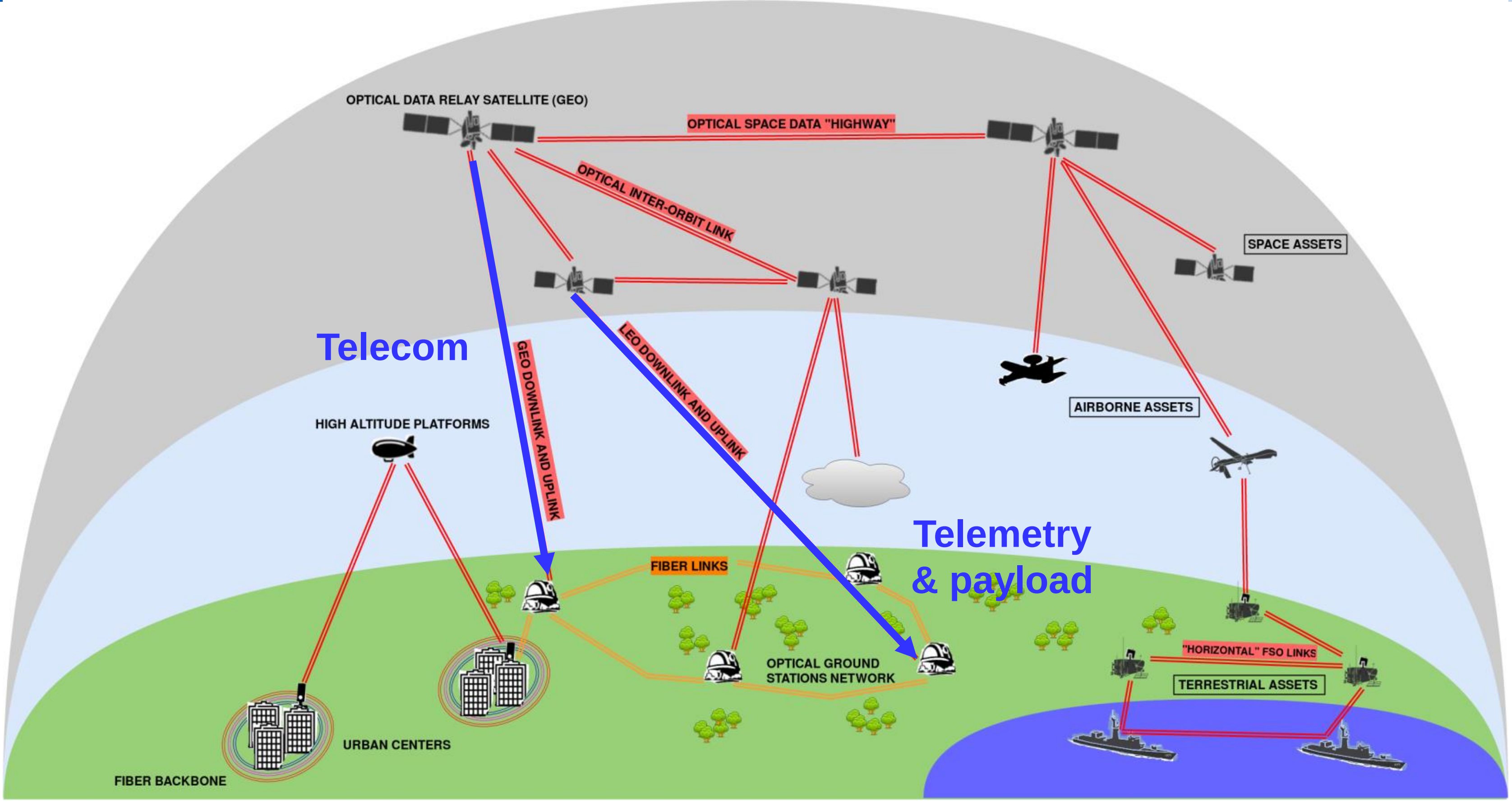
Reliability of satellite-to-ground optical transmissions

Lucien Canuet

Jérôme Lacan (ISAE)
Angélique Rissons (ISAE)
Nicolas Védrenne (ONERA)
Géraldine Artaud (CNES)

retour sur innovation

SATELLITE OPTICAL DOWNLINKS - GENERAL CONTEXT

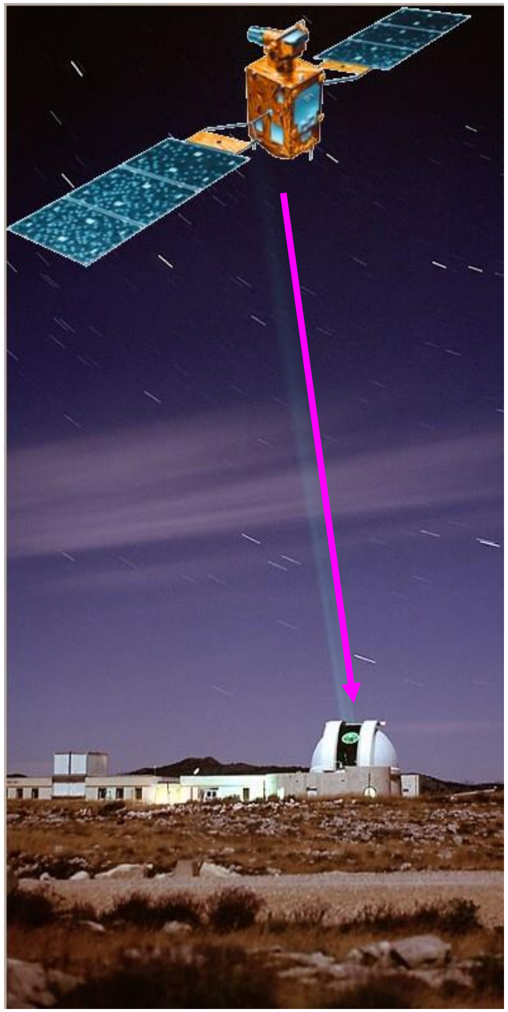


Applications of optical links

- Data transfer (telemetry/payload) from scientific or defense spacecraft (LEO)
- Telecommunication (GEO satellites)
- Metropolitan area networks (where fiber optics impractical)
- Deep space probes

…

SATELLITE OPTICAL DOWNLINKS - GENERAL CONTEXT



- **High to very high data rates**
  - ~10 Gbps
  - >1 Tbps achievable if optical fiber technologies are exploited (WDM, DWDM, Optical amplifiers etc.)

- **Decongestion of the RF spectrum**

- **Enhanced security (high directivity of the beam)**
  - Stealthy links and jamming capacity reduced

- **Very large range (« Deep Space » applications)**

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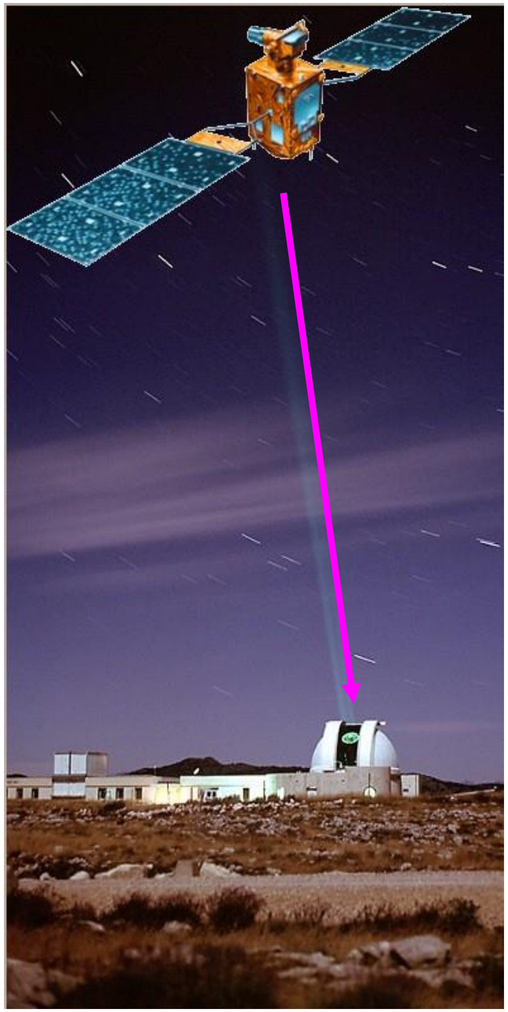

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Links highly affected by atmospheric turbulence

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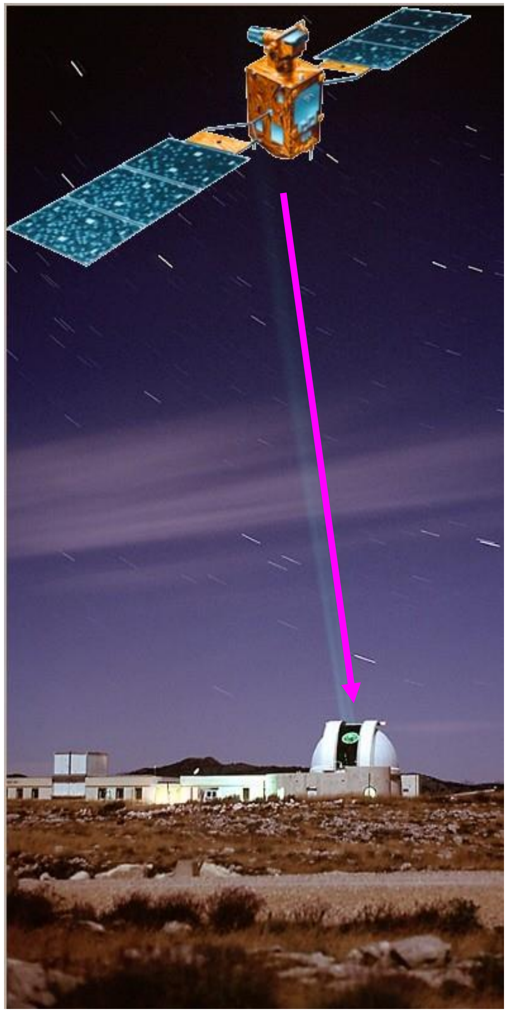

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Stealthy links and jamming capacity reduced

❖ **Very large range (« Deep Space » applications)**

Links highly affected by atmospheric turbulence

☐ **Improvement of the link budget and telecom performances:**
+ Coupling of incident flux into optical fiber (SMF)
+ Adaptive Optics (AO)
+ Optimisation of digital (coding/interleaving) techniques

Joint optimisation of AO and coding techniques to improve reliability of LEO and GEO downlinks (telemetry and telecoms applications)

PRESENTATION OUTLINE

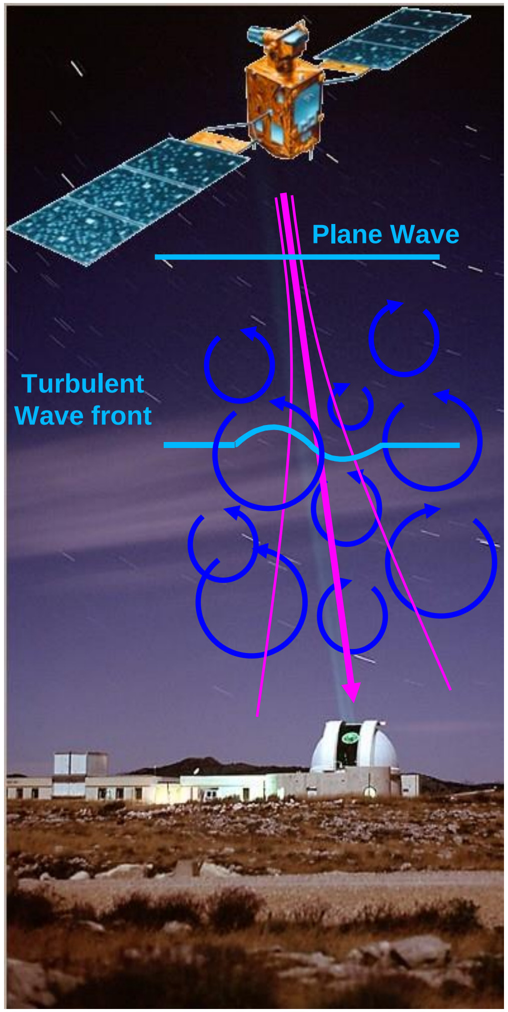
PART I : JOINT OPTIMIZATION – PROBLEM OVERVIEW

PART II : AO FOR OPTICAL DONWLINKS

PART III : PHYSICAL LAYER PERFORMANCE ASSESSMENT

PART IV : AO/CROSS-LAYER OPTIMIZATION

THE ATMOSPHERIC PROPAGATION CHANNEL

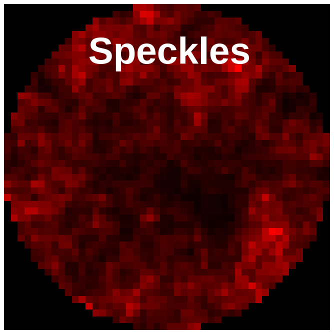


Atmospheric propagation channel

Δ(Temperature, Pressure, Humidity) → Δ(refractive index) → Perturbed wave front

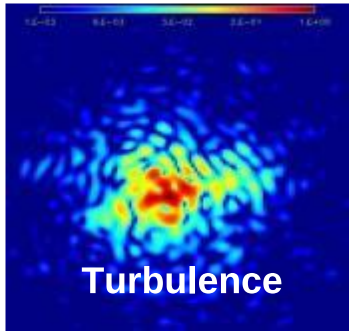
Atmospheric optical turbulence

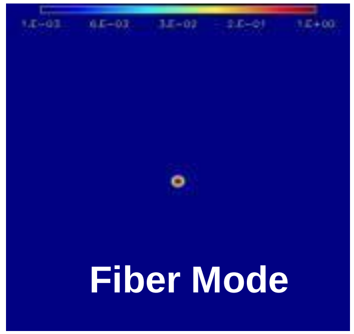
Scintillation
(Pupil plane)



