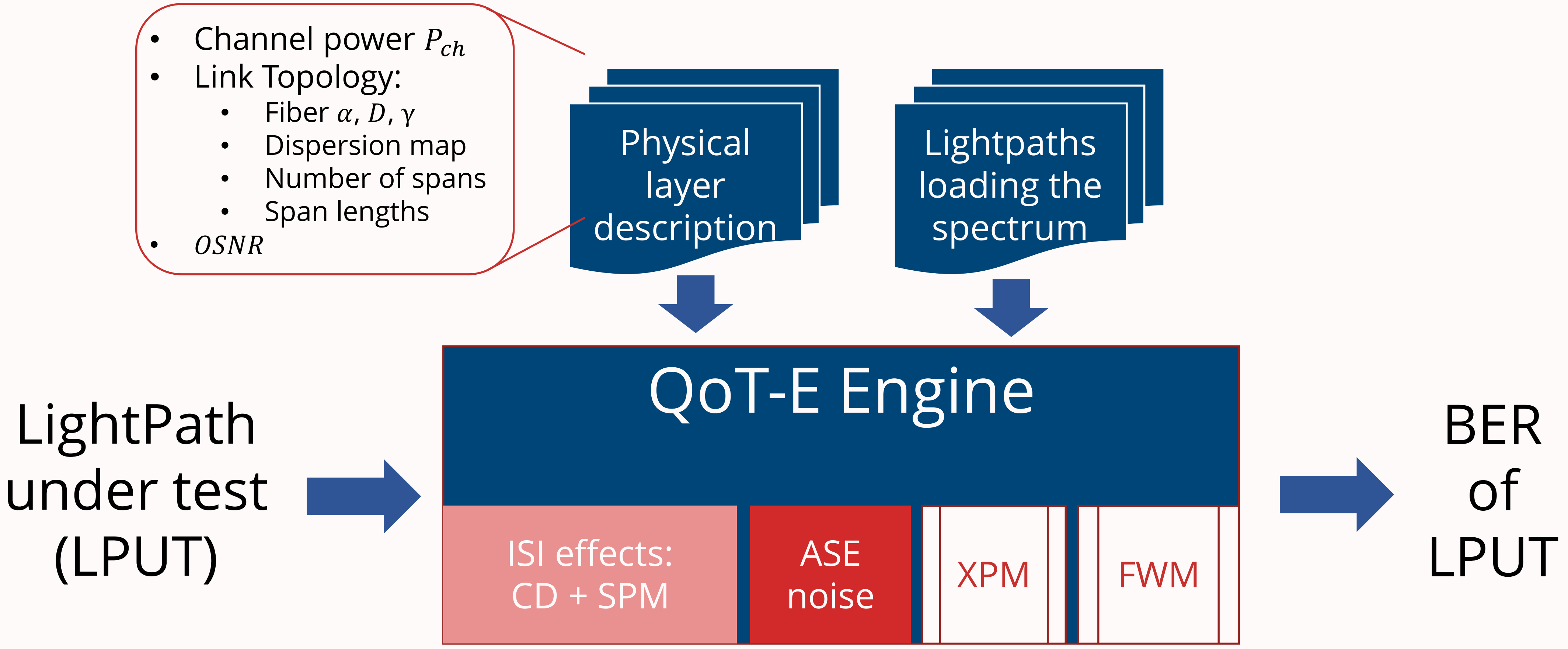
$$\frac{1}{2} erfc\left(\frac{V_{th} - \boldsymbol{\mu_{0,[100]}}}{\sqrt{2}\cdot \boldsymbol{\sigma_{0,[100]}}}\right)$$

$[\mu_{0,i}, \mu_{1,i}]$: 0 and 1 average levels due to SPM and CD

$$[\sigma_{0,i}, \sigma_{1,i}] = \sqrt{\sigma^2_{ASE} + \sigma^2_{XPM} + \sigma^2_{FWM}}$$

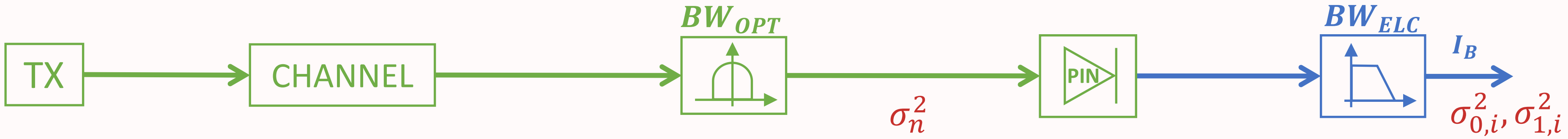
- 0 and 1 levels standard deviations
- Estimated ***analytically***

THE QOT-E TOOL



ASE VARIANCE ESTIMATION

- We compute the $\boldsymbol{\sigma_{0,i}}$ and $\boldsymbol{\sigma_{1,i}}$ for each $OSNR$ and $[\boldsymbol{\mu_{0,i}}, \boldsymbol{\mu_{1,i}}]$ levels considering that:



$$I_B = \mu + 2\sqrt{\mu} n_{ASE,XI} + \left[n_{ASE,XI}^2 + n_{ASE,XQ}^2 + n_{ASE,YI}^2 + n_{ASE,YQ}^2\right]$$

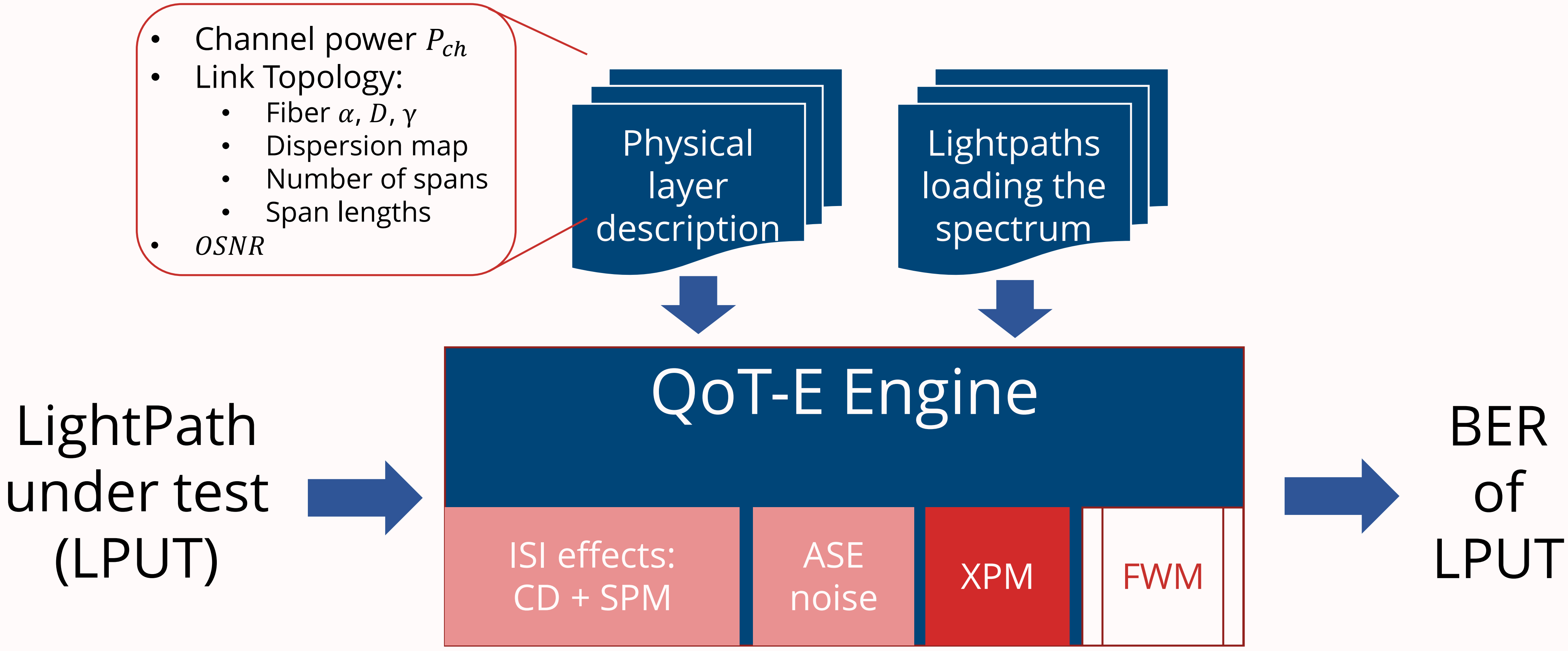
Signal-Noise beating variance
(Gaussian distributed)

Squared-Noise variance
(Chi-squared distributed, quasi-Gaussian distributed after Bessel filtering)

$$\sigma^2 \cong Var[I_B] = \sigma_{GSS}^2 + \sigma_{CHI}^2$$

$$\sigma_{n_{T,F}}^2 = \frac{P_{TX}}{OSNR} = f(OSNR) \longleftarrow$$ ***Optical Noise Variance after Optical Filter***

THE QOT-E TOOL



XPM ANALYTICAL MODEL

The goal is to obtain an analytical expression for the ***XPM*-induced noiselike variance**, using the following approach:

$$\sigma^2_{\mathrm{XPM},i} = \bar{P}(0)^2 \sum_{j=1, j\neq i}^{M} \frac{1}{2\pi} \int_{-\infty}^{+\infty} |H_{\mathrm{XPM},ij}(\omega)|^2 \, \mathrm{PSD}_j(\omega) \, |H_{\mathrm{tot,filter}}(\omega)|^2$$

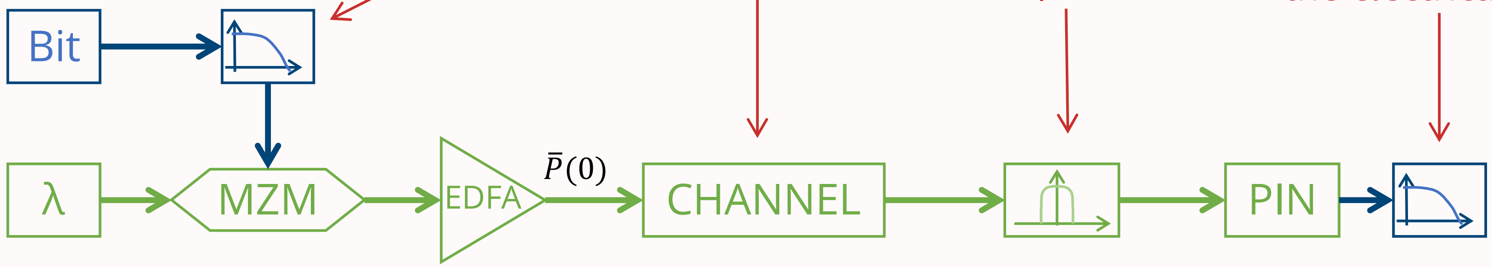
Total number of channels

Average power at the beginning of the fiber

Power spectral density of the pump channel *j*

Transfer function of the optical filter

Transfer function of the electrical filter

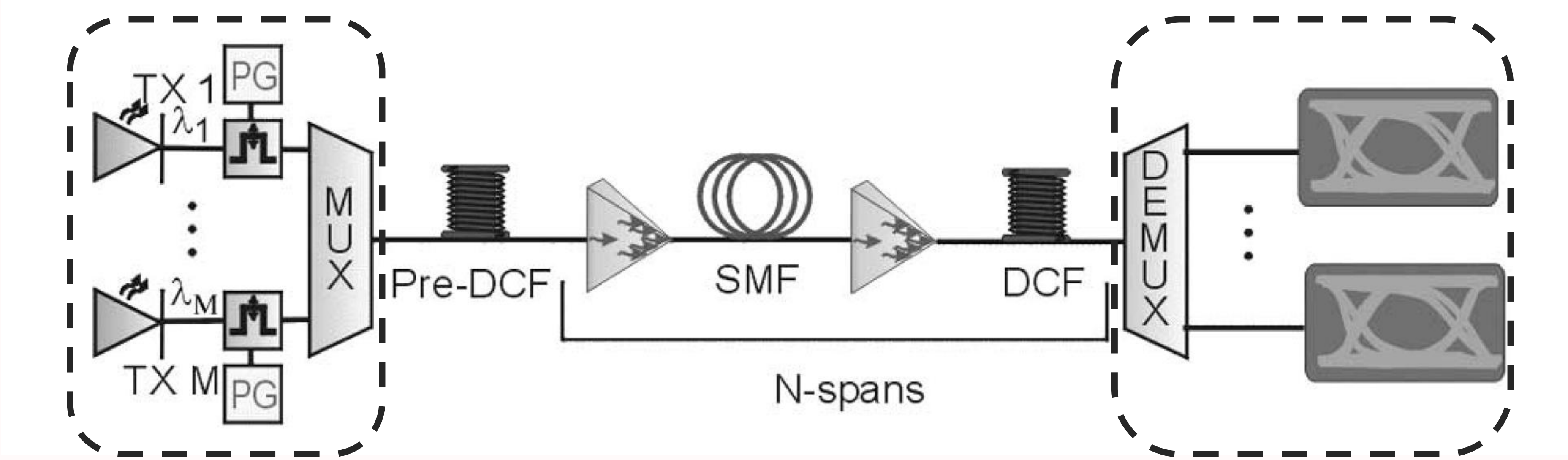


[1] S. Pachnicke et al., "Fast Analytical Assessment of the Signal Quality in Transparent Optical Networks", Journal of Lightwave Technology, Vol. 24, No. 2, 2006.