+

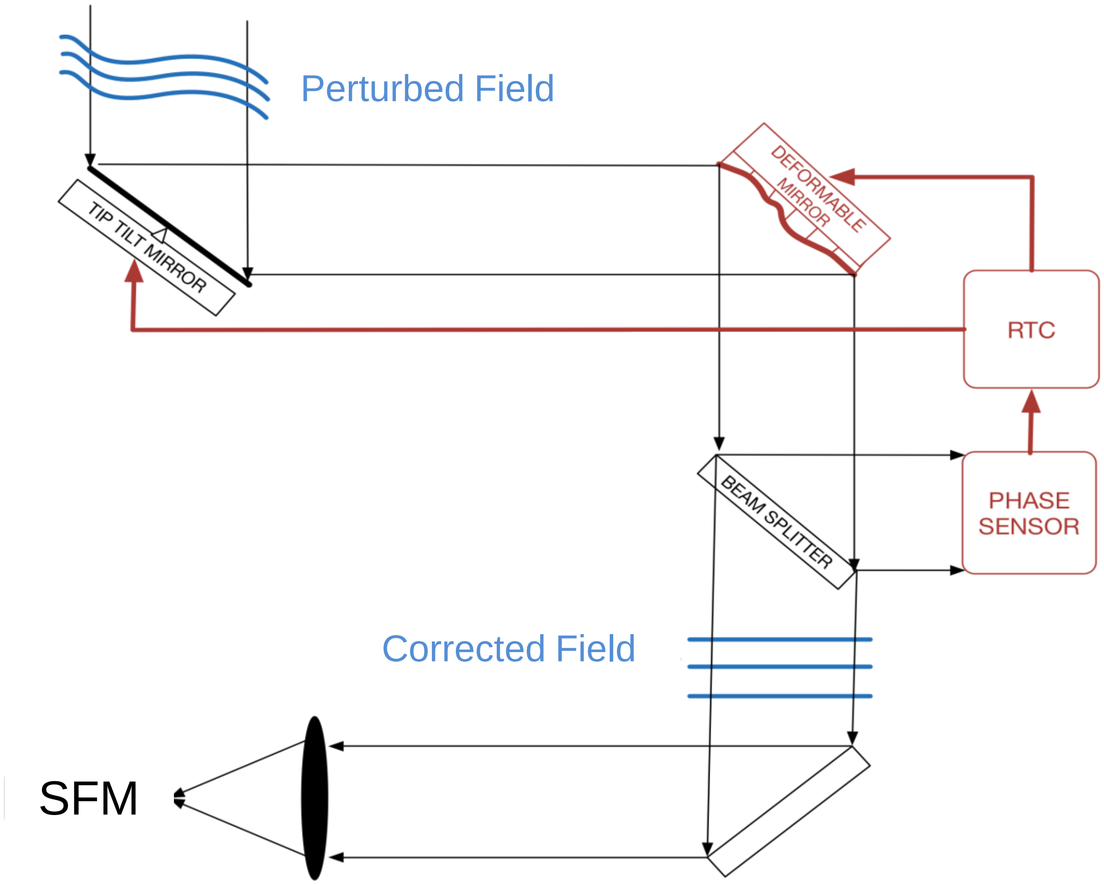
Phase fluctuations
(Focal plane)





→ **Coupling losses** and **signal fadings**

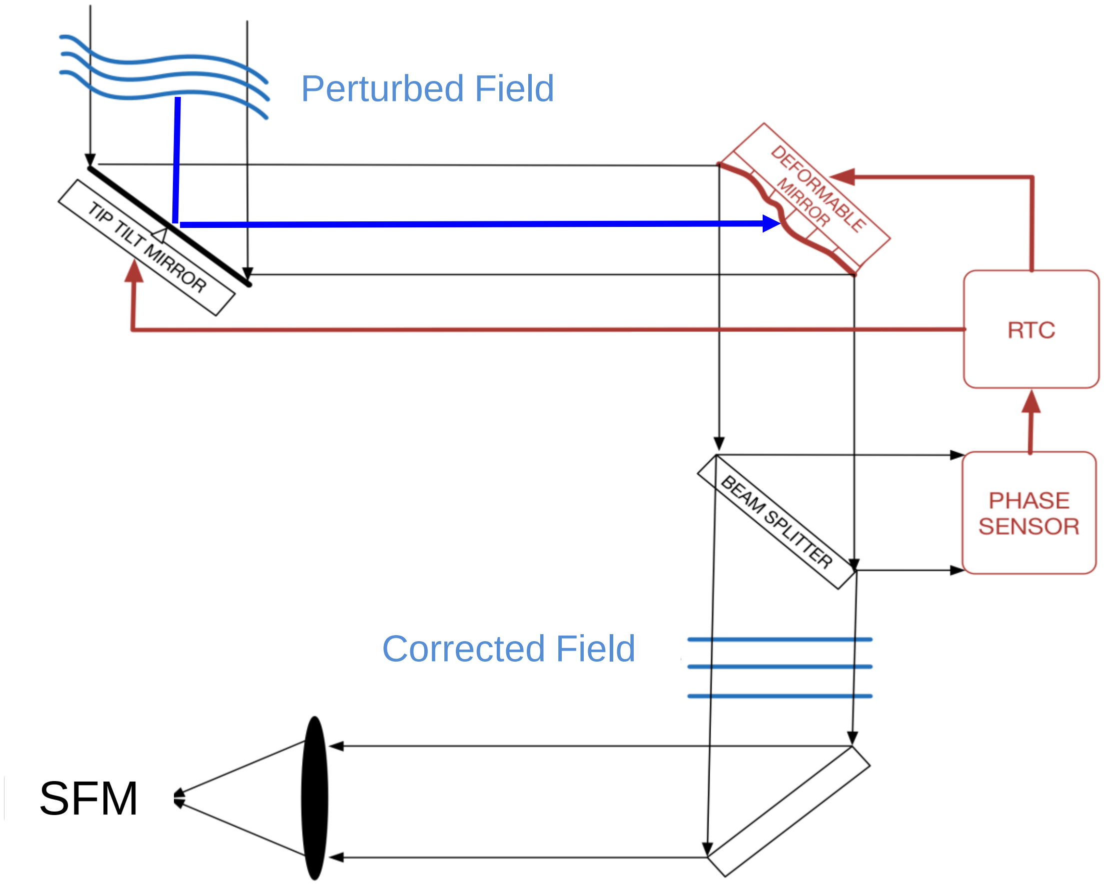
Mitigation techniques ?



Principle overview

- **Opto-mechanical system:**
  Real time correction of phase distorsions

- **Three key components:**
  Deformable mirror
  Wavefront sensor
  Real-time computer



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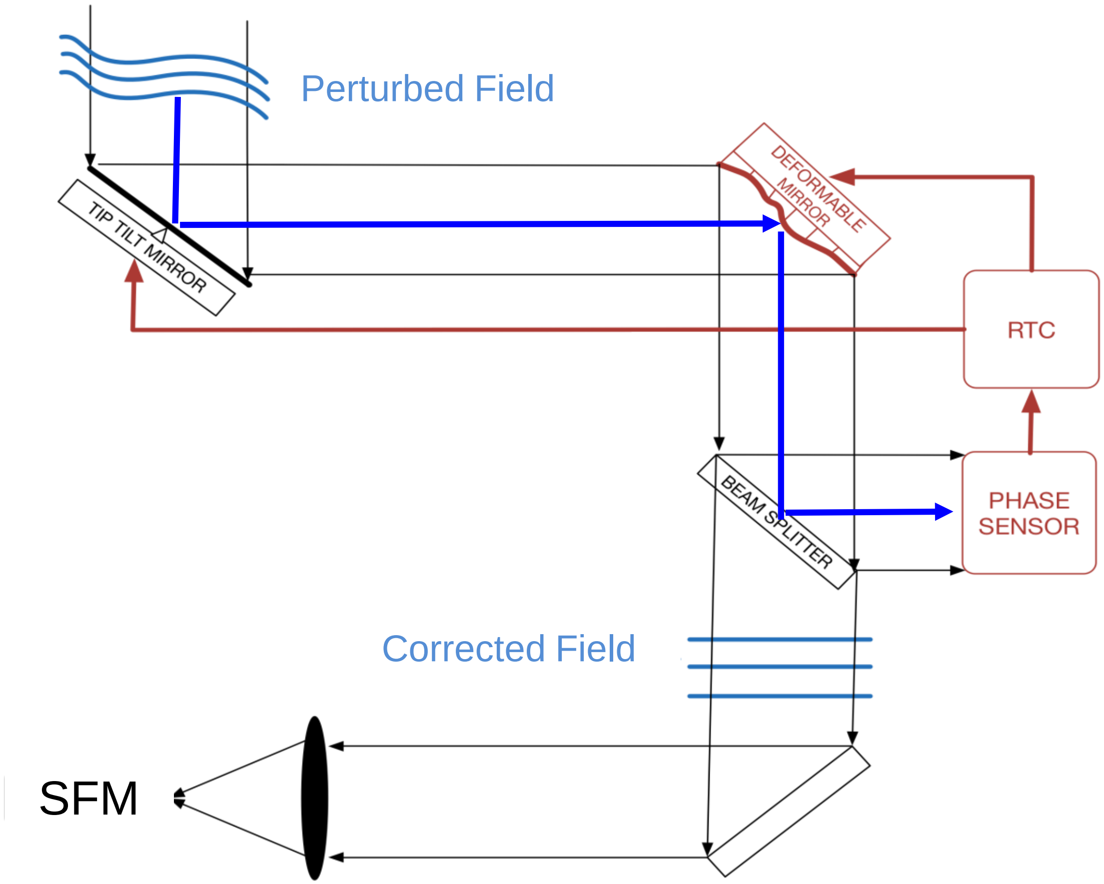

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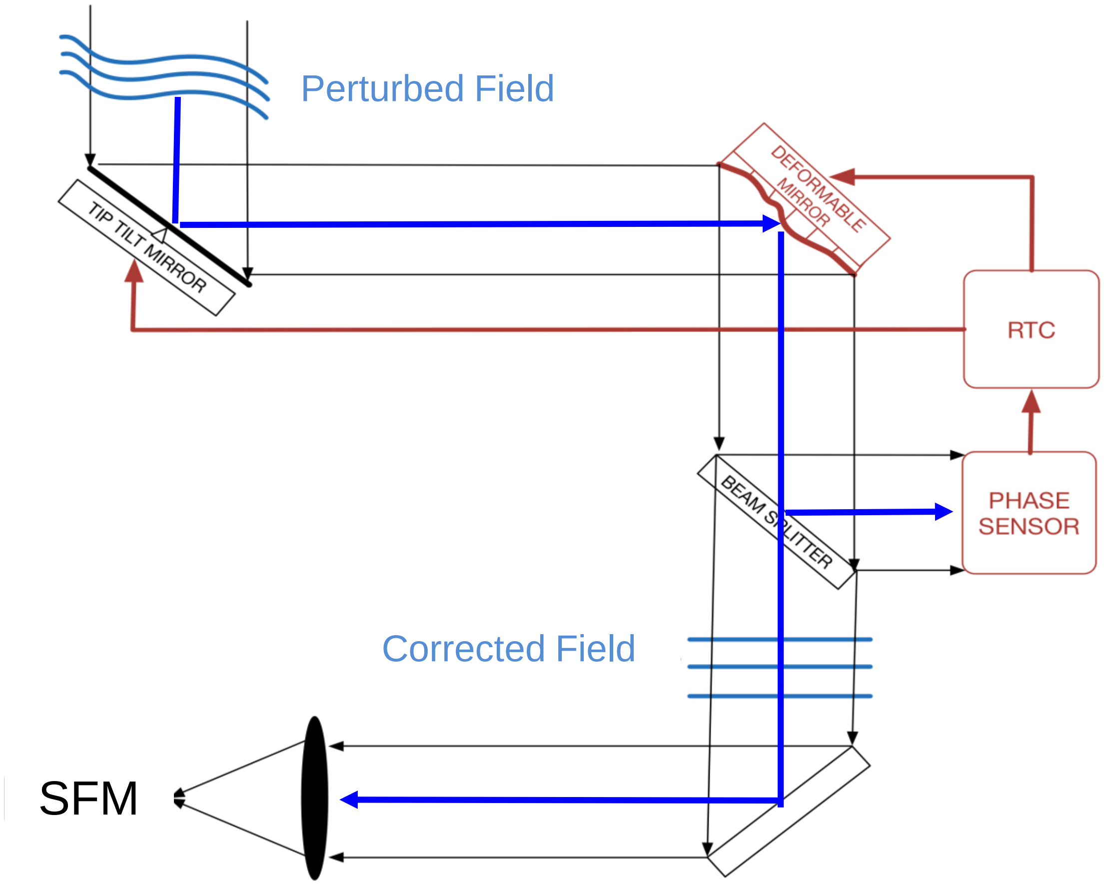

Minimization of residual phase variance

$$\sigma^2_{\phi res} = \left\langle \frac{1}{S} \int (\phi(r) - \phi_{corr}(r))^2 \, dr \right\rangle_{\phi}$$

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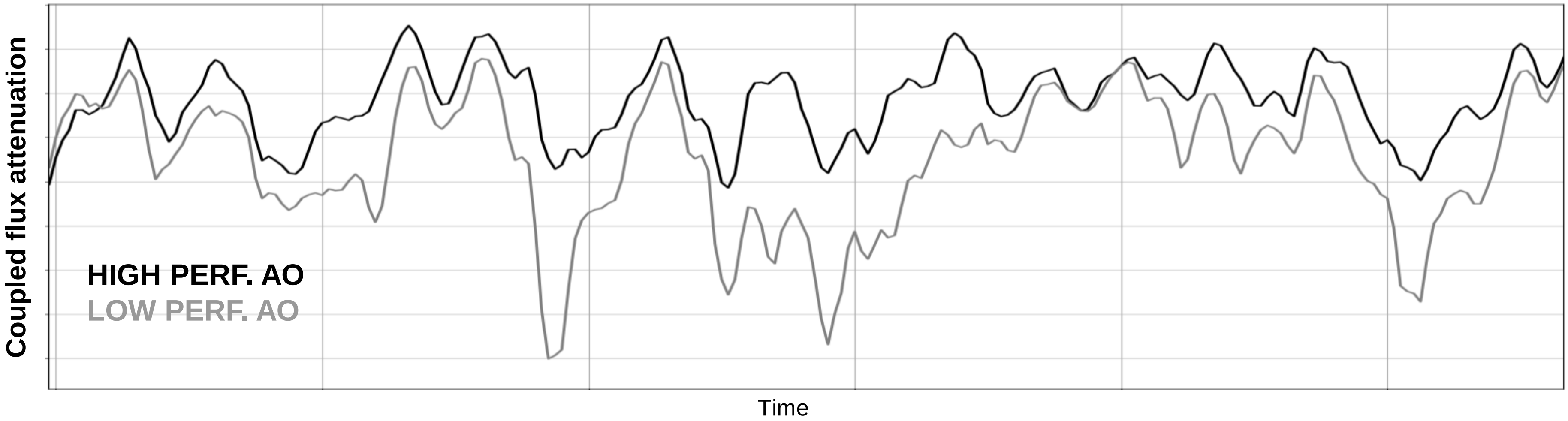
Limitations?

PHYSICAL LAYER DIGITAL MITIGATION TECHNIQUES



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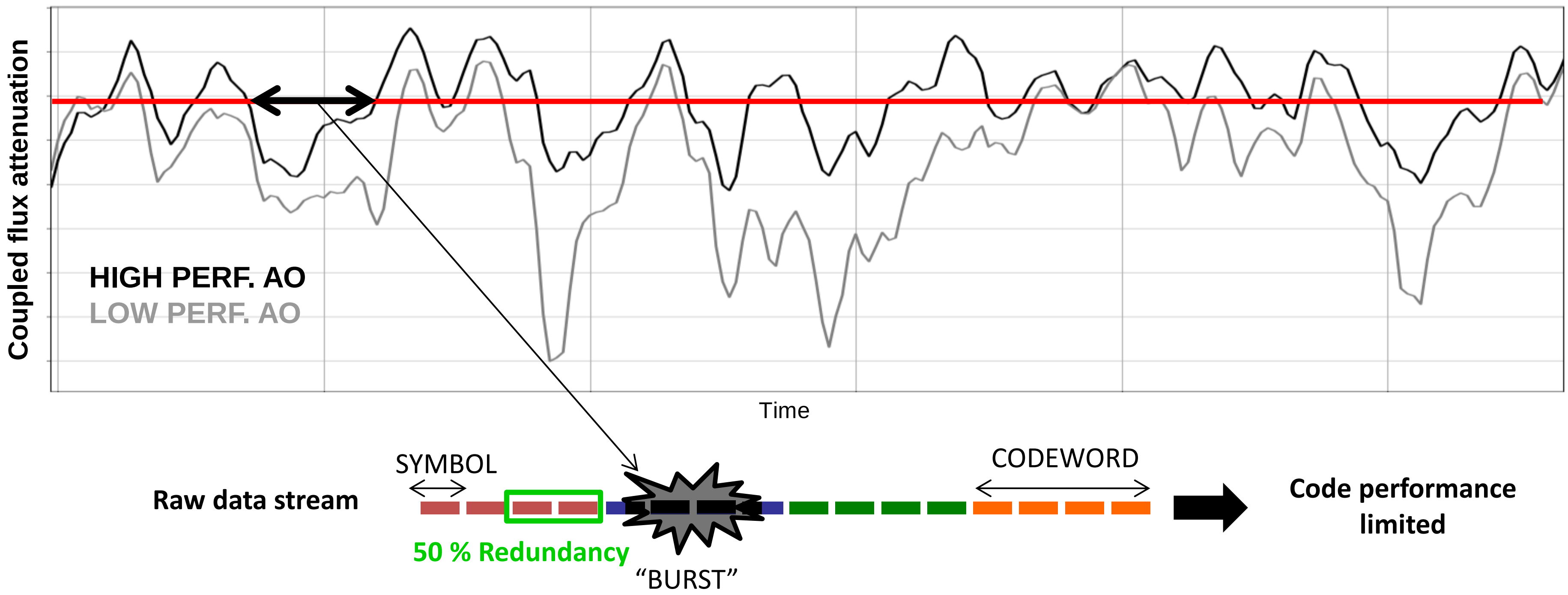

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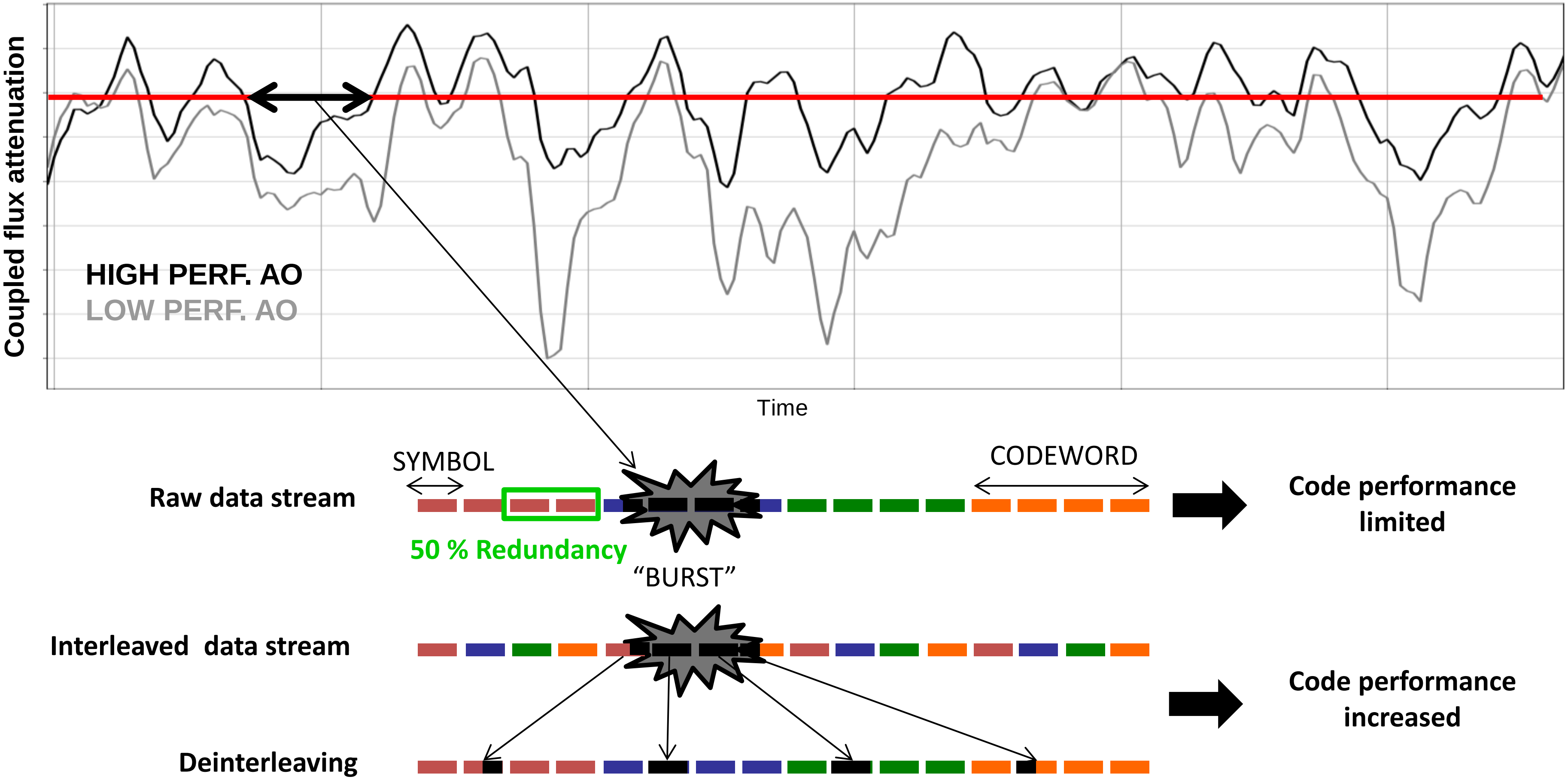

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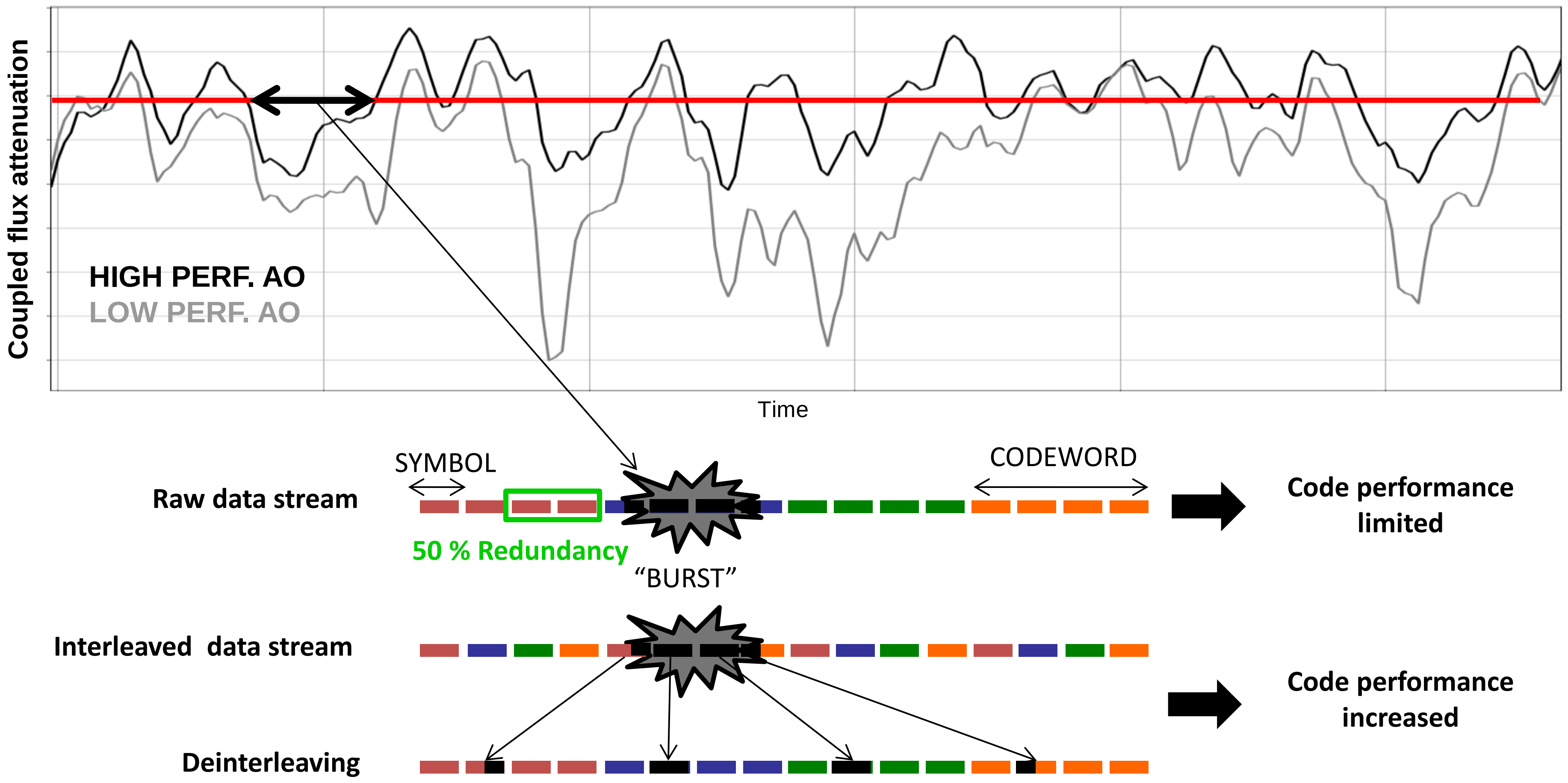
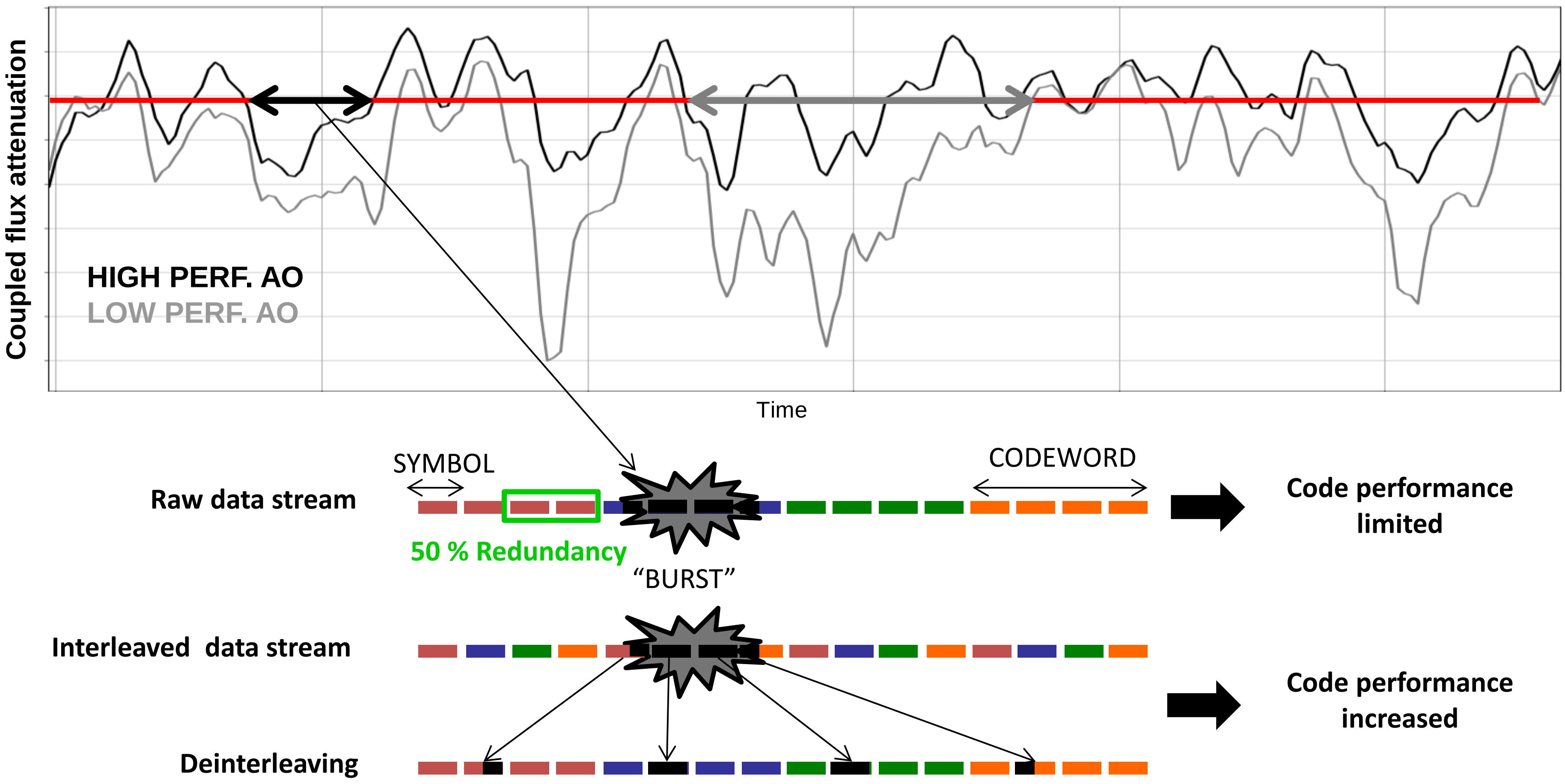


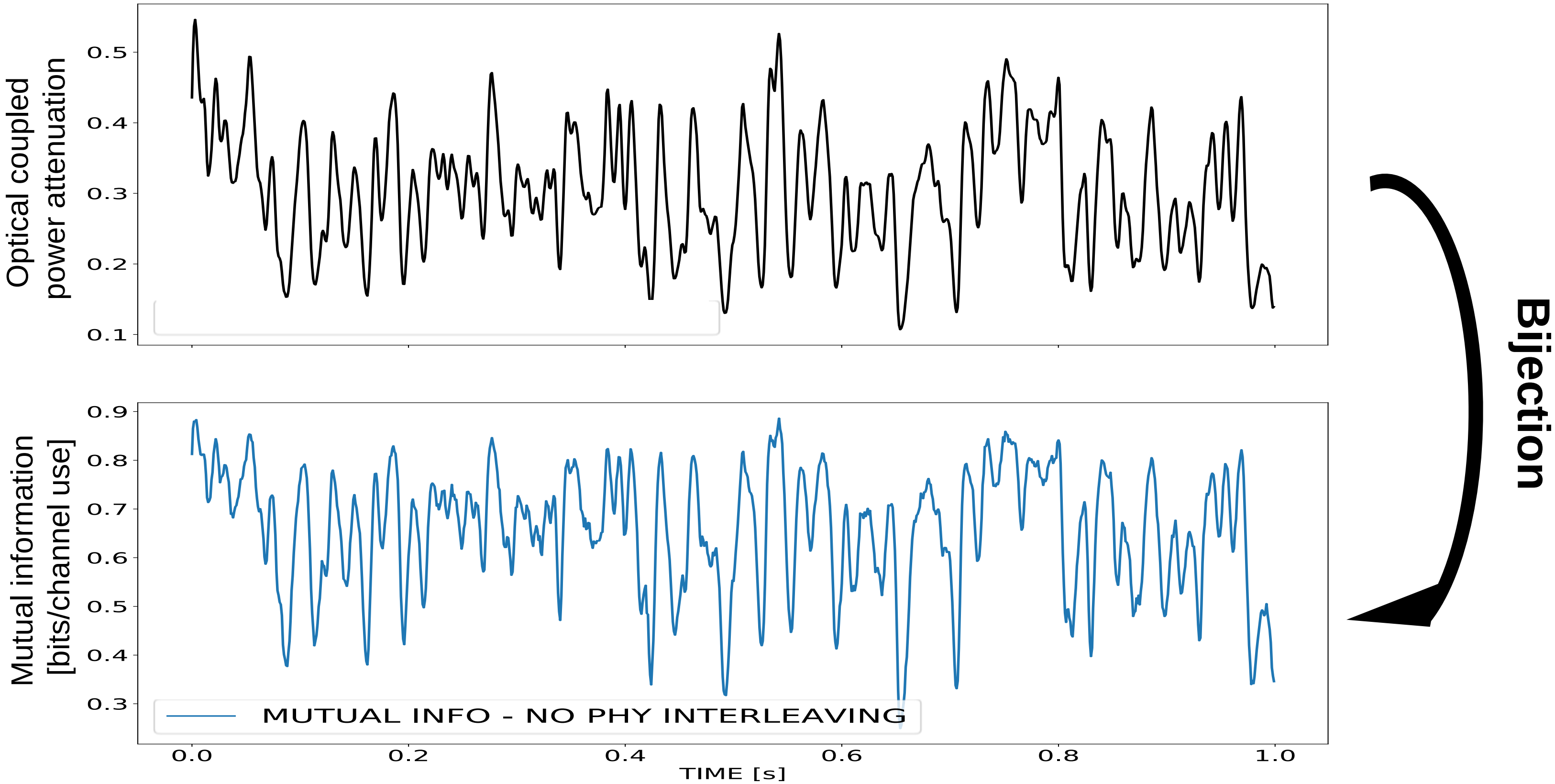
How to effectively allocate memory (interleaver) and redundancy (code)?