QOT-E VALIDATION

EXPERIMENTAL SETUP

In the PhotonLab of ISMB, we emulated the setup depicted in this picture [1]



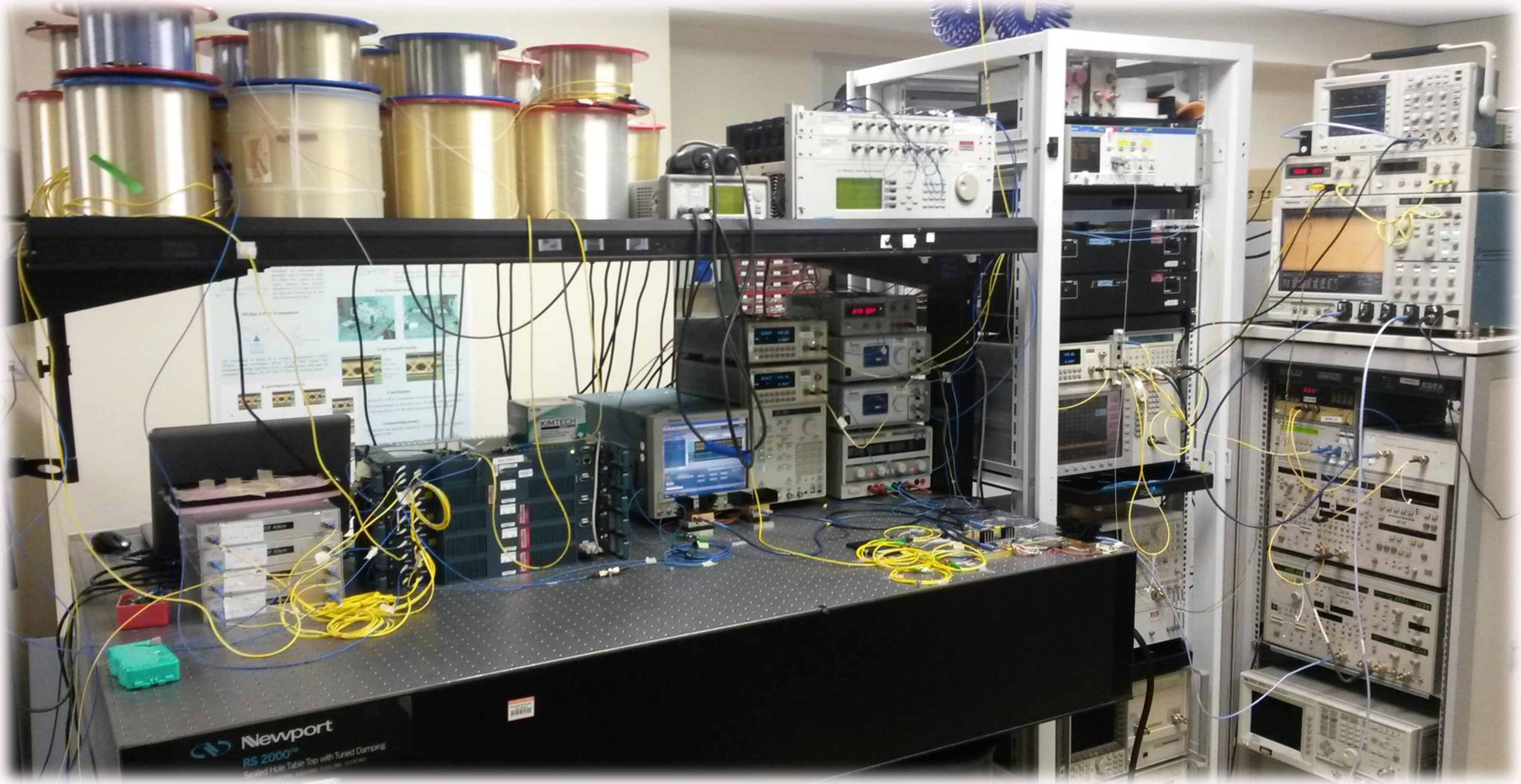
TRANSMITTER

RECEIVER

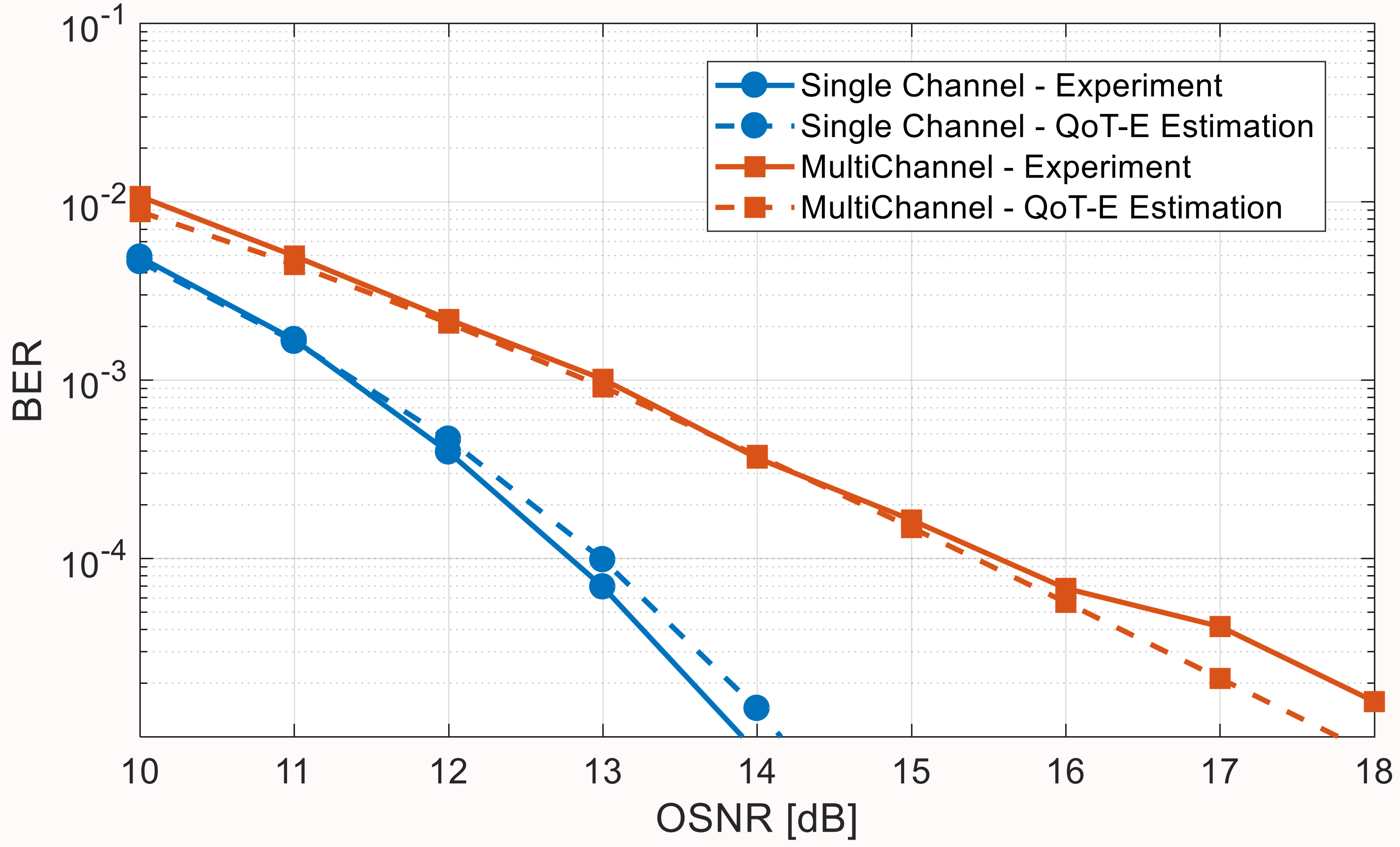
[1] S. Pachnicke et al., "Fast Analytical Assessment of the Signal Quality in Transparent Optical Networks", Journal of Lightwave Technology, Vol. 24, No. 2, February 2006.

EXPERIMENTAL SETUP

… A pic of our setup:

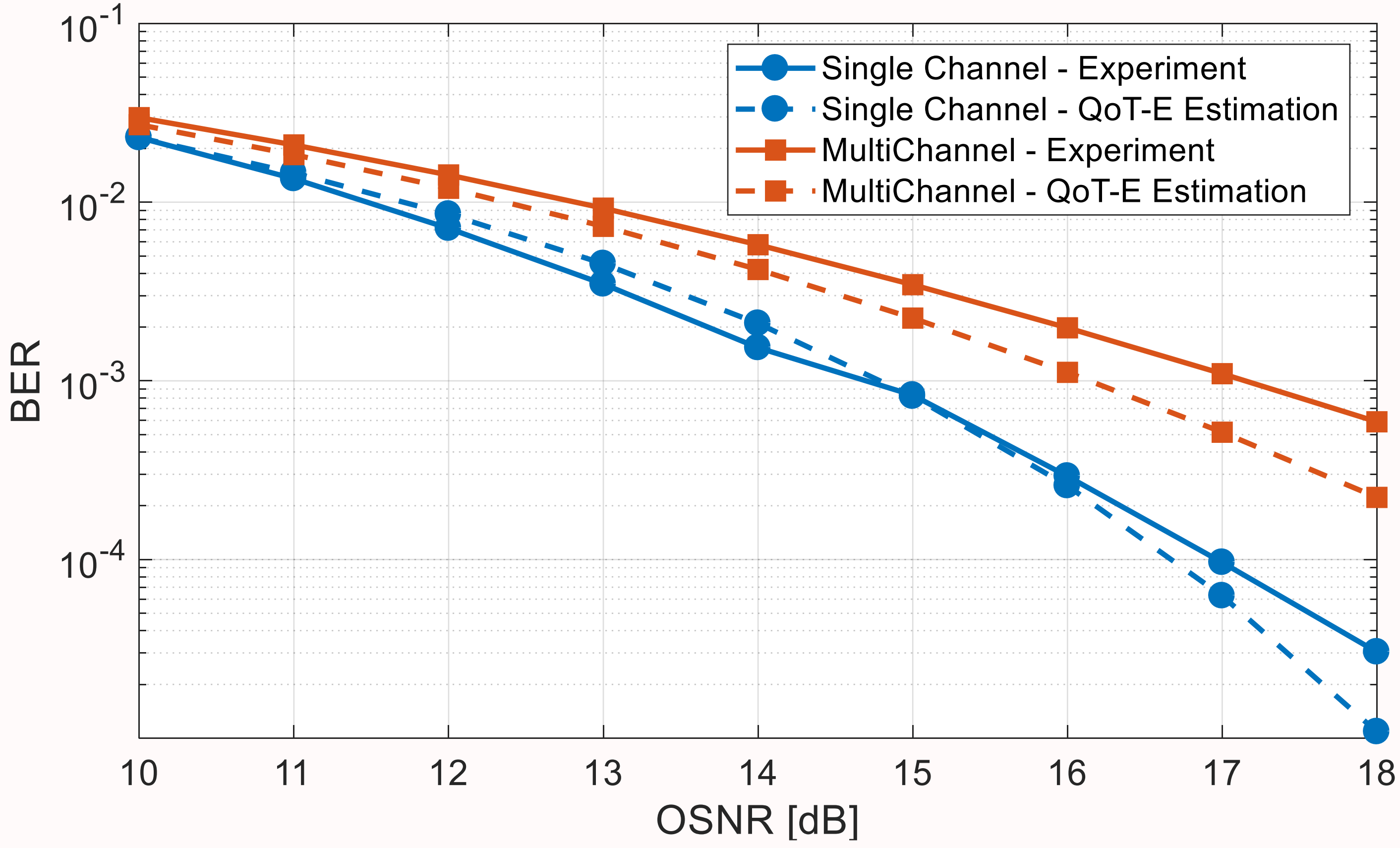


MULTI-CHANNEL BER ESTIMATION: SINGLE MODE FIBER



- SMF 16 spans
- Inline Residual: 0 ps/nm
- Total Accumulated Dispersion: 700 ps/nm

MULTI-CHANNEL BER ESTIMATION: TRUEWAVE



- TrueWave 16 spans
- Inline Residual: 154 ps/nm
- Total Accumulated Dispersion: 864 ps/nm

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QOT-E APPLICATIONS: POWER MASK

AN EXAMPLE OF QOT-E ENABLED PERFORMANCE ESTIMATION

UNALLOCATED MARGIN

Unallocated Margin

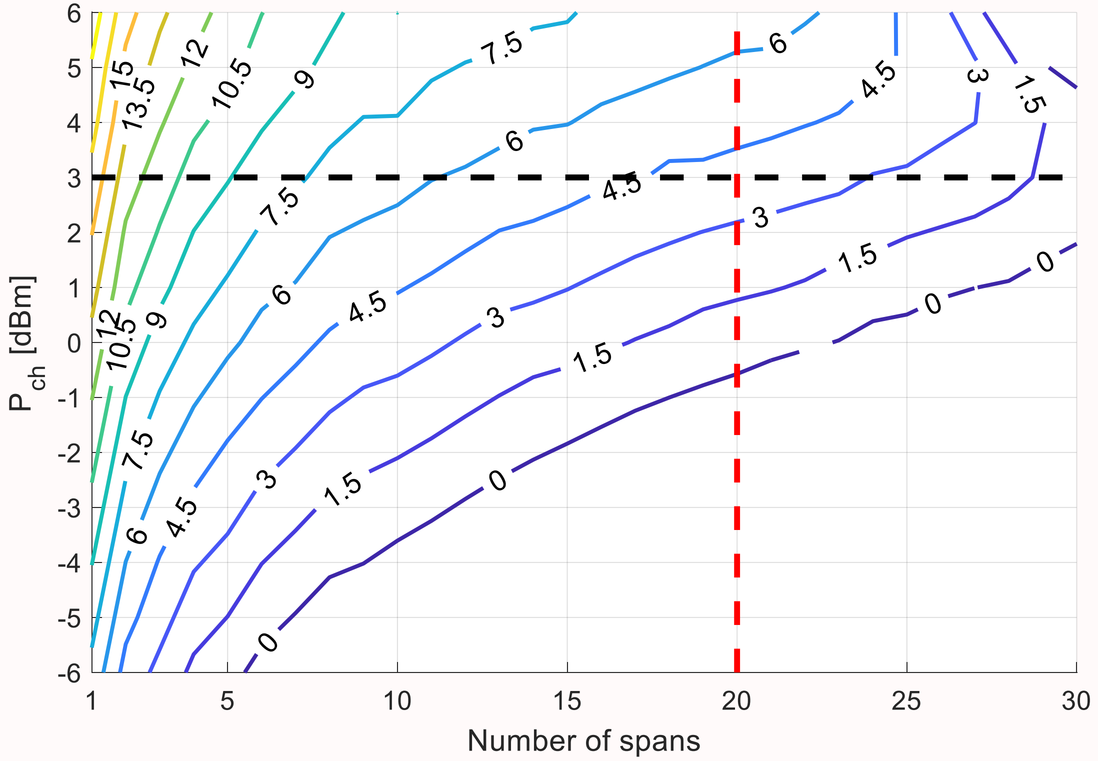
Difference between the ***Available OSNR*** at the receiver and the ***Required OSNR*** to get a certain target BER [1]