PHYSICAL LAYER DIGITAL MITIGATION TECHNIQUES



Statistical and temporal characterizations of the channel needed:
instantaneous coupled optical power after partial AO

PHYSICAL LAYER DIGITAL MITIGATION TECHNIQUES
MUTUAL INFORMATION



Instantaneous mutual information (~channel capacity)

Theoretical maximal data rate at which information can be transferred over the channel given noise level

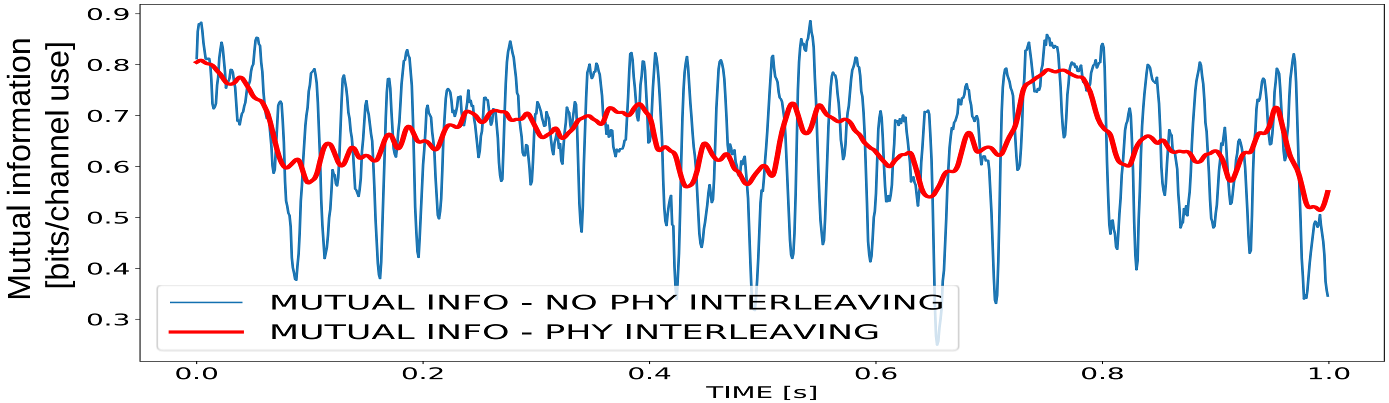
The greater the better

Advantages of instantaneous mutual information (MI):

Emulation of interleaving-deinterleaving at Rx

⟺

Sliding average window



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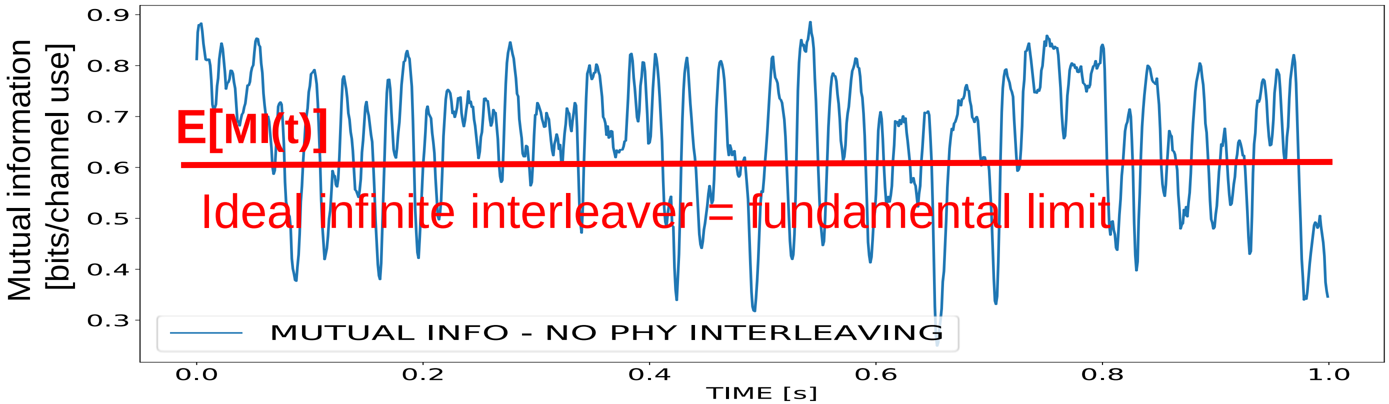


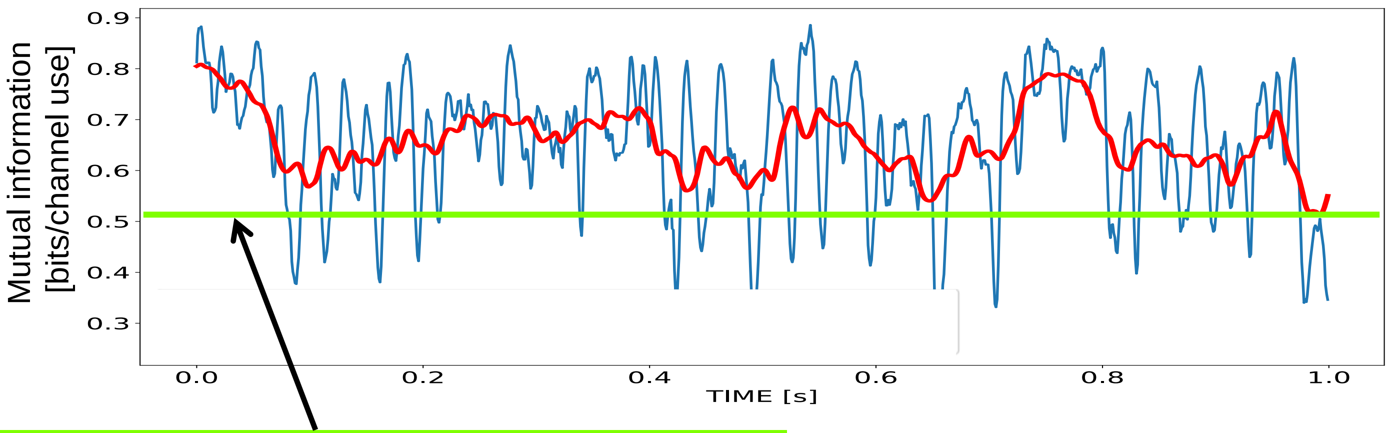
➡ Average power losses not recoverable by interleaving

Advantages of instantaneous mutual information (MI):

Emulation of Error Correcting Code (ECC) decoding

⟷

Shannon decoding theorem



ECC coding rate = amount of non-redundant information in message

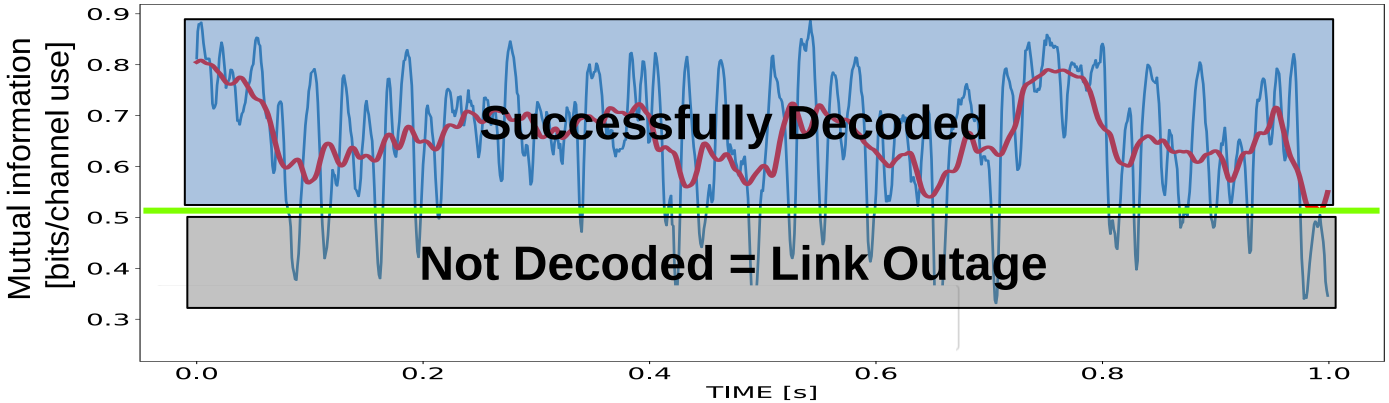
$R_0^{PHY} = 0.5$

Advantages of instantaneous mutual information (MI):

Emulation of Error Correcting Code (ECC) decoding

⟷

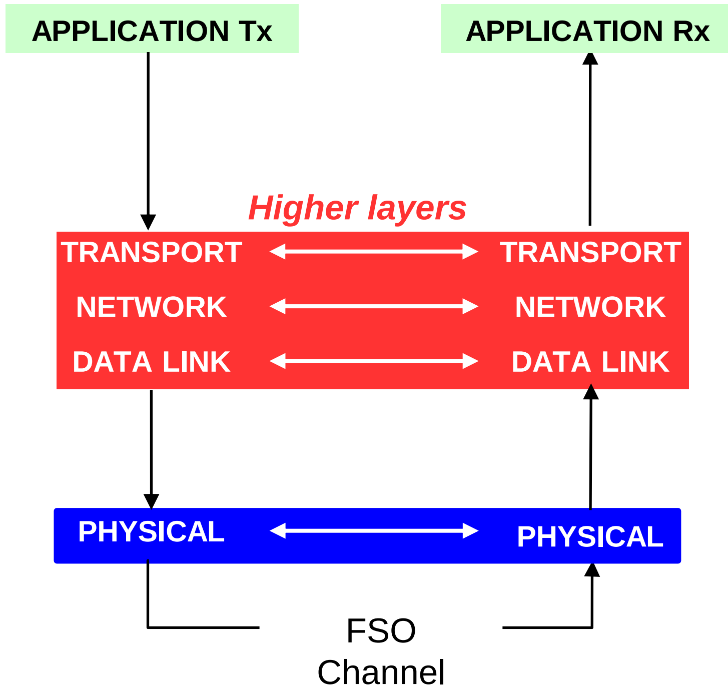
Shannon decoding theorem



→ PHY layer performance metric = Outage probability

CROSS-LAYER APPROACH

CODING possible at both **PHY LAYER** and **HIGHER LAYERS**



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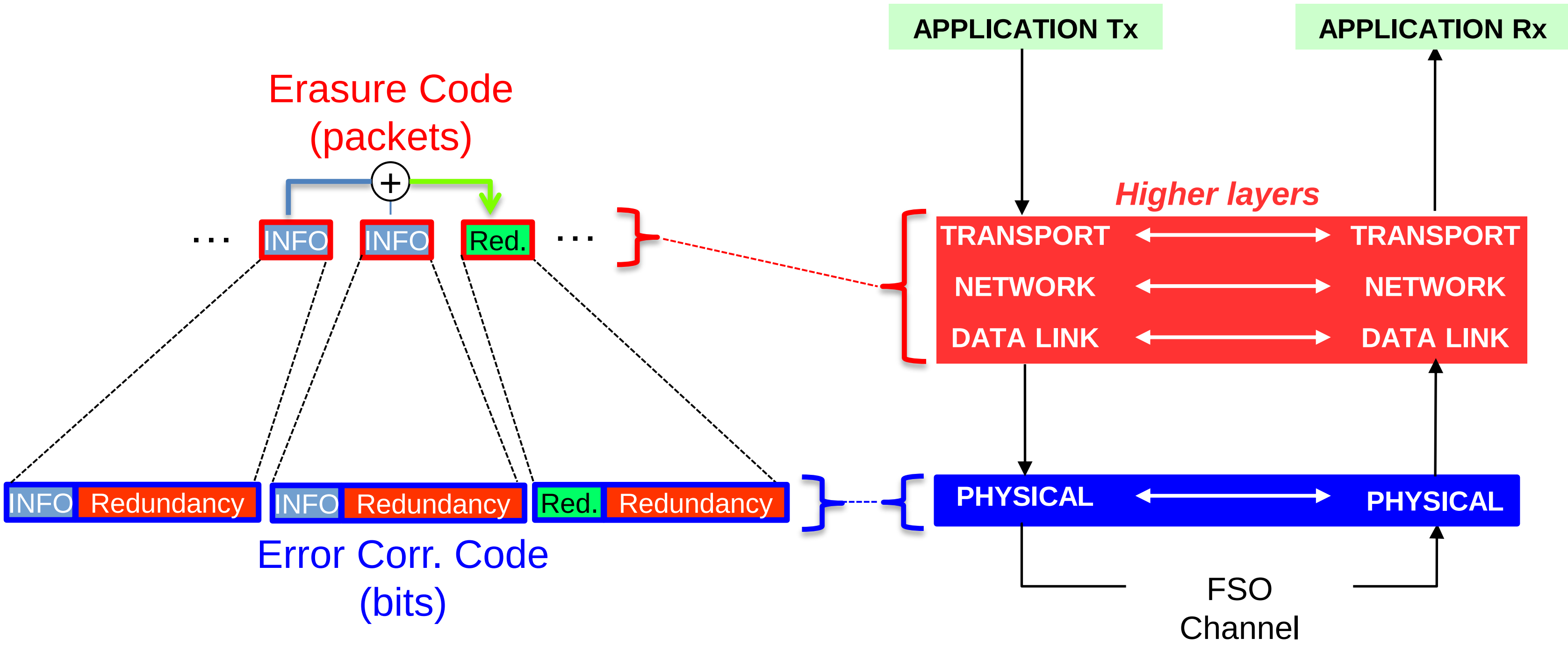
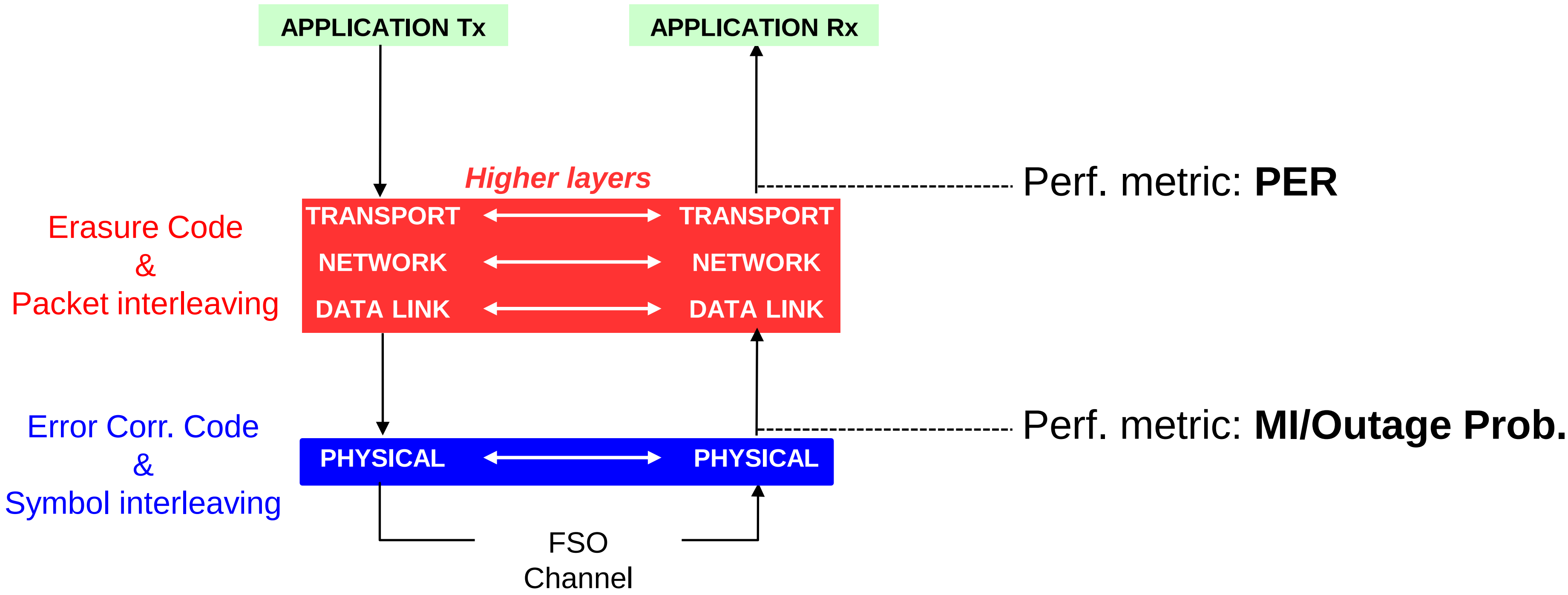


Red. *HL Erasure code redundancy*

Redundancy *PHY Error correcting code redundancy*

CROSS-LAYER APPROACH

CODING and **INTERLEAVING** possible at both **PHY LAYER** and **HIGHER LAYERS**



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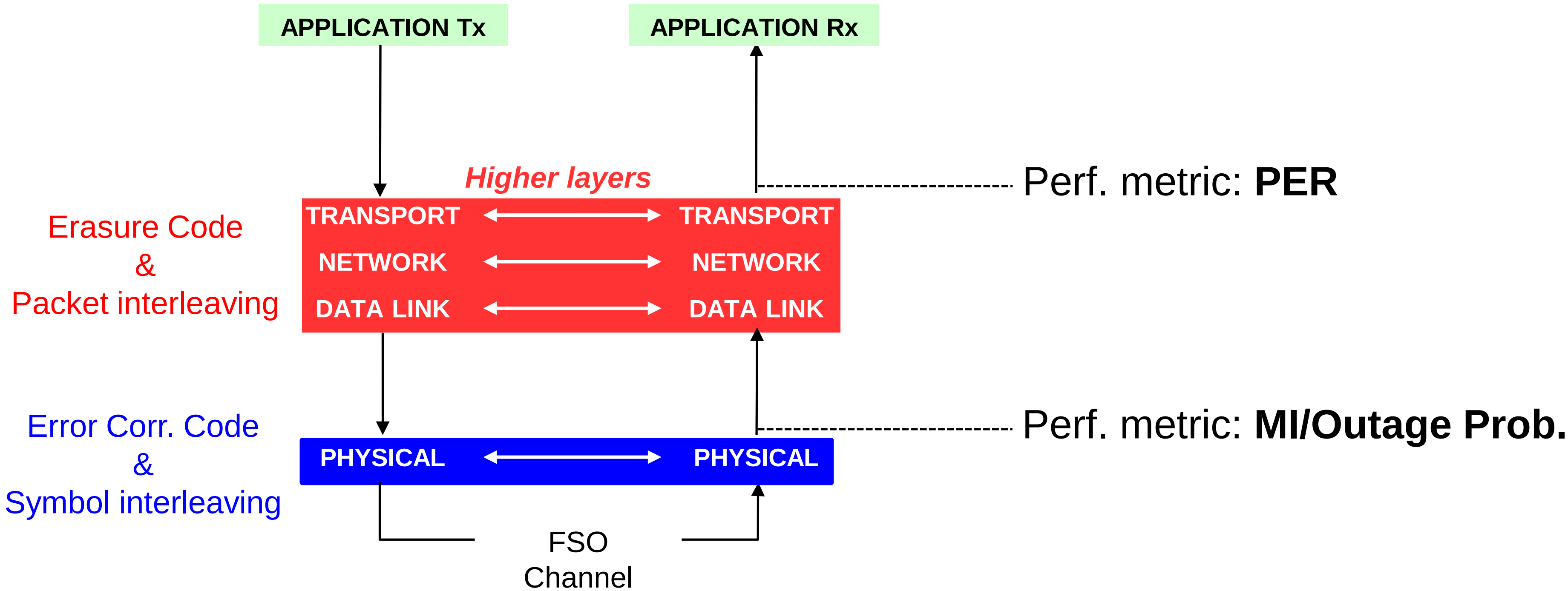
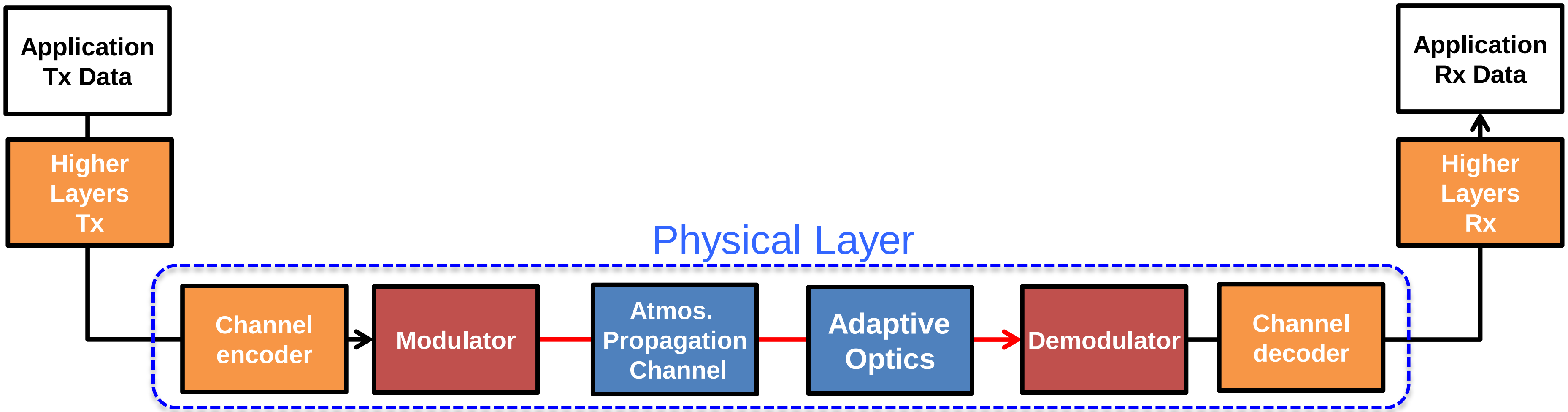


Benefits of (optimized) cross-layer coding scheme:

- Lowering Packet Error Rate (PER)
- Alleviate drawbacks required by long interleavers needed on bursty channel

OVERALL SYSTEM OVERVIEW



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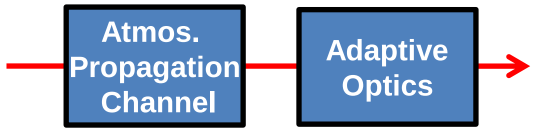


Partial AO Analytic Modeling

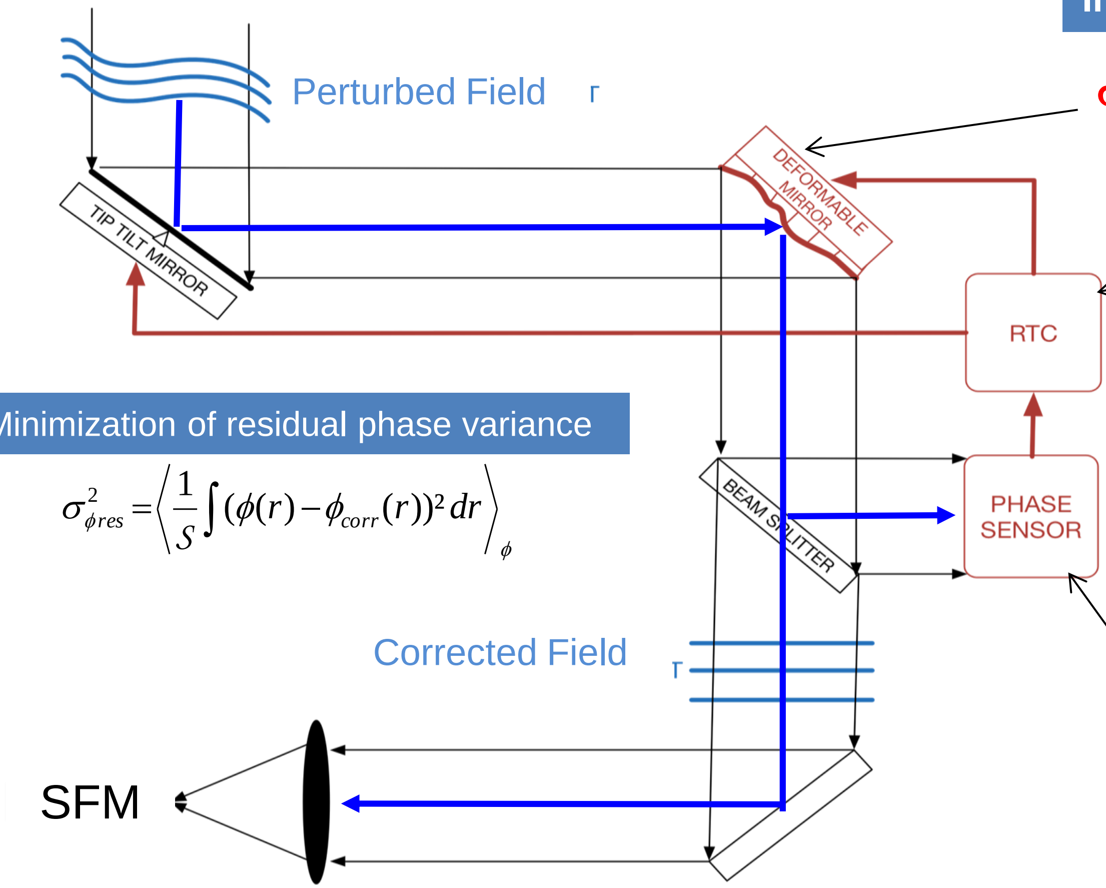
Analytic Modeling of Partially Corrected Coupled Flux into SMFs

PART III : PHYSICAL LAYER PERFORMANCE ASSESSMENT

PART IV : AO/CROSS-LAYER OPTIMIZATION

PARTIAL ADAPTIVE OPTICS

Intrinsic limitations = partial AO



$\sigma^2_{fitting}$ **Fitting Error**

$+\ \sigma^2_{Tempo}$ **Temporal Error**

$+\ \sigma^2_{PS}$

$\left\{ \begin{array}{l} \sigma^2_{ph\ \&\ ron} \\ +\ \sigma^2_{Alias} \\ +\ \sigma^2_{scintill.} \end{array} \right.$ **Aliasing Error**

Neglect impact of noise and scintillation on phase sensor error

Minimization of residual phase variance

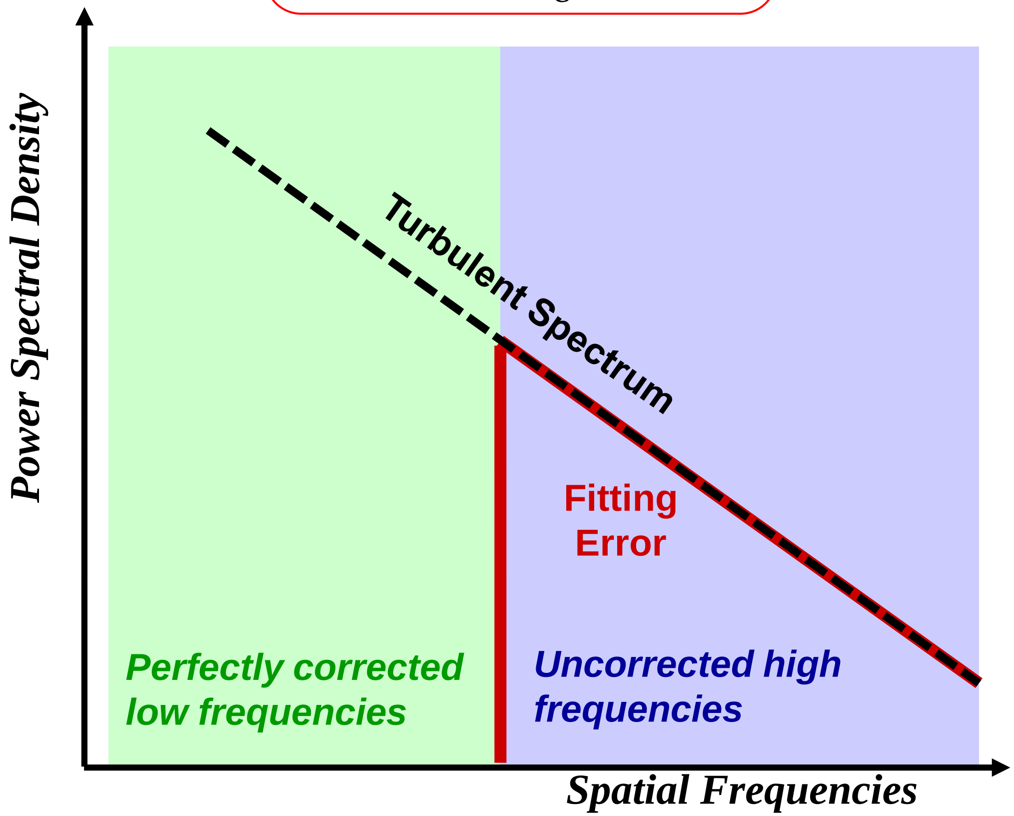
$$\sigma^2_{\phi res} = \left\langle \frac{1}{S} \int (\phi(r) - \phi_{corr}(r))^2 \, dr \right\rangle_{\phi}$$