Power Mask

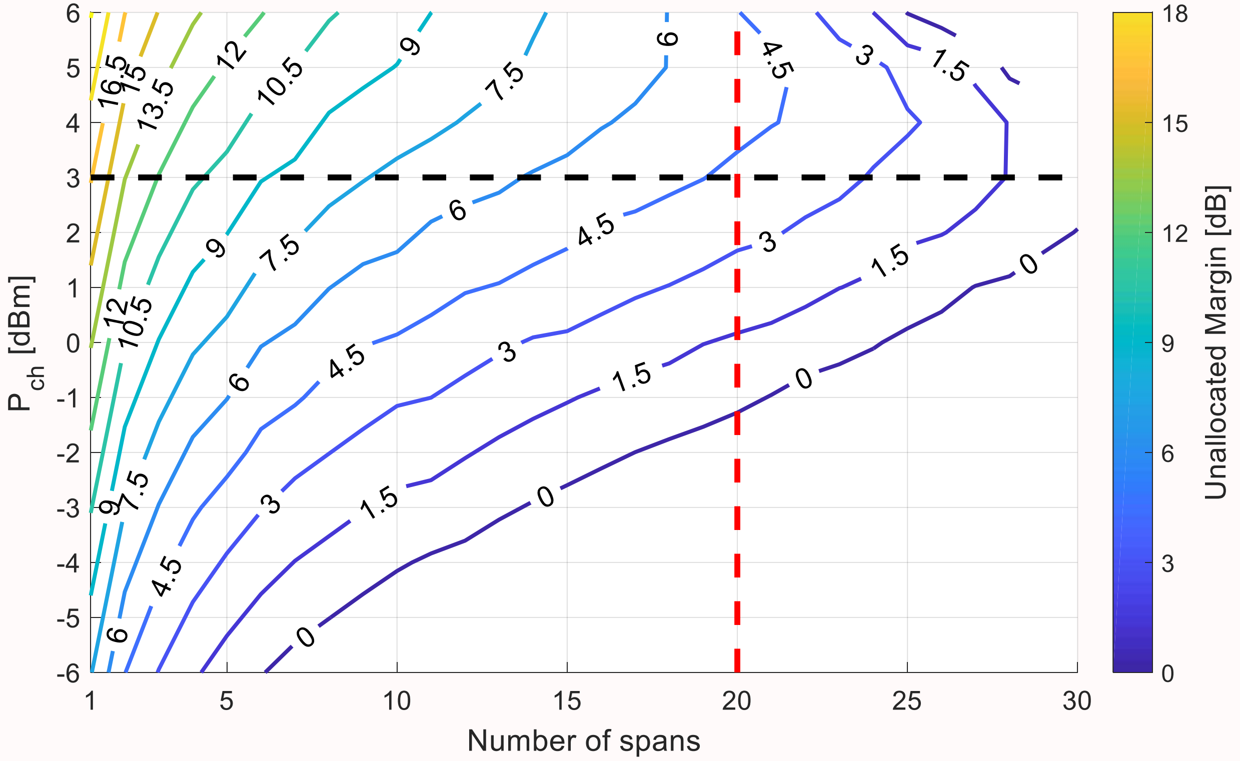
Set of contour lines of the Unallocated Margin vs **Channel Power** and **Number of Spans** defining the network dimension.