Analytical laws for each one of the errors are known

Ideal AO correction system: the low order residuals are perfectly corrected

Total residual error

$$\sigma^2_{\text{res}} \simeq \underbrace{\sigma^2_{\text{Fitting}}}_{\text{High orders}}$$

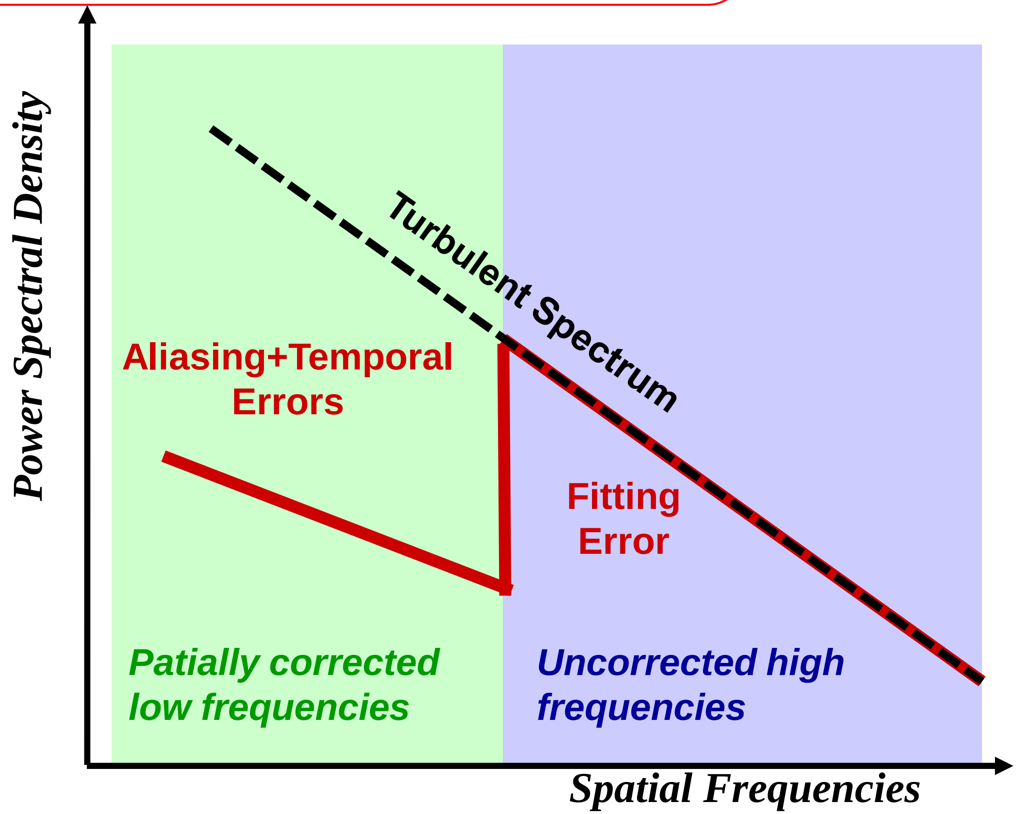


Partial AO correction system: low order residuals that are highly correlating

Total residual error

$$\sigma^2_{\text{res}} \simeq \underbrace{\sigma^2_{\text{Fitting}}}_{\text{High orders}} + \underbrace{\sigma^2_{\text{Tempo}} + \sigma^2_{\text{Alias}} + (\sigma^2_{\text{Other}})^{\text{neglected}}}_{\text{Low orders}}$$

→ Non negligible impact on communication performances



INSTANTANEOUS COUPLED OPTICAL POWER ATTENUATION

Neglecting amplitude spatial structures influence on coupling fluctuations:

Scintillation

Injection losses

Average coupling losses

$$A_{SMF} = \exp(-\sigma_\chi^2)\exp(2\chi_P)\left|\int_{-\infty}^{\infty} W(\mathbf{r})\exp(i\phi(\mathbf{r}))d\mathbf{r}\right|^2$$

Collected power fluctuations

Rough approx, validated for medium elevation, small perturbations

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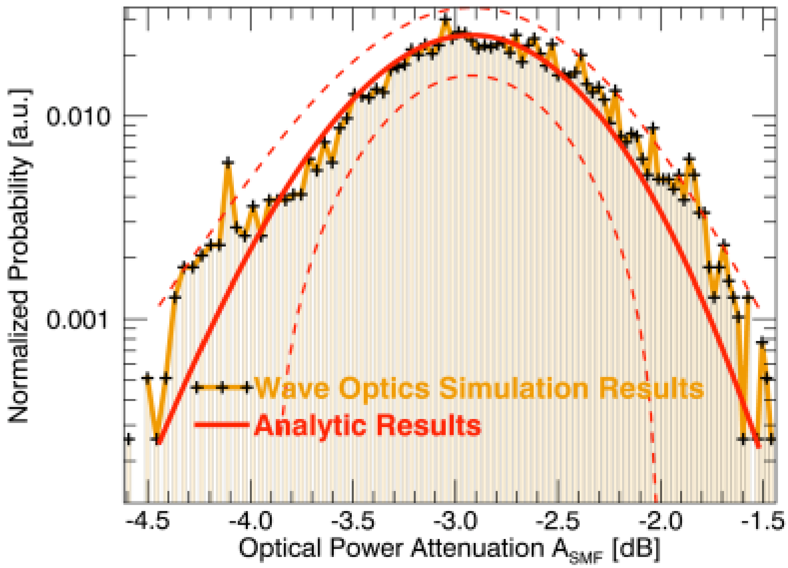
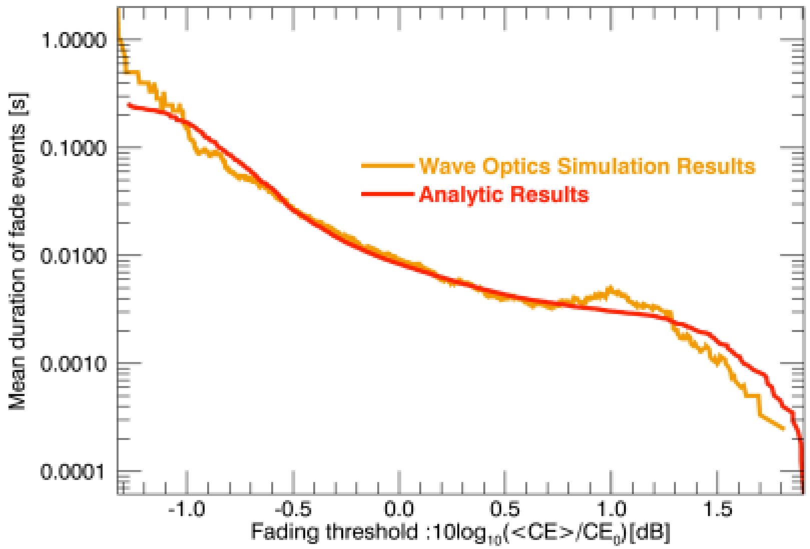
Rough approx, validated for medium elevation, small perturbations

Illustration GEO-Downlink, Drx = 50cm, r_0= 0.069 m, 9 radial orders at 1 kHz

Optical power attenuation probability density distribution



Average fading time against normalized threshold



Canuet L., Védrenne N., Conan J-M. , Petit C., Artaud G., Rissons A., and Lacan J., « *Statistical properties of single-mode fiber coupling of satellite-to-ground laser links partially corrected by adaptive optics* » J. Opt. Soc. Am. A 35, 148-162 (2018)

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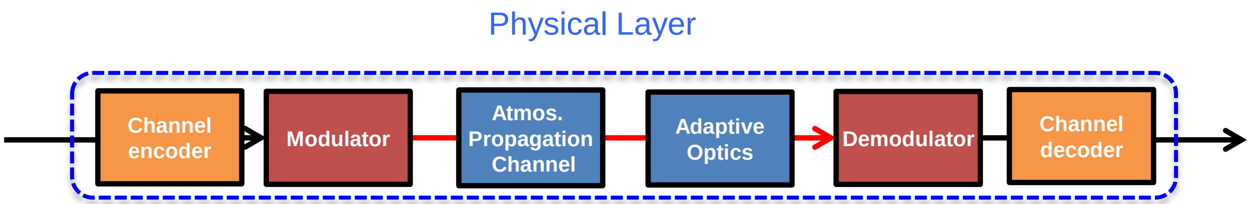
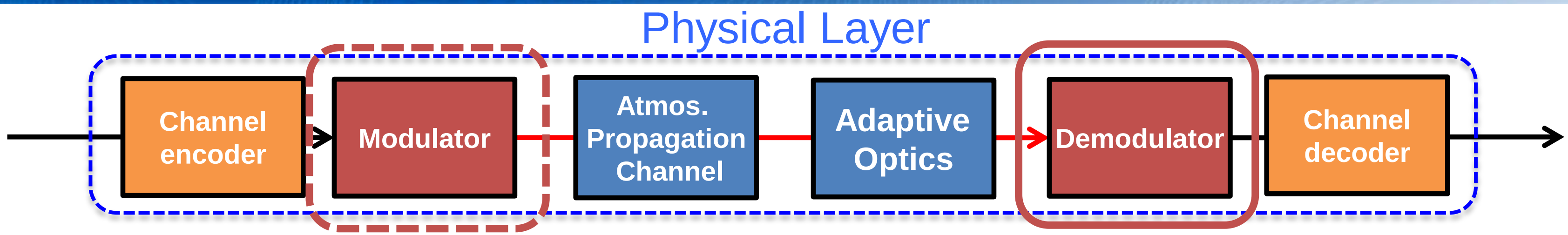


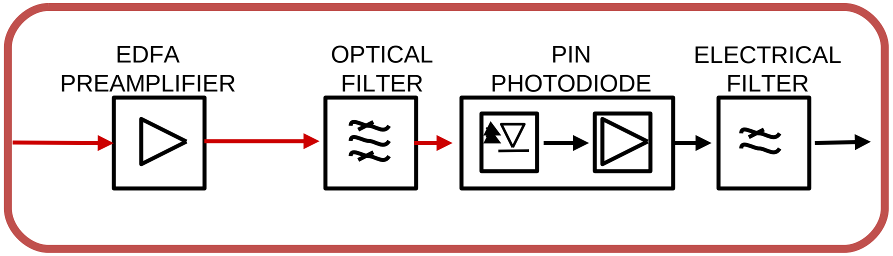
Optical Communication Subsystem Overview
Outage Probability
Minimum Required Interleaver

PART IV : AO/CROSS-LAYER OPTIMIZATION

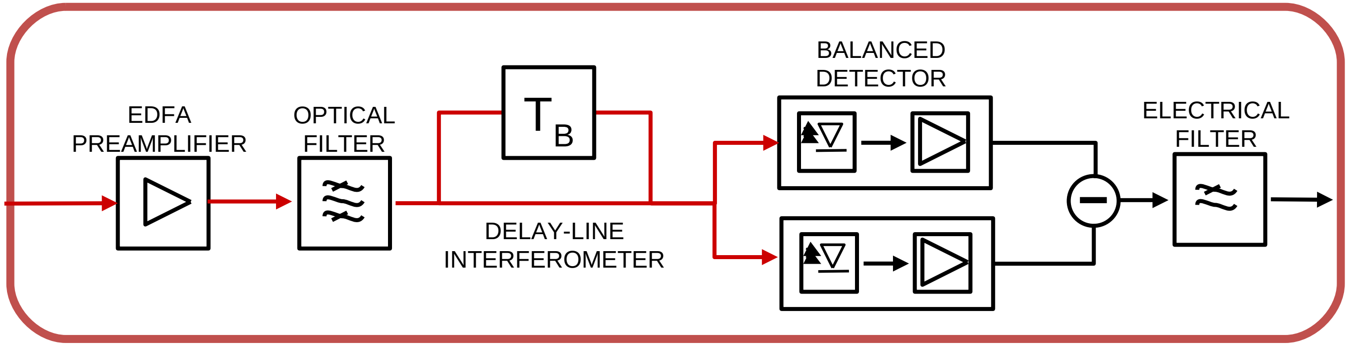
PHYSICAL LAYER PERFORMANCE END-TO-END MODELING



OOK Preamplified Detector

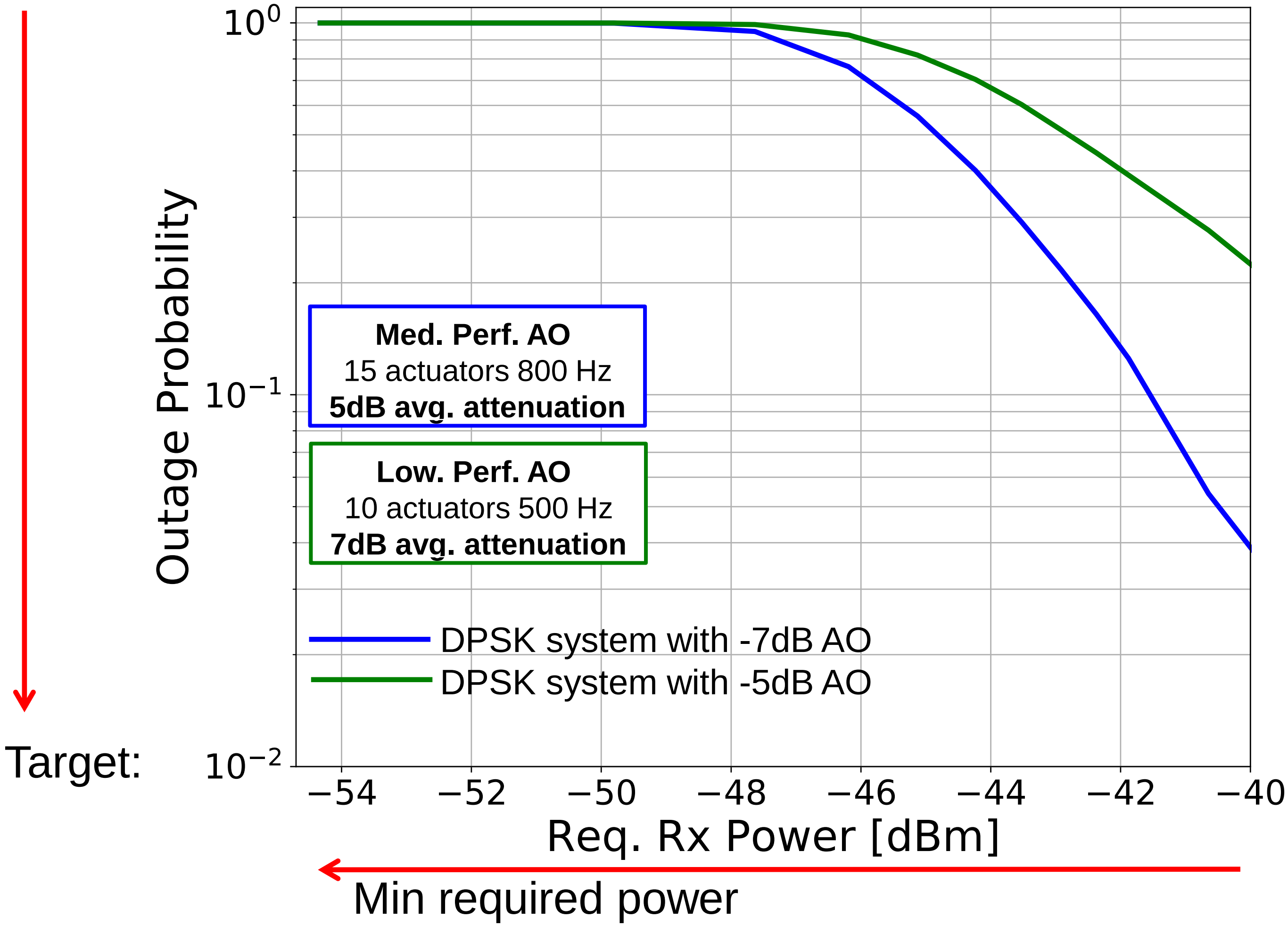


DPSK Balanced Detector



PHYSICAL LAYER TRADE-OFF ASSESSMENT
LEO application case Drx = 0.25 m | r_0 = 0.056 m

Outage probability for 10 Gbps link coderate R_0=0.5



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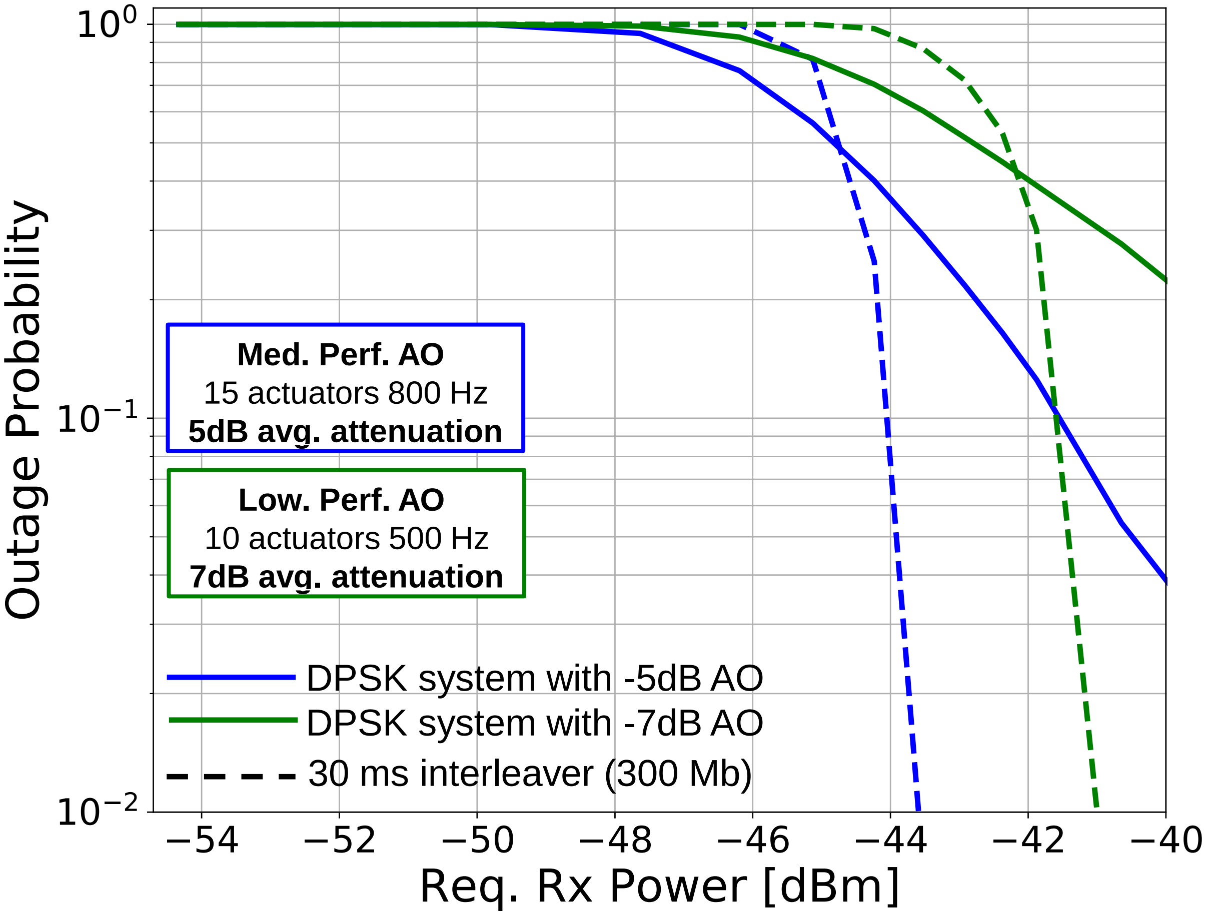
Target:



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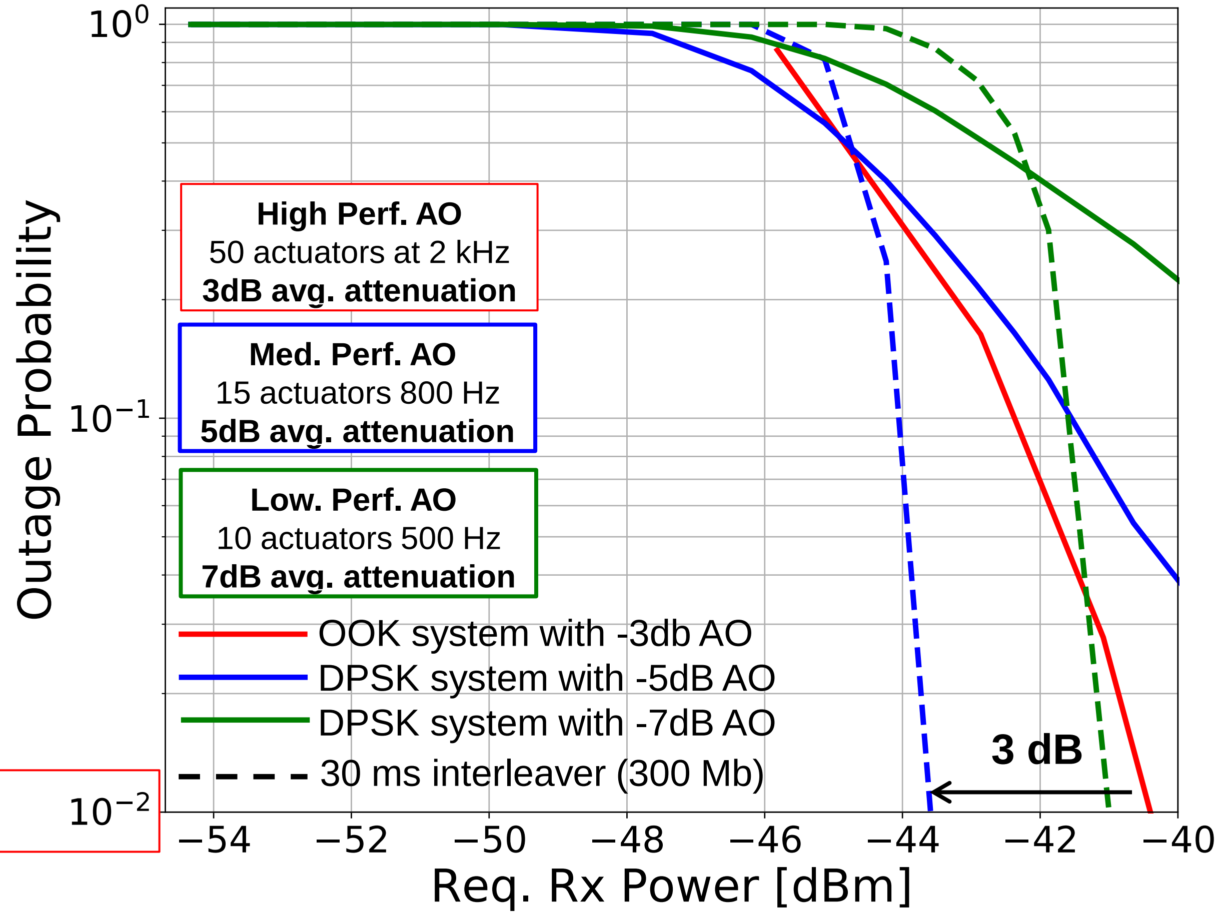
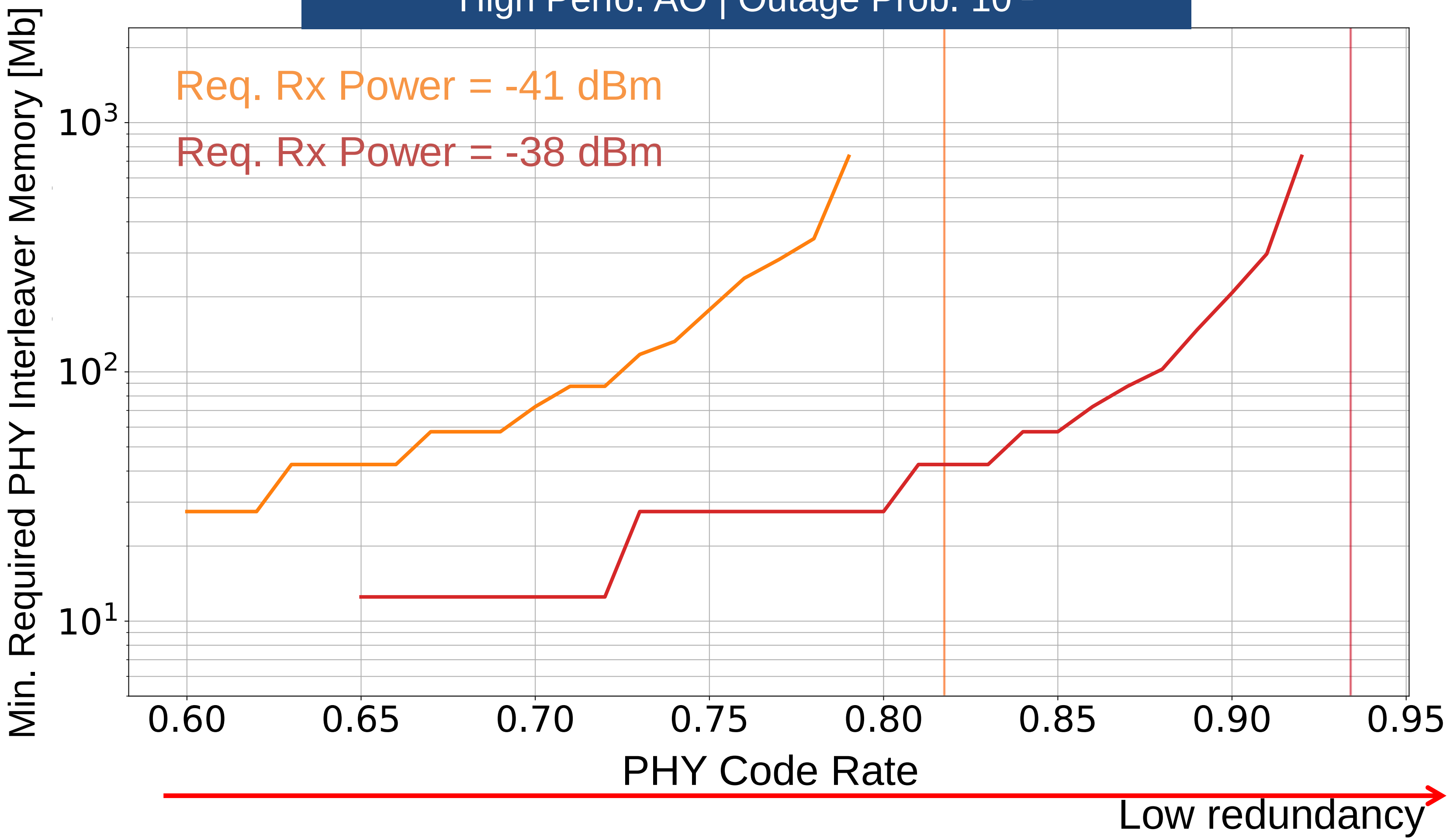


Target: 10^{-2}

Optimizing interleaver at targeted outage probability & required power?

PHYSICAL LAYER TRADE-OFF ASSESSMENT
LEO application case Drx = 0.25 m | r_0 = 0.056 m | OOK

Minimum Required PHY interleaving depth
High Perfo. AO | Outage Prob. 10^{-2}



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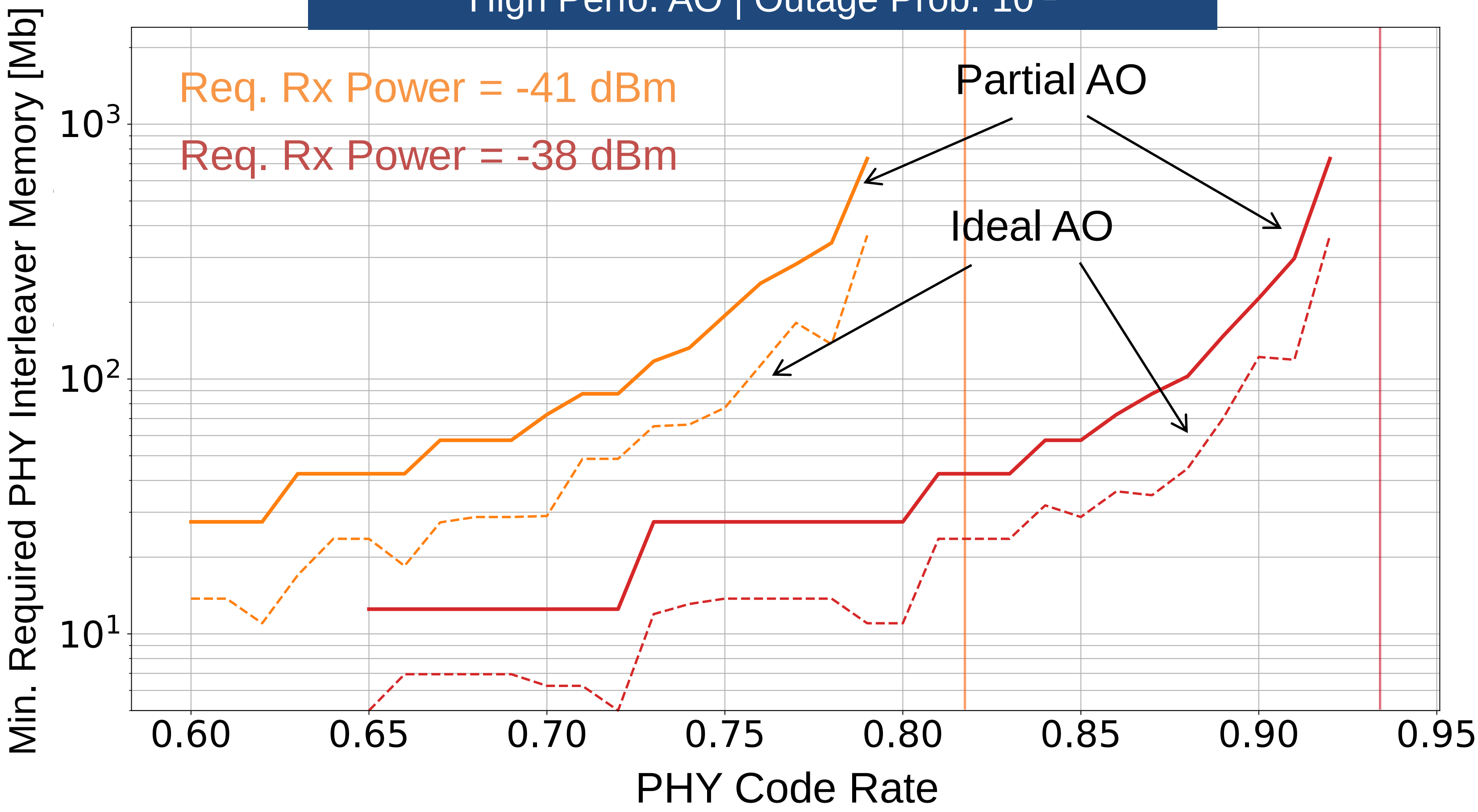