POWER MASK - 50 GHZ FREQUENCY SPACING

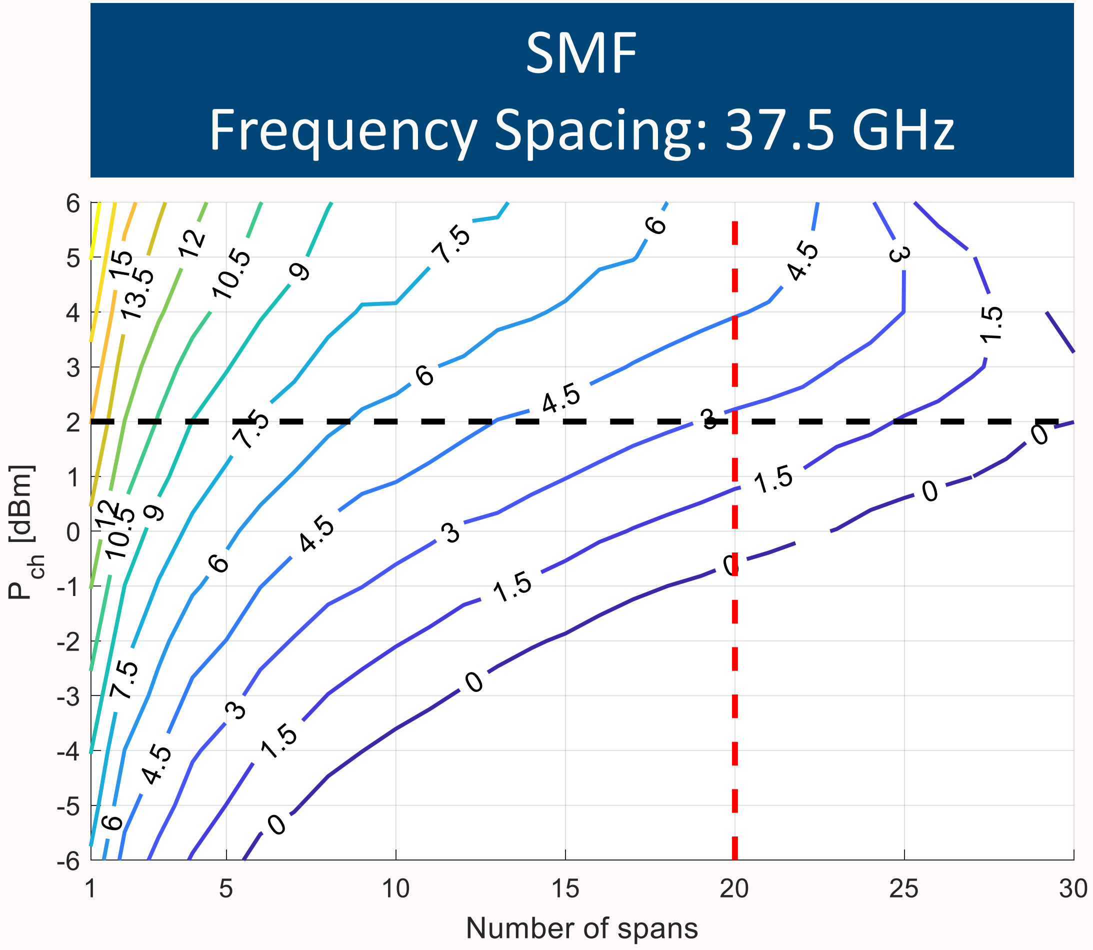
SMF
Frequency Spacing: = 50 GHz

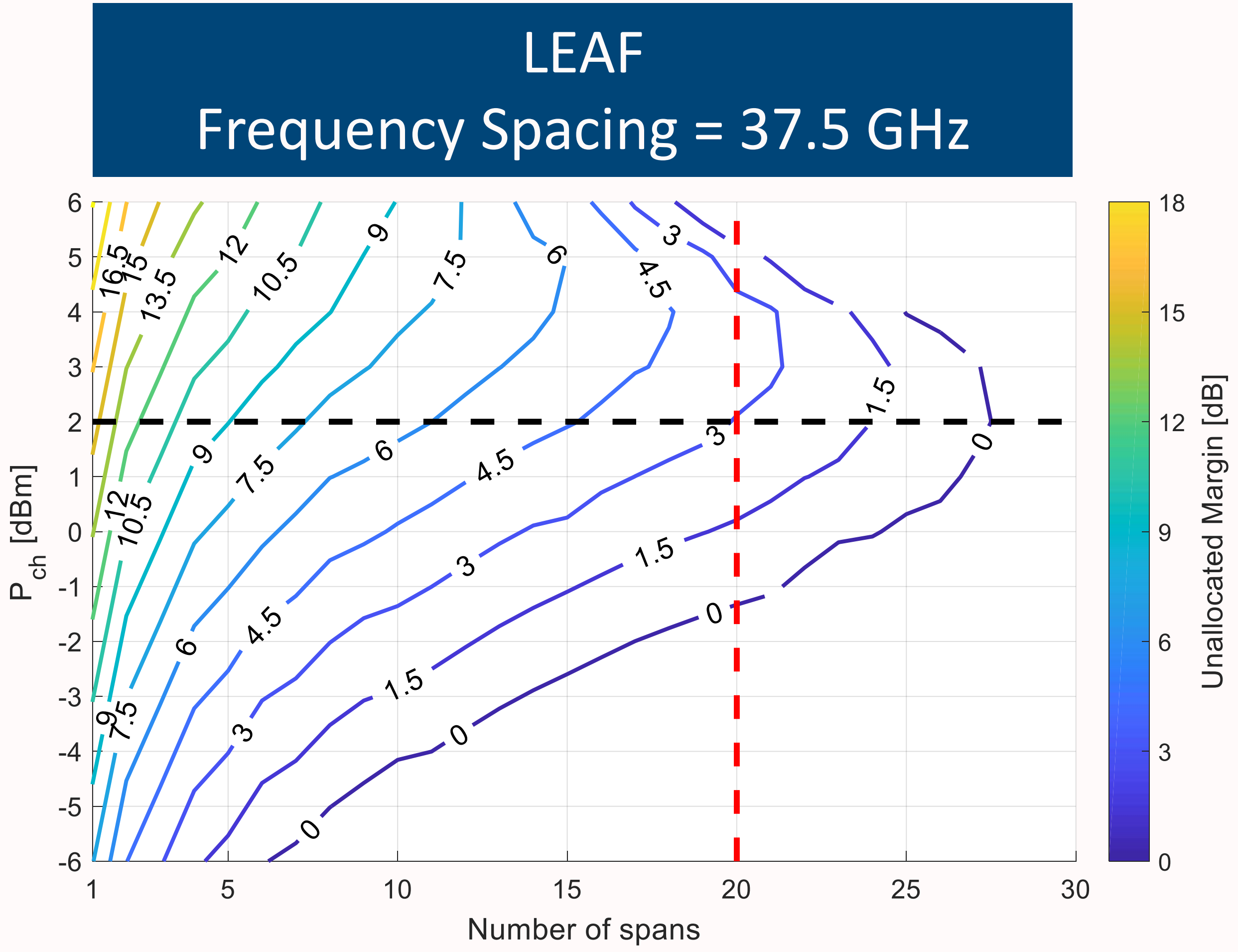


LEAF
Frequency Spacing: 50 GHz



POWER MASK - 37,5 GHZ FREQUENCY SPACING





CONCLUSIONS

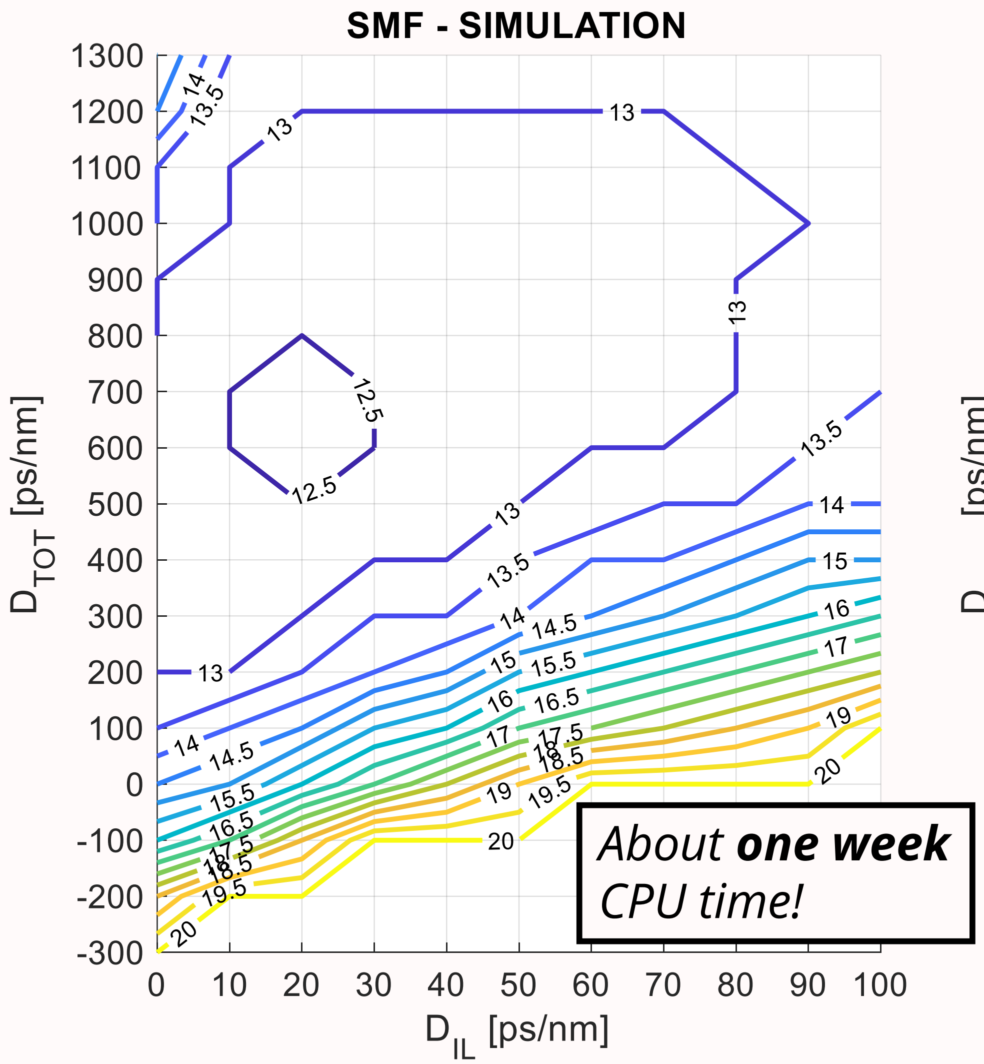
CONCLUSIONS

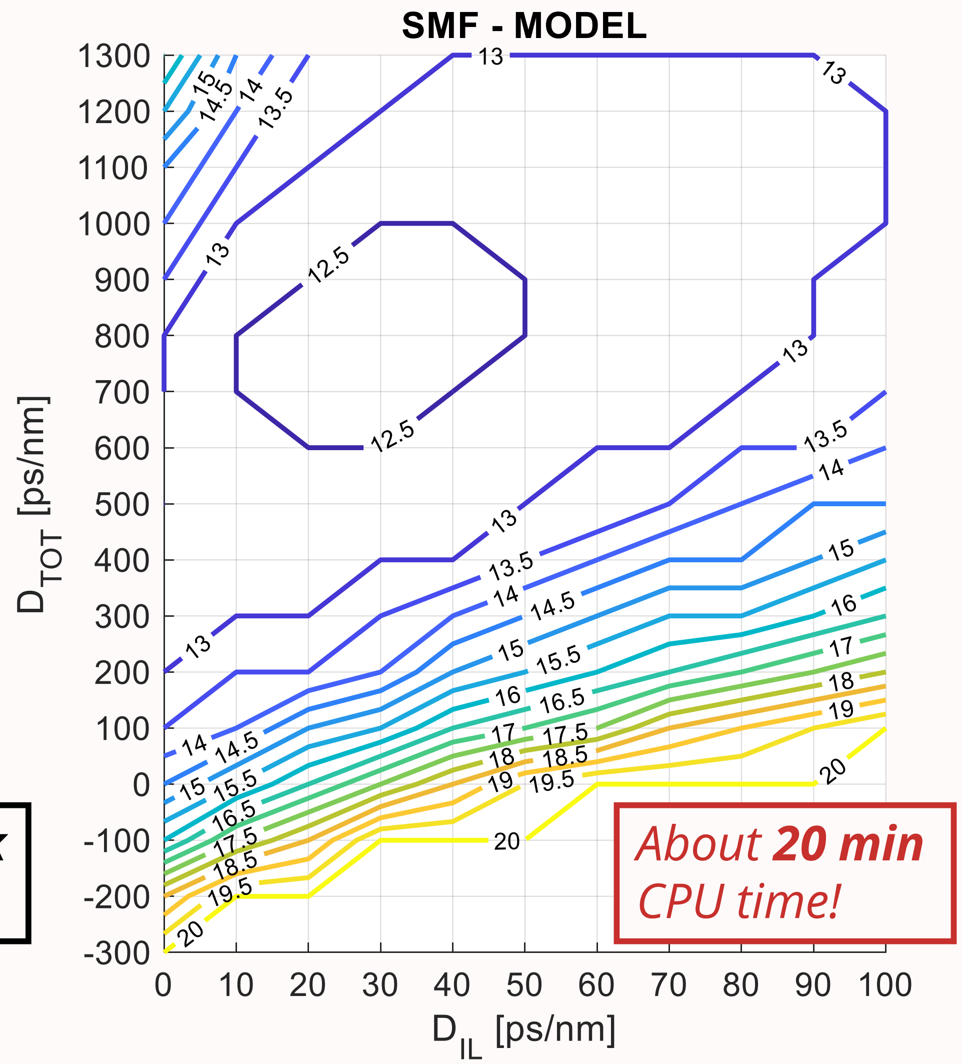
- We developed a QoT-E for IMDD over DM links allowing realiable and real-time performance estimation
- QoT Estimation will be pivotal to enable physical layer awareness at the networking level
- This will allow:
  - Faster network design and upgrade iterations
  - Enhanced Flexibility and Optimization in network operations such as
    - Circuit turn up
    - Proactive reactions to failures
    - Improved Path Computation (capacity aware)

THANK YOU FOR YOUR ATTENTION!

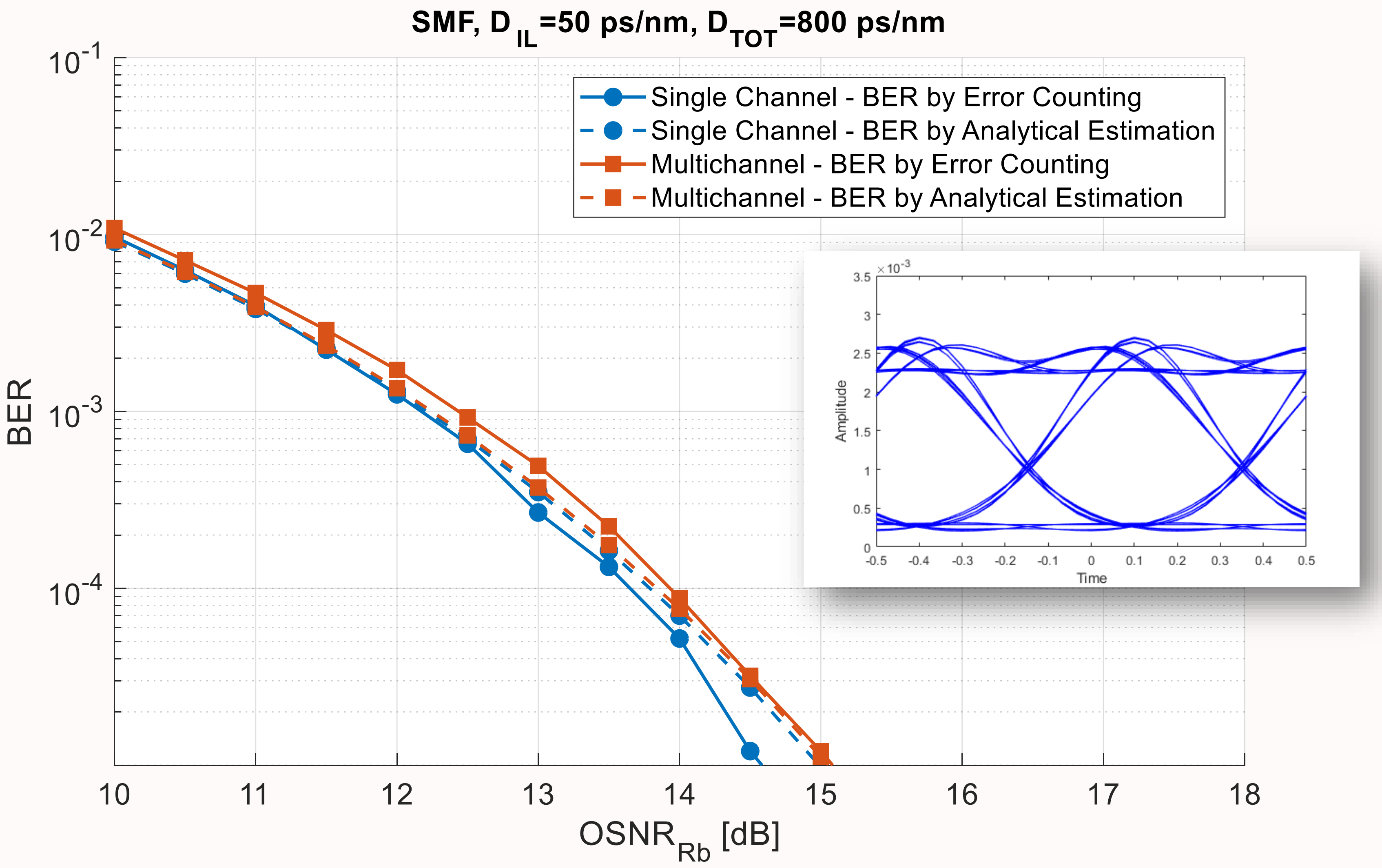
BACKUP SLIDES

MULTI-CHANNEL BER ESTIMATION: SMF

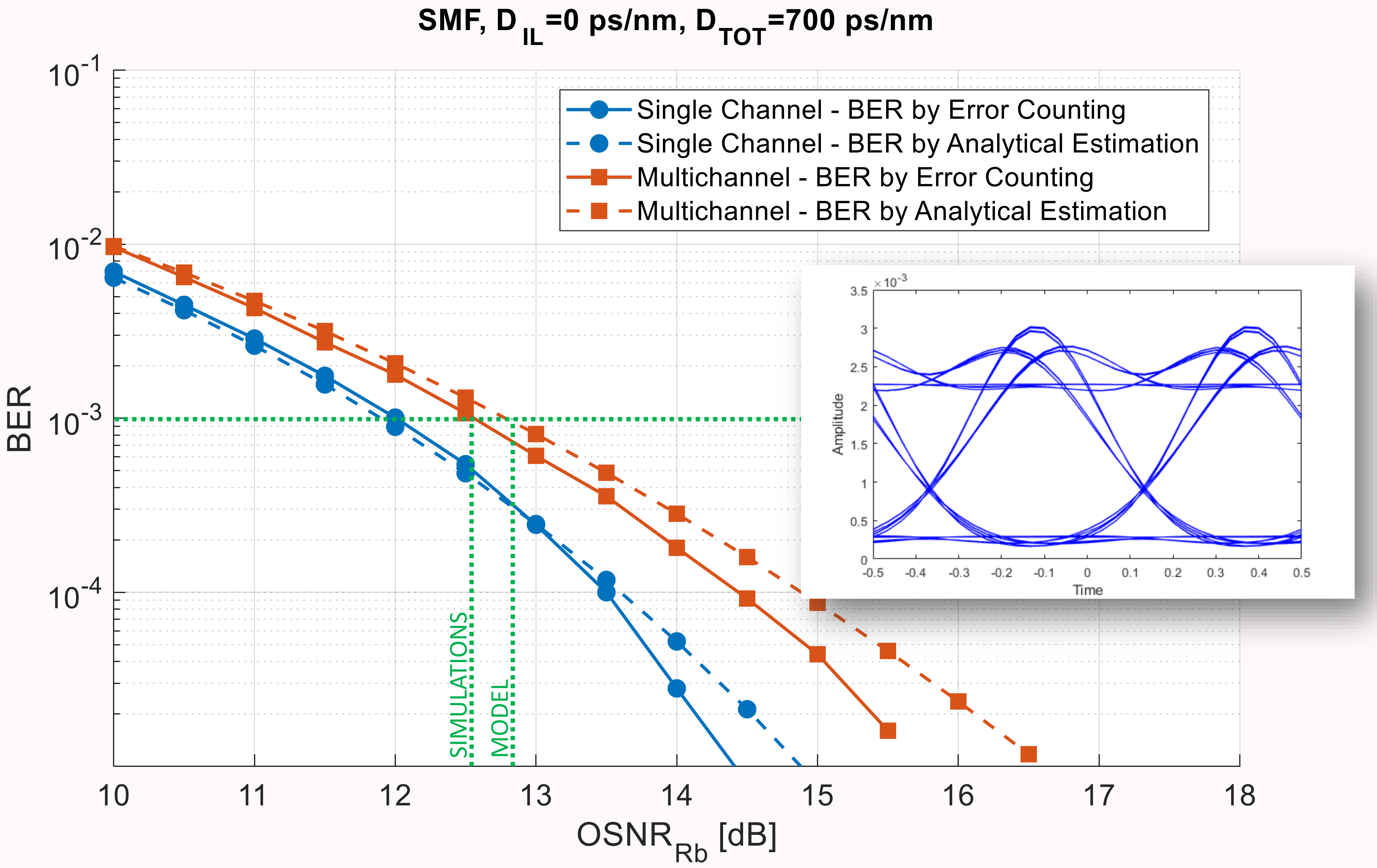




MULTI-CHANNEL BER ESTIMATION: SMF



MULTI-CHANNEL BER ESTIMATION: SMF



MULTI-CHANNEL BER ESTIMATION: TW

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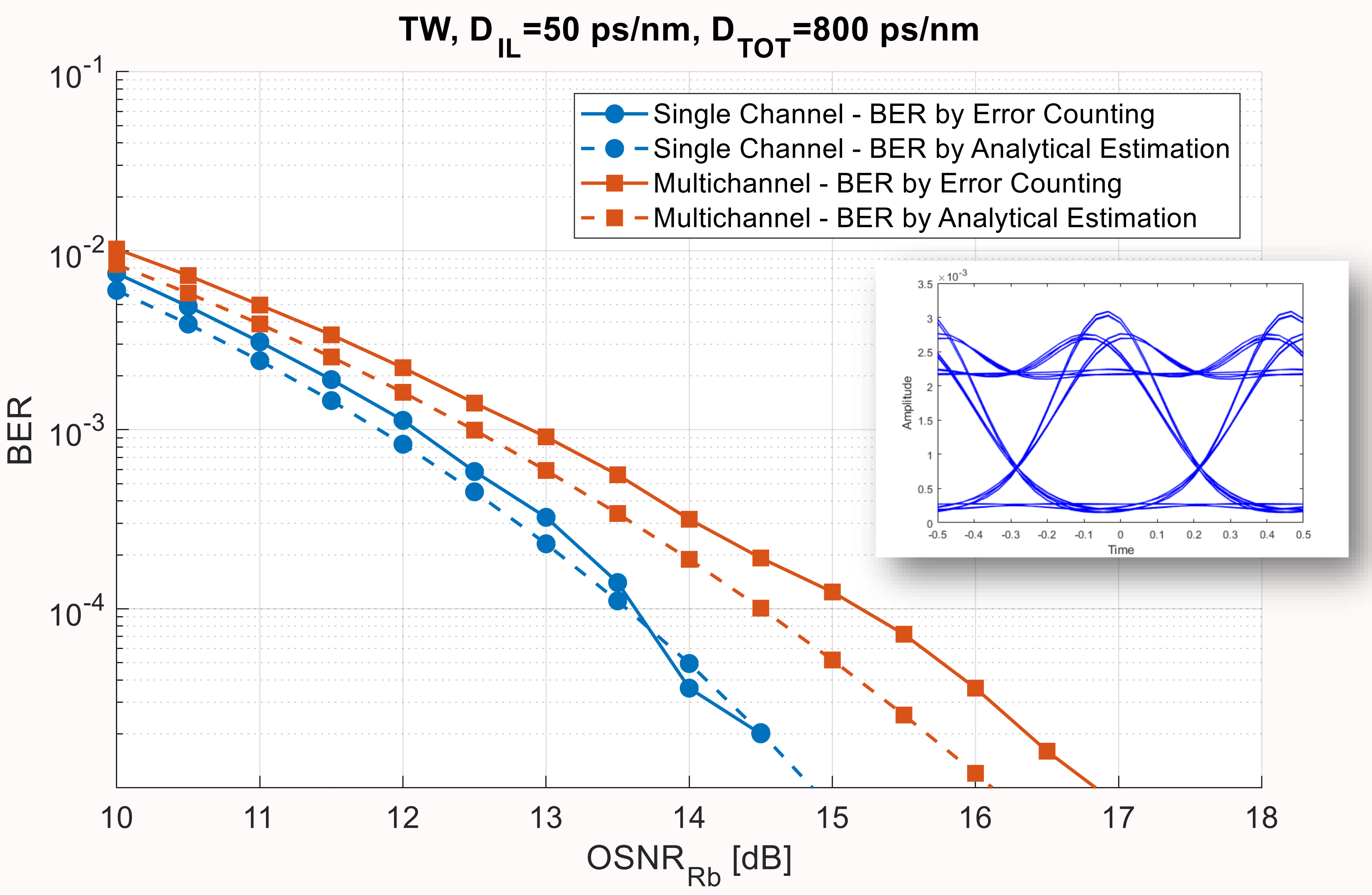
ISMB Istituto Superiore Mario Boella



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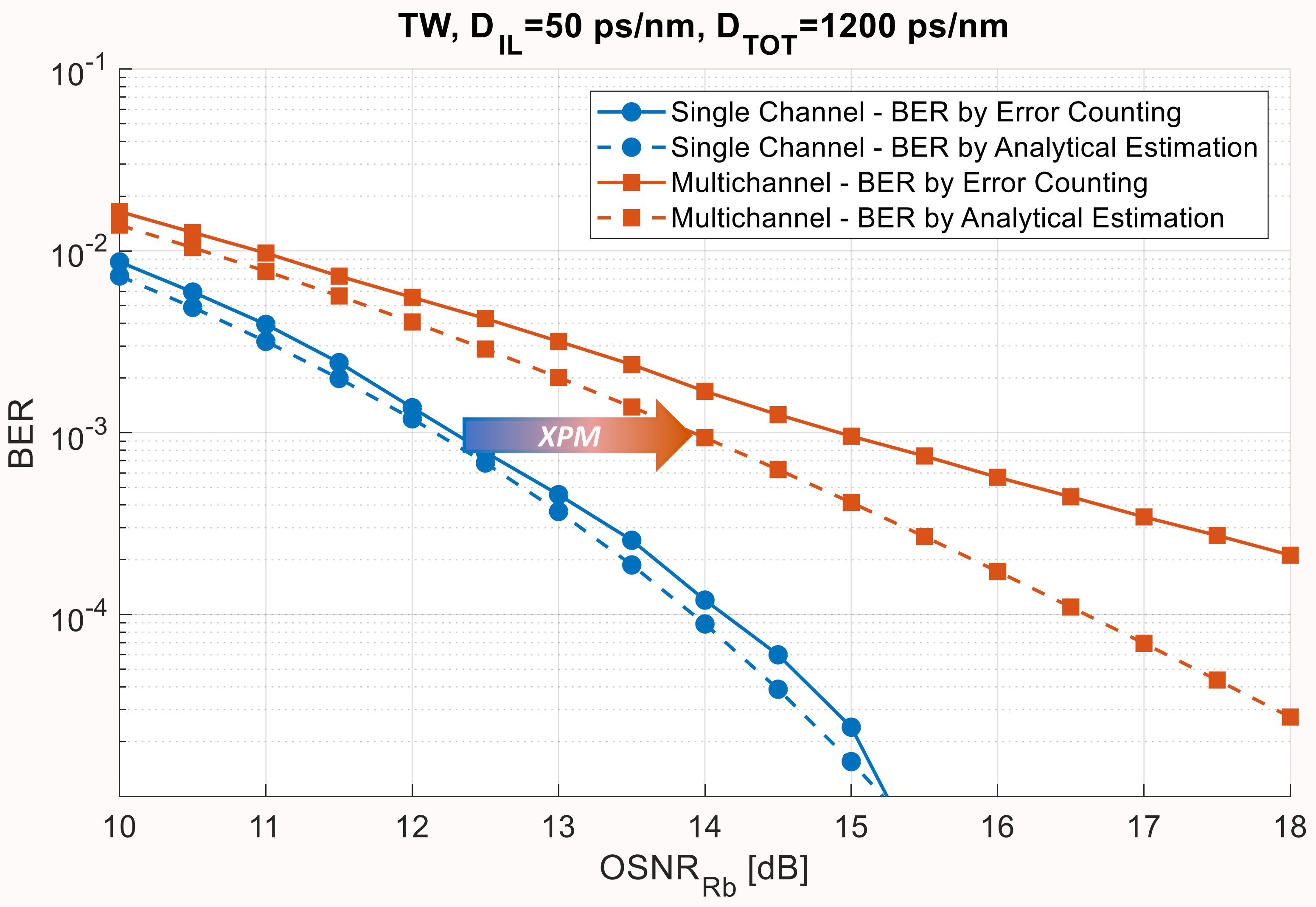
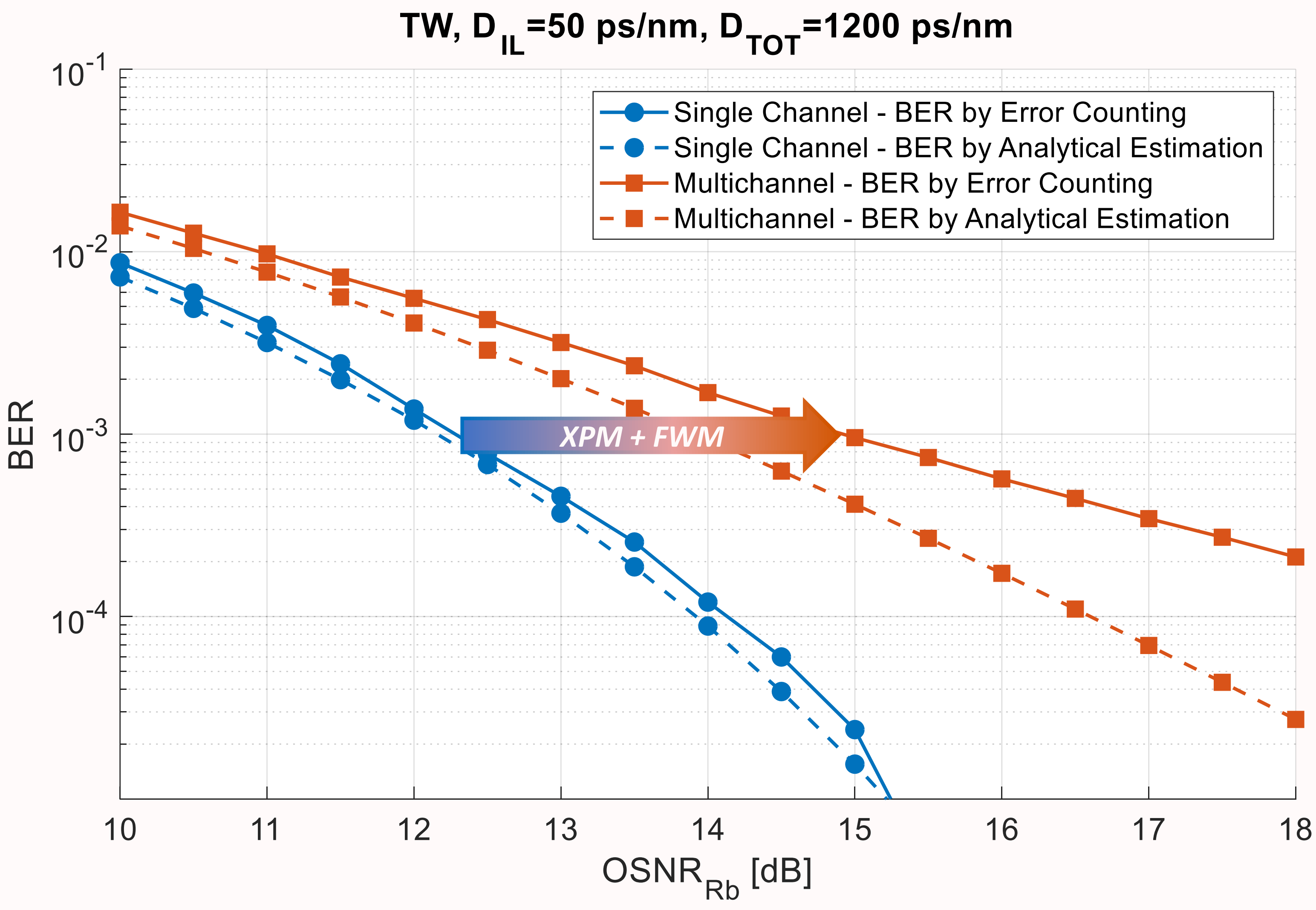
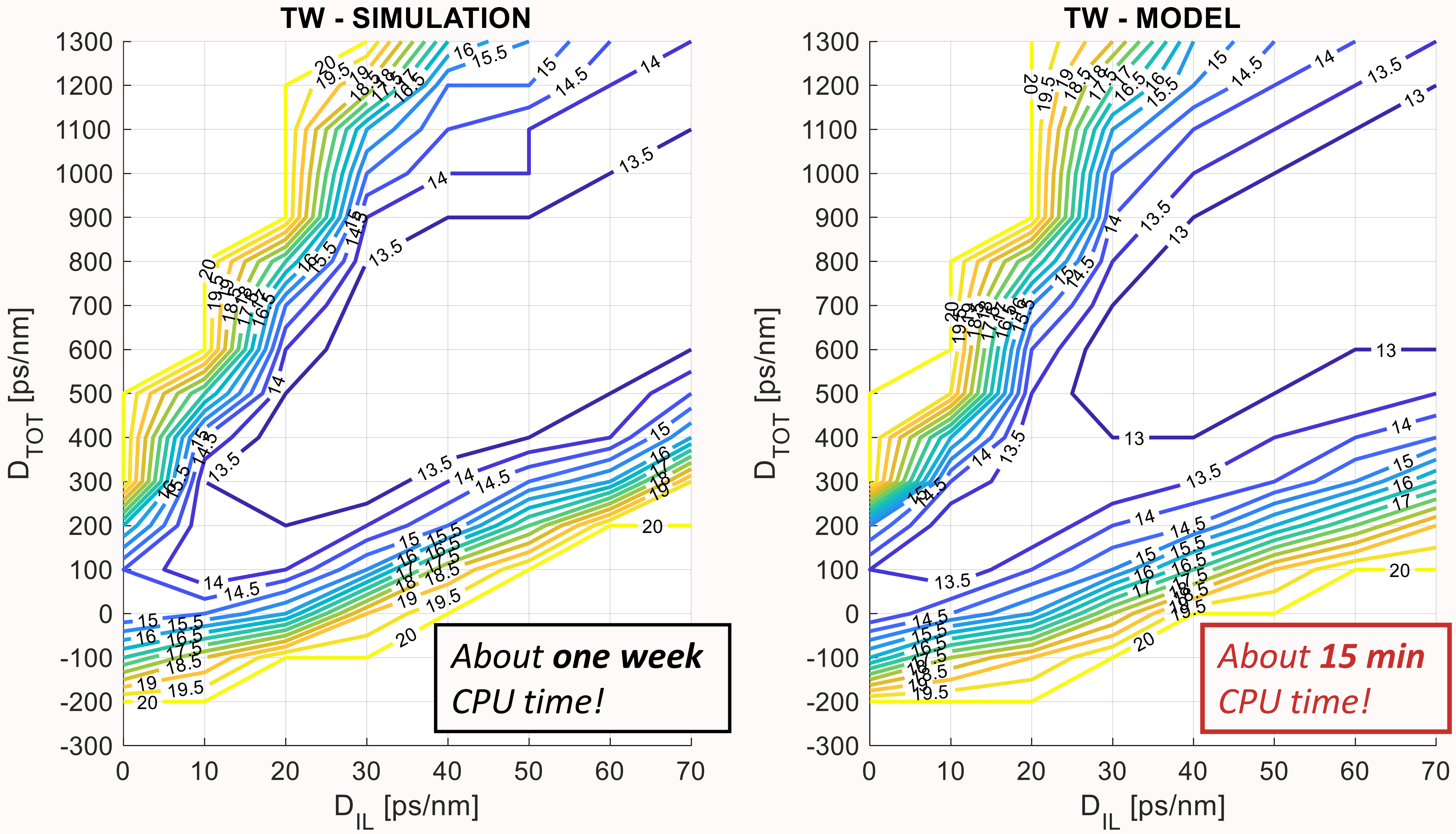


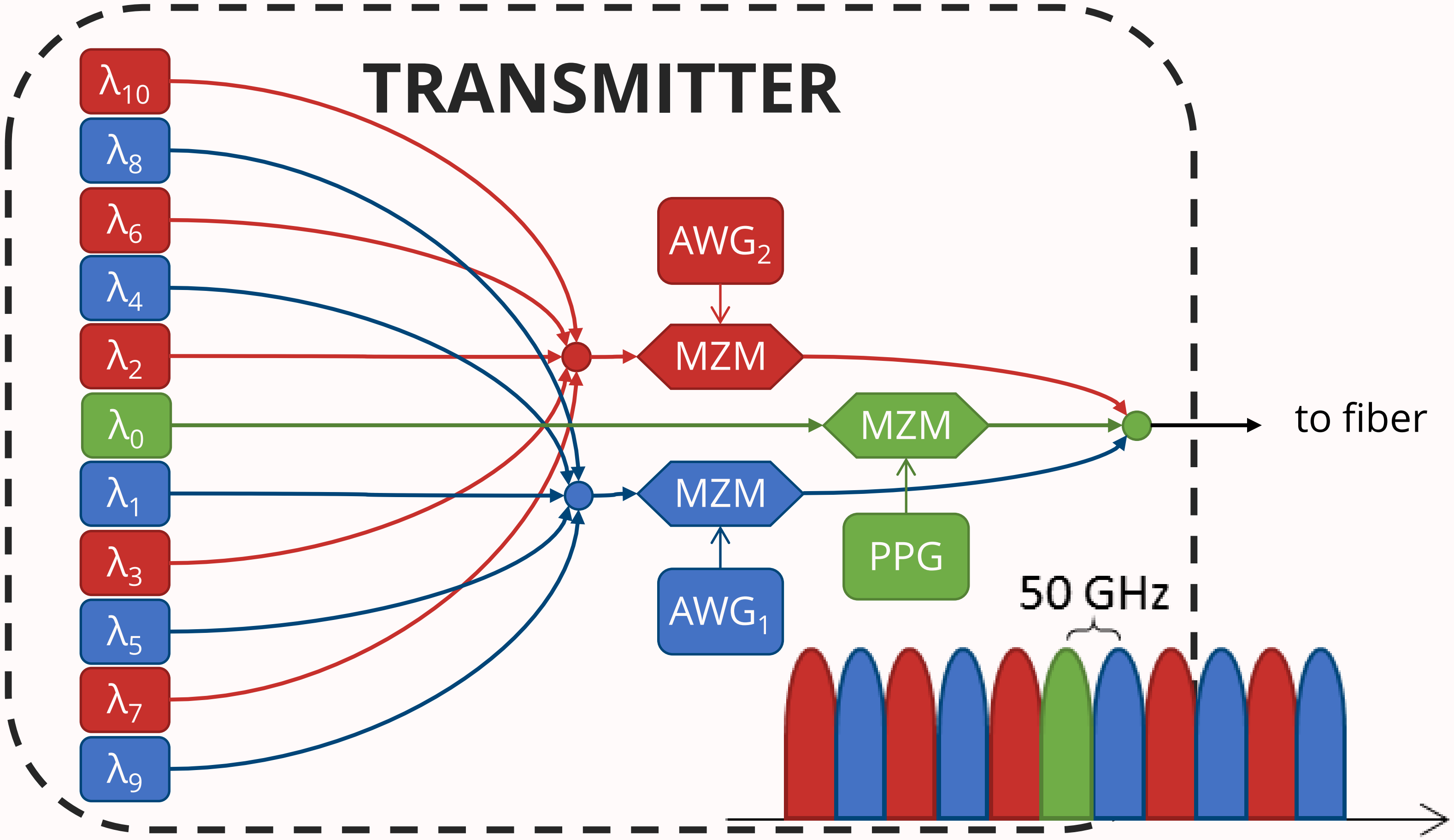
MULTI-CHANNEL BER ESTIMATION: TW



MULTI-CHANNEL BER ESTIMATION: TW

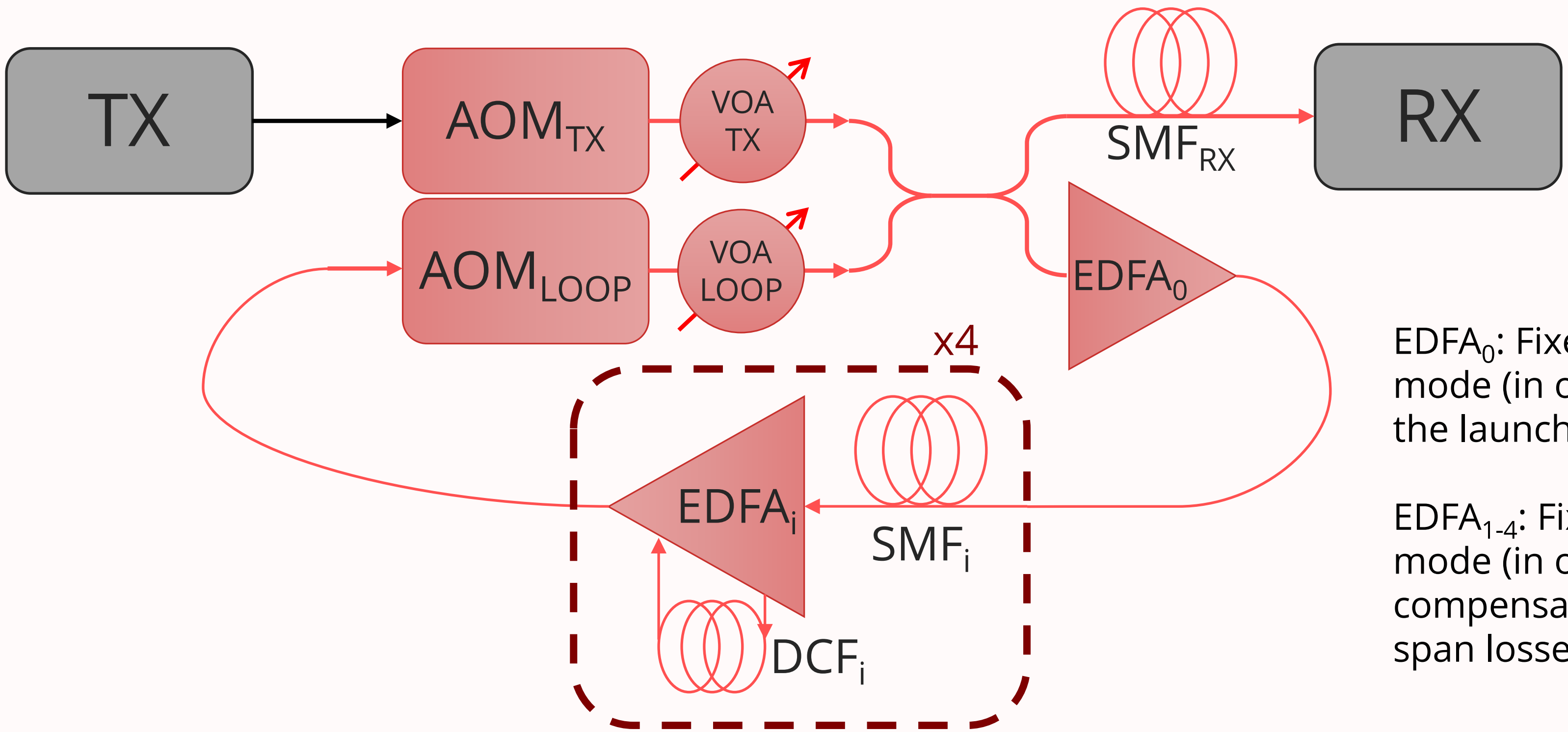


The transmitter is composed by 1 channel under test and 10 interfering channels. They are independently modulated and then coupled into the system.



EXPERIMENTAL SETUP – FIBER LOOP

The spans are placed inside a recirculating fiber loop, in order to emulate the signals propagation through 4, 8, 12, 16… spans. The loop is composed as depicted in this slide:

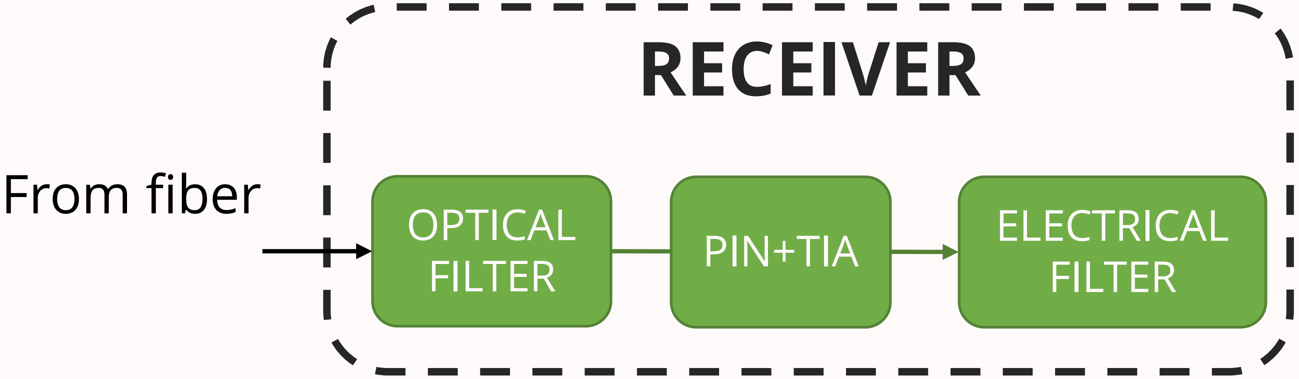


EDFA$_0$: Fixed POWER mode (in order to fix the launch power)

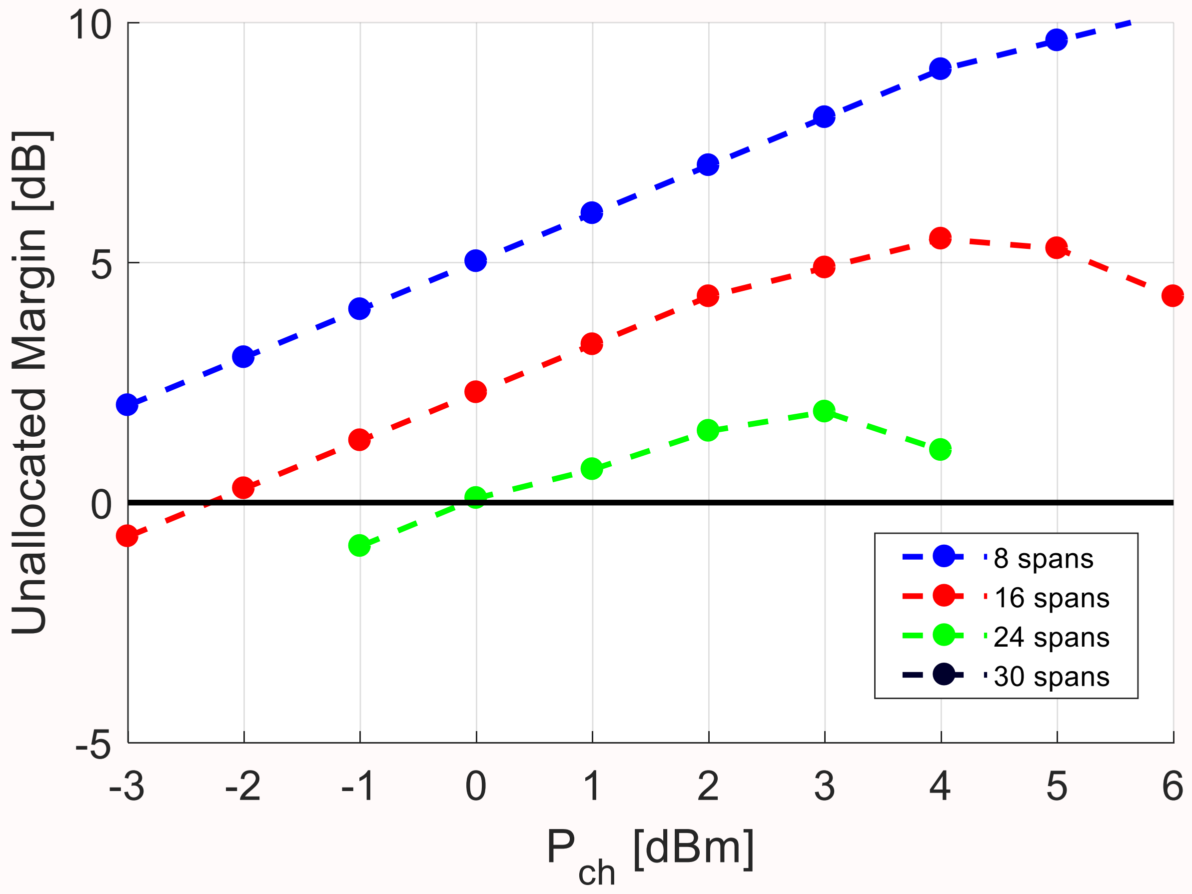
EDFA$_{1-4}$: Fixed GAIN mode (in order to compensate for the span losses)

EXPERIMENTAL SETUP - RECEIVER

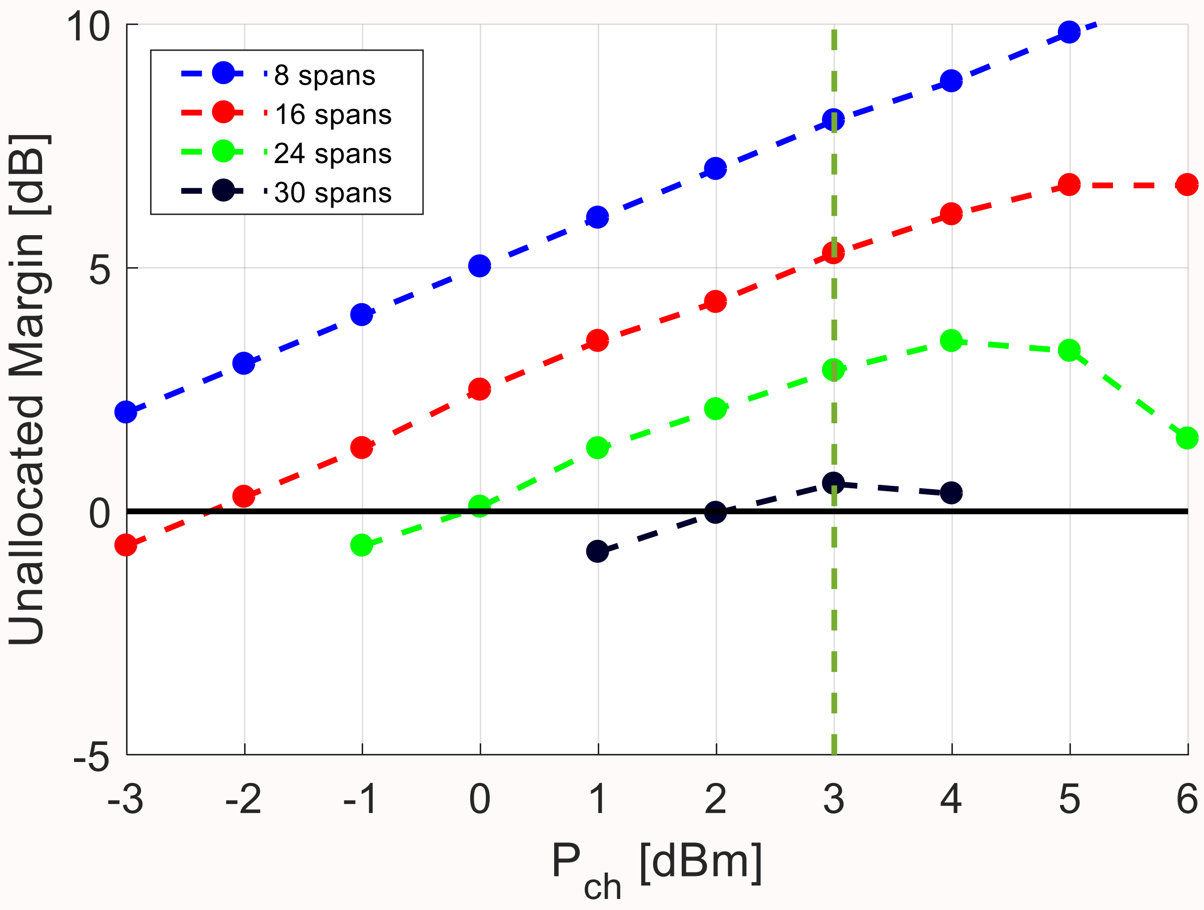
The receiver is composed by a band-pass optical filter, an optical receiver (PIN+TIA) and a low-pass electrical filter.



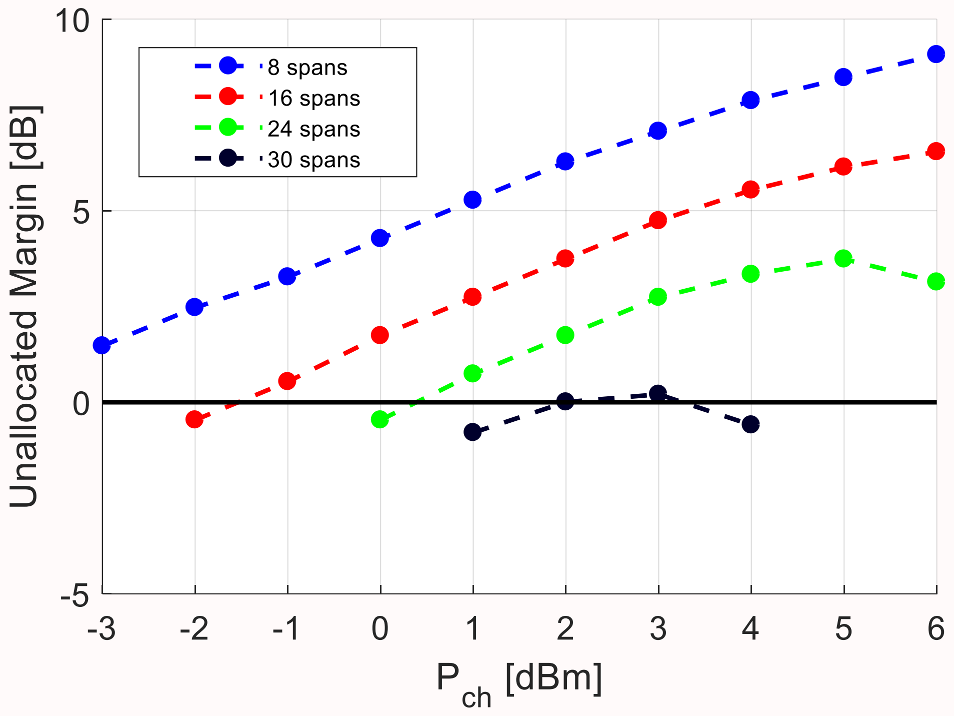
MARGIN VS PCH LEAF 50PS DF37,5



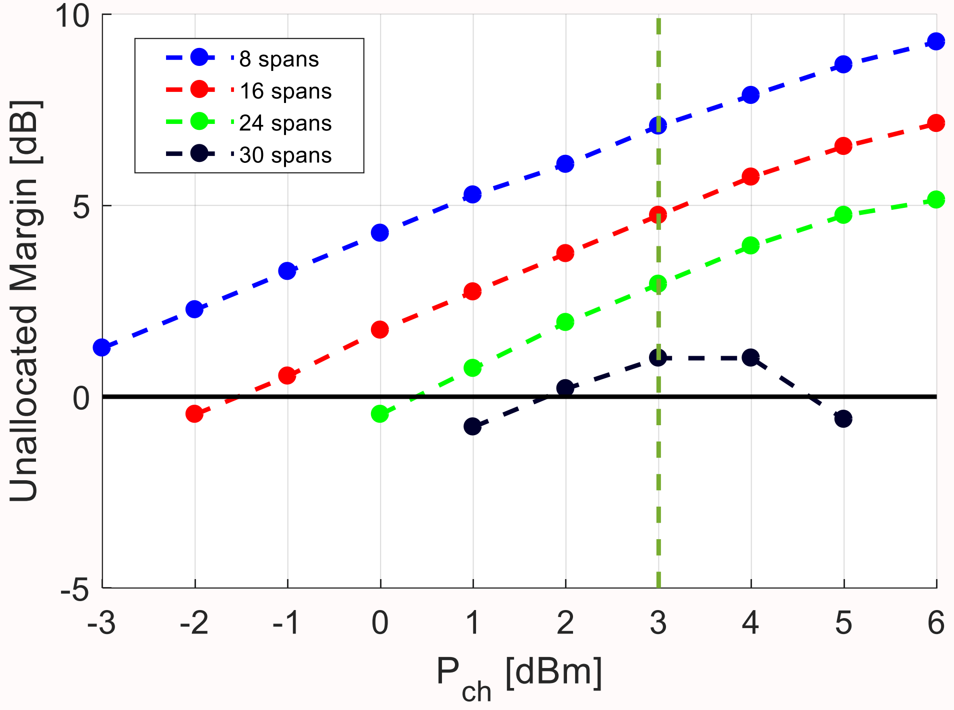
MARGIN VS PCH LEAF 50PS DF50

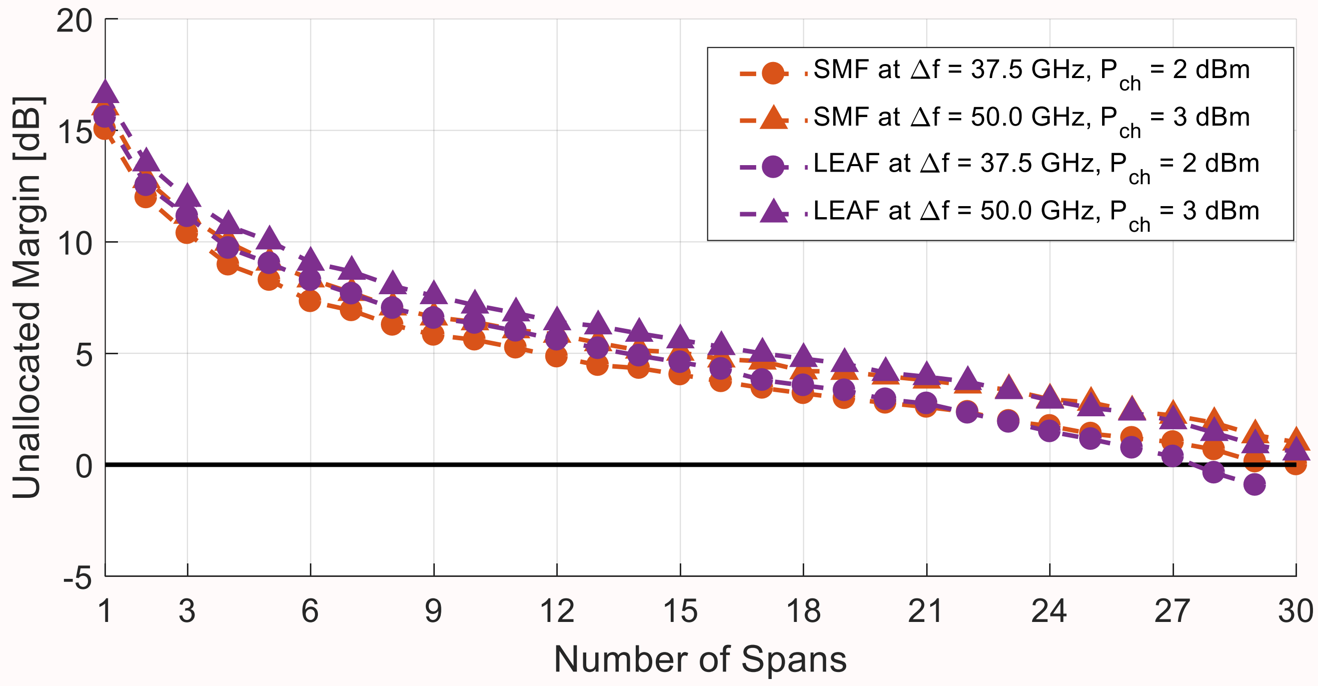


MARGIN VS PCH SMF 50PS DF37,5



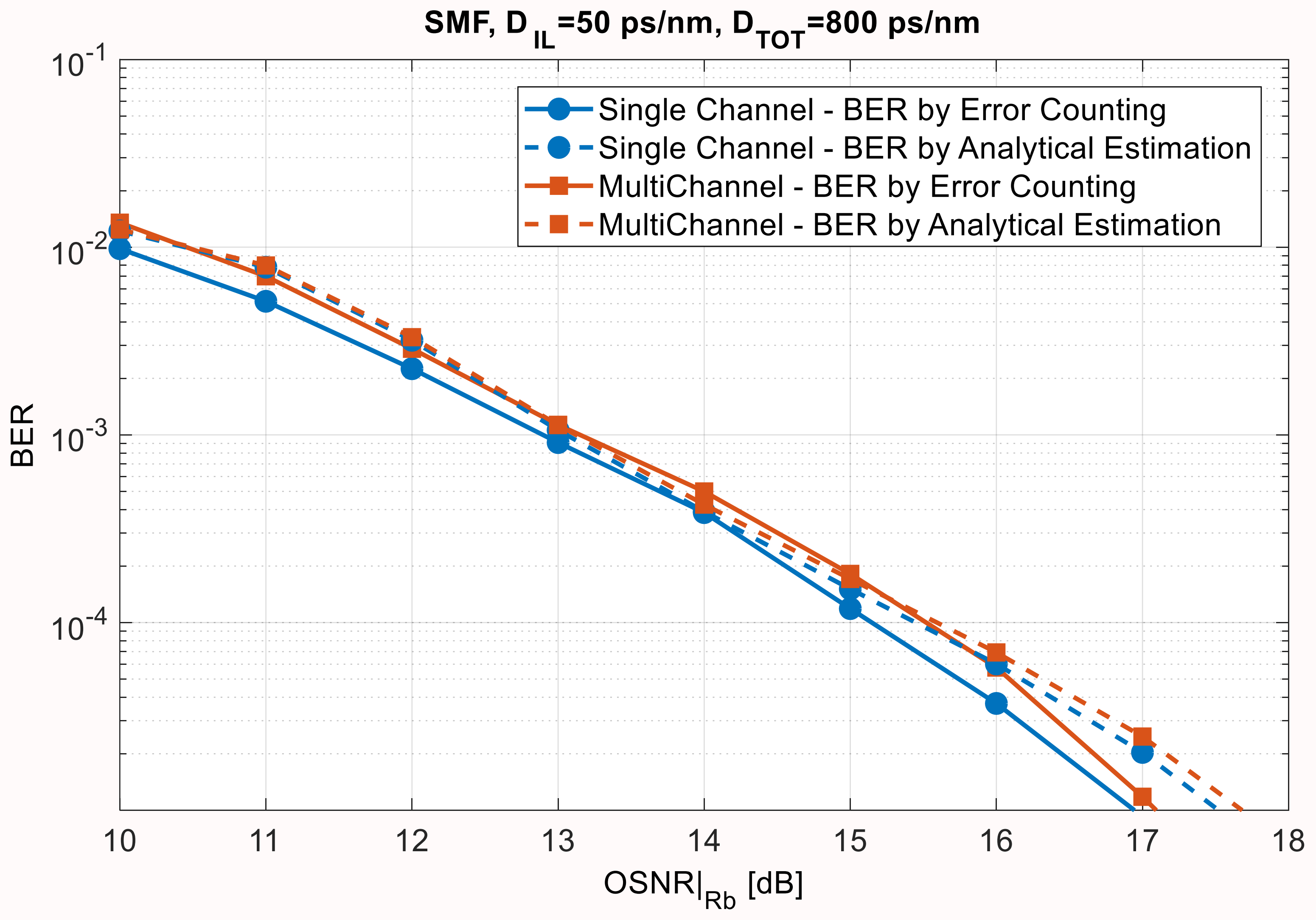
MARGIN VS PCH SMF 50PS DF50





SMF at Δf = 37.5 GHz, P ch = 2 dBm
SMF at Δf = 50.0 GHz, P ch = 3 dBm
LEAF at Δf = 37.5 GHz, P ch = 2 dBm
LEAF at Δf = 50.0 GHz, P ch = 3 dBm
Unallocated Margin [dB]
Number of Spans
20
15
10
5
0
-5
1
3
6
9
12
15
18
21
24
27
30

MULTI-CHANNEL BER ESTIMATION: SMF



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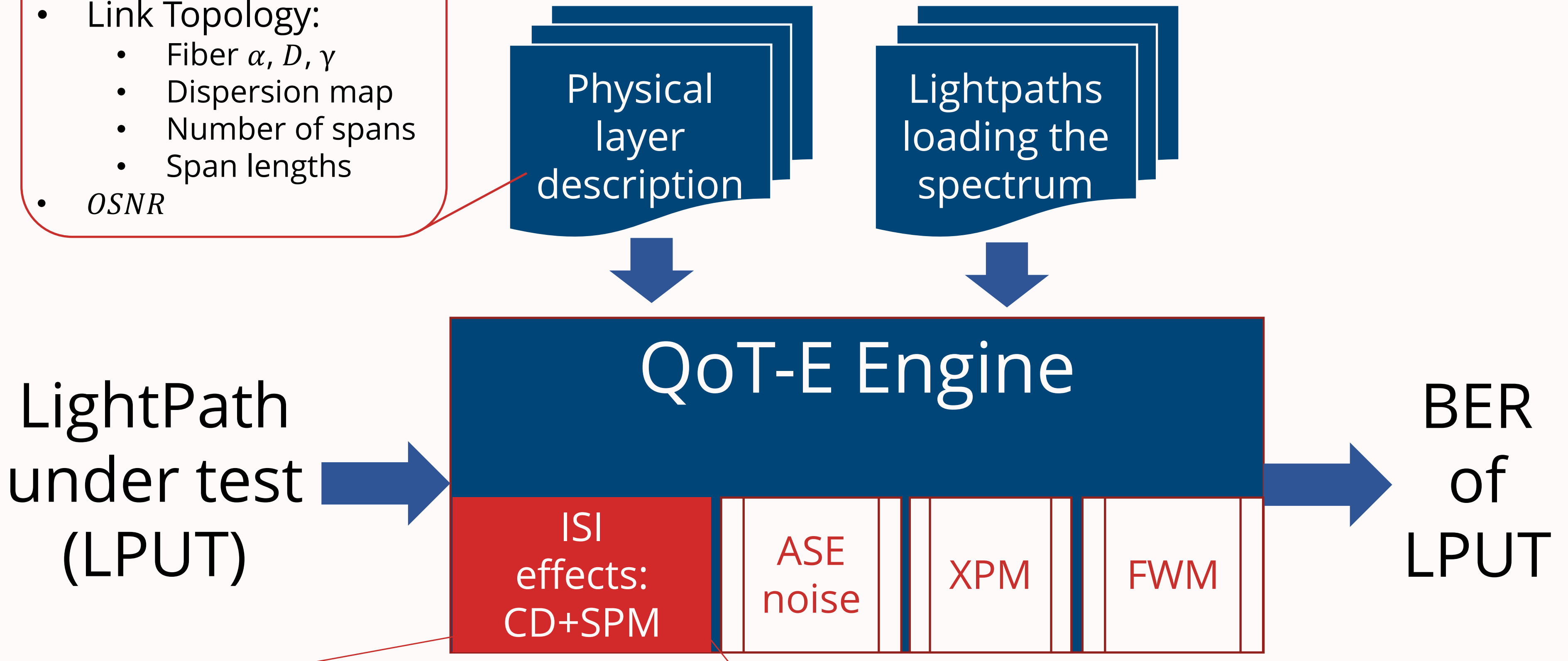
THE QOT-E TOOL

- Channel power P_{ch}
- Link Topology:
  - Fiber α, D, γ
  - Dispersion map
  - Number of spans
  - Span lengths
- $OSNR$



- μ levels for different topologies ***obtained by simulation***
- Noiseless (SPM + CD effects only)

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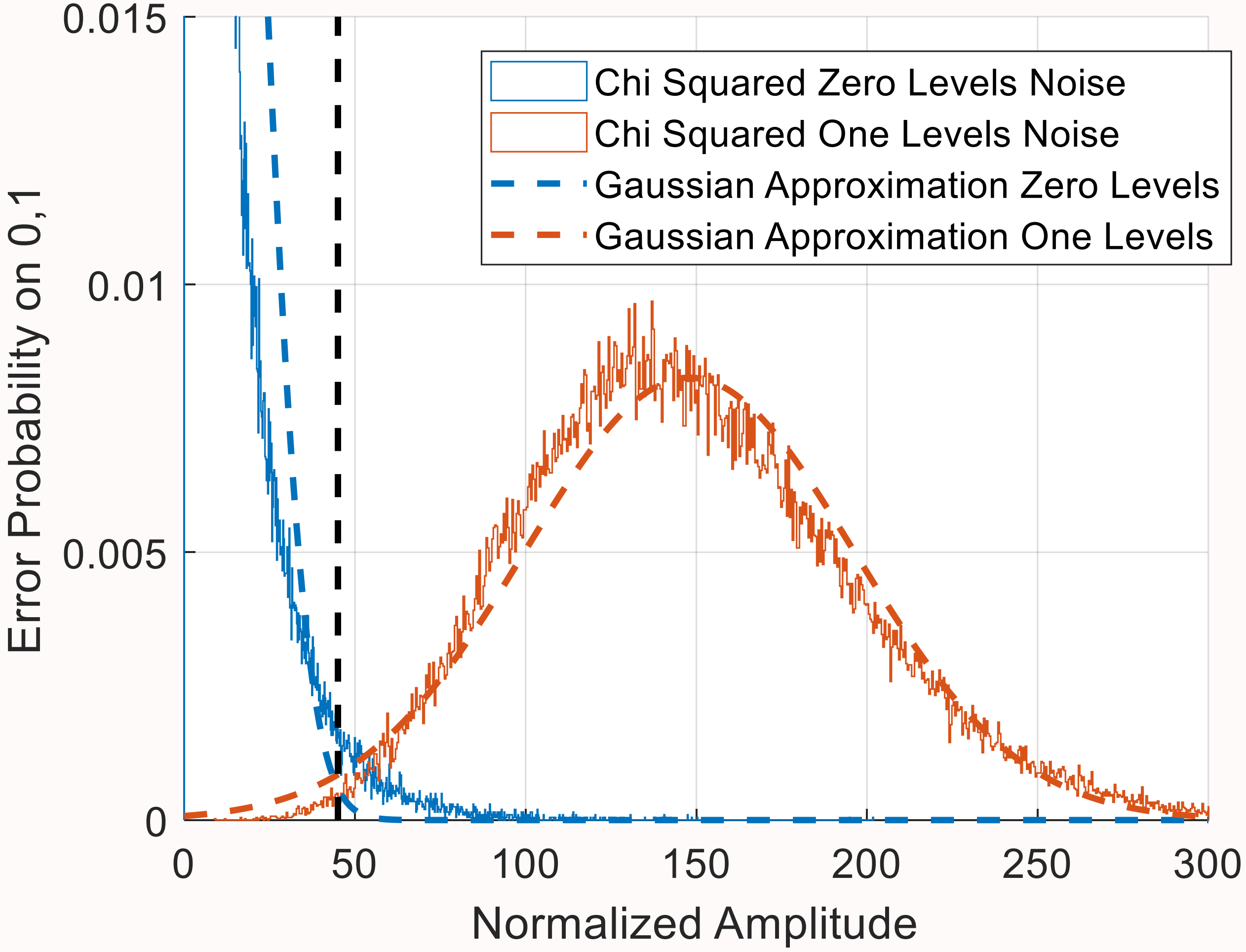
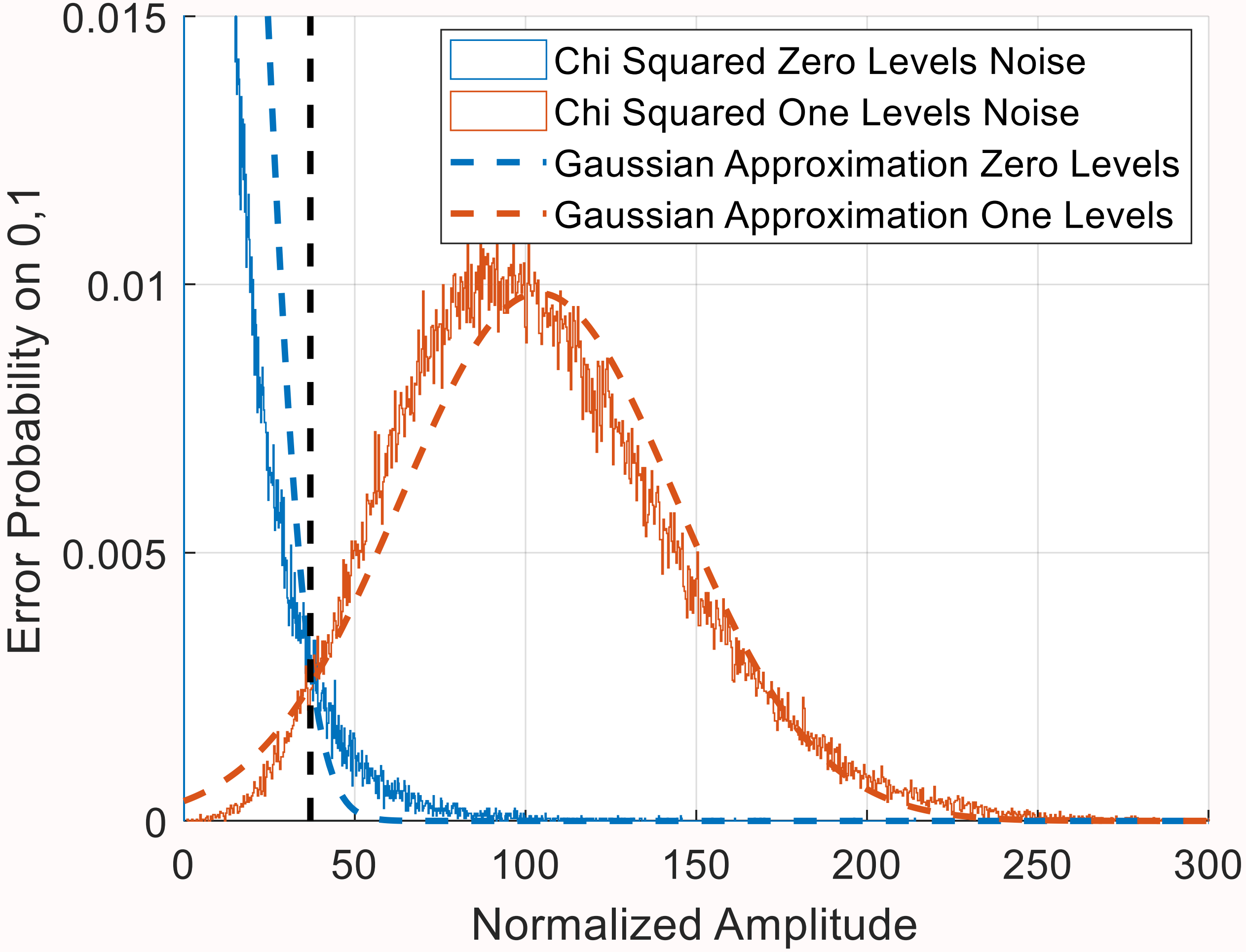
GAUSSIAN APPROXIMATION



- Older systems required BER such as 10^{-12}
- Such low BER is determined by the superposition of the tails of the Chi-Squared distributions of 0 and 1
- The Gaussian approximation led to substantial error in performance evaluation

GAUSSIAN APPROXIMATION



- Modern FEC allow to work at higher pre-FEC BER target (10^{-3})
- In this case the error probability contribution are not dominated only by the Chi-Squared tails.
- Gaussian approximation holds enabling more reliable BER estimation.

NETWORK CONTROL AND ORCHESTRATION