Neglecting lower order residuals underestimate required memory by 50%

PHYSICAL LAYER TRADE-OFF ASSESSMENT
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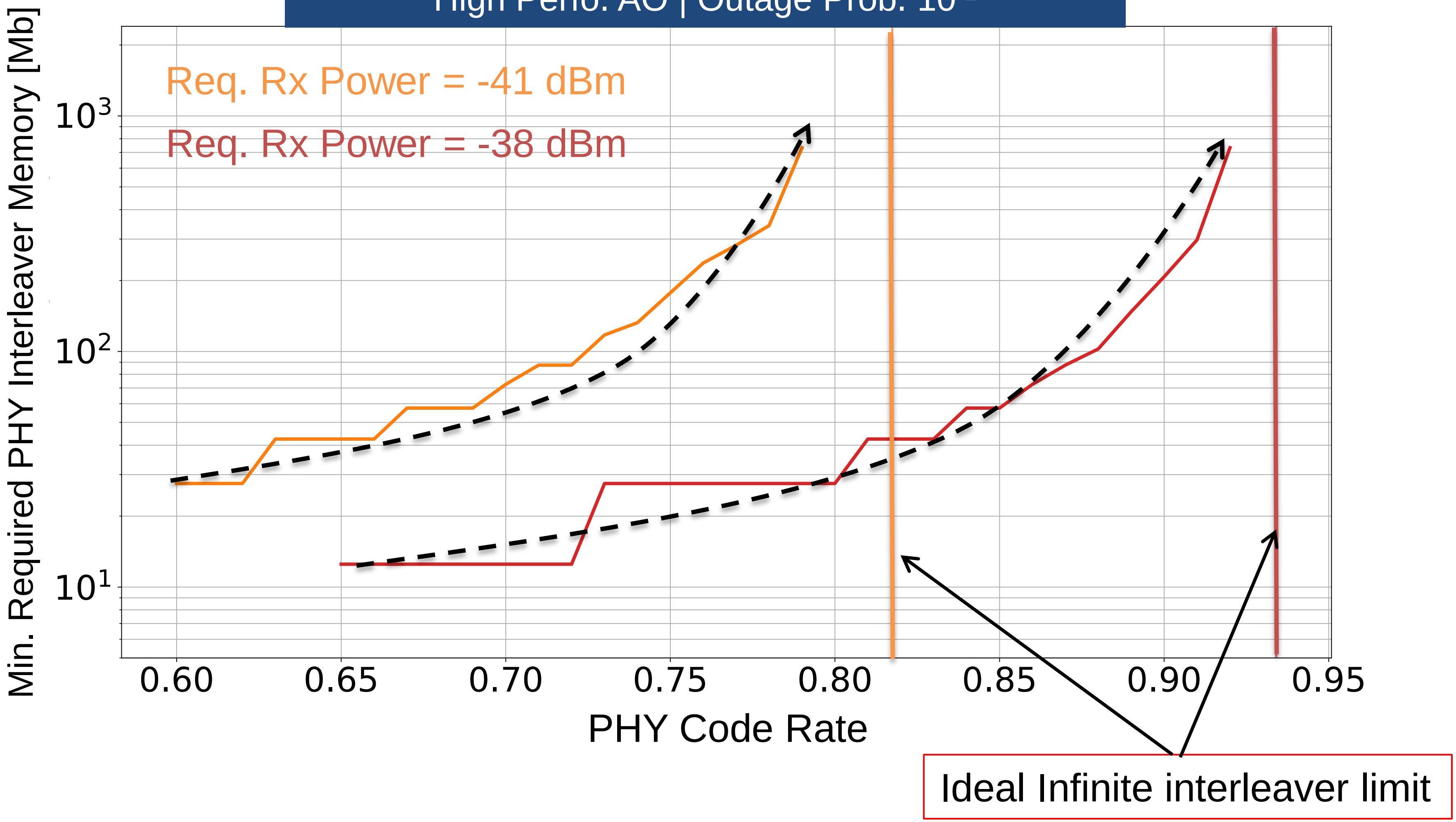
Minimum Required PHY interleaving depth
High Perfo. AO | Outage Prob. 10^{-2}



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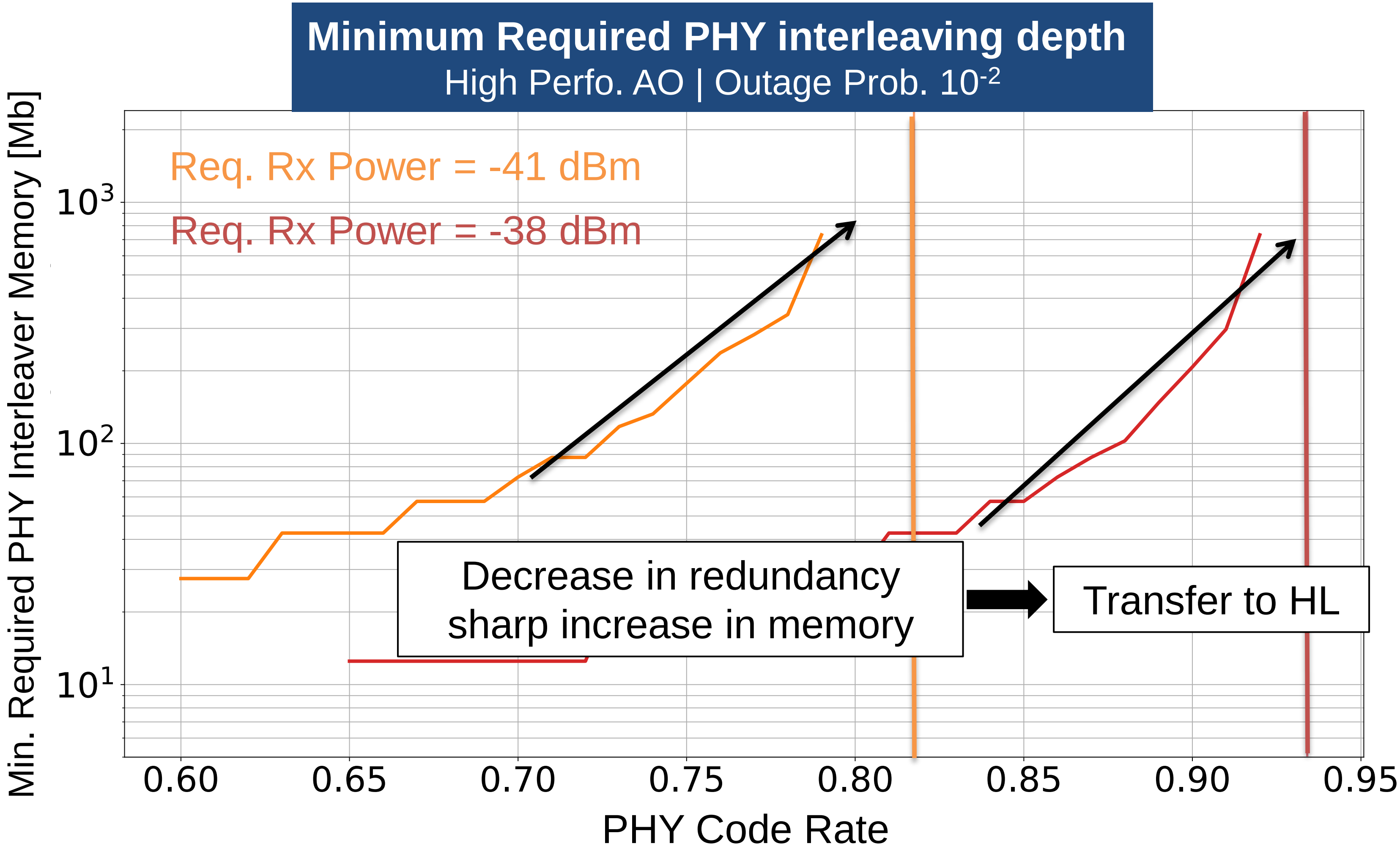

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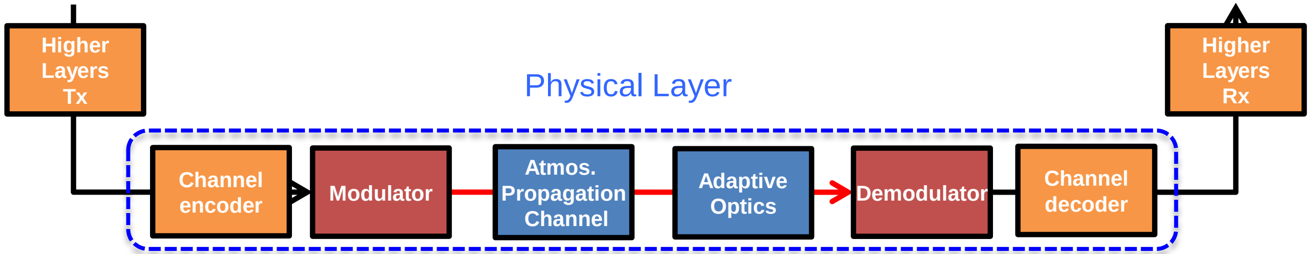
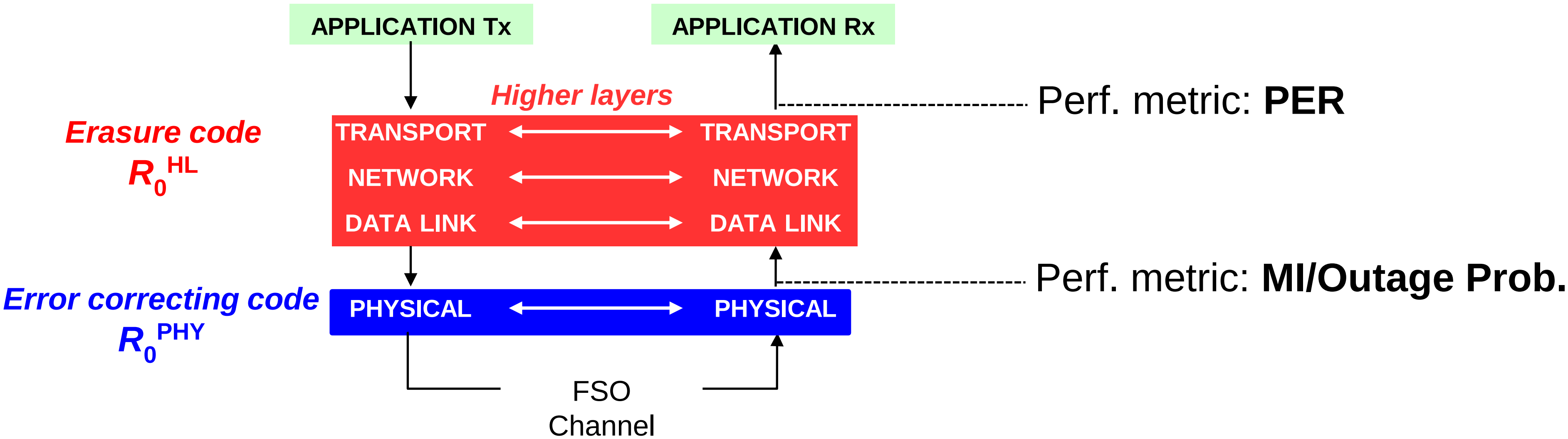


Modeling of Cross-layer Coding Scheme
Case Study: LEO Downlink Using DPSK

CROSS-LAYER APPROACH : Overview

CODING and **INTERLEAVING** possible at both **PHY LAYER** and **HIGHER LAYERS**

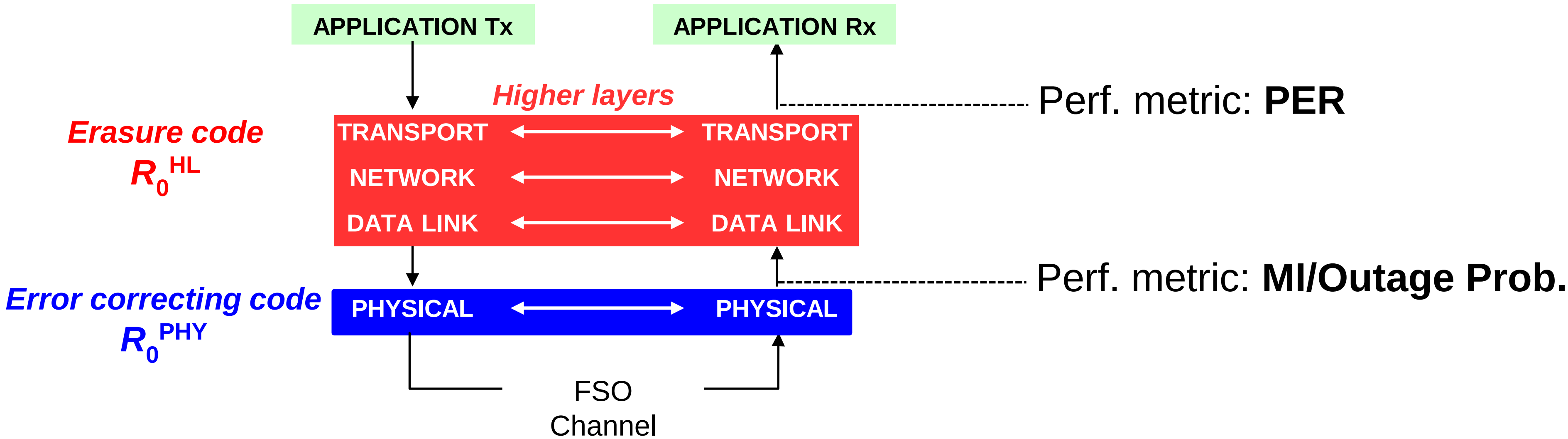


The PHY and HL coderates inherently related through definition of global coderate:

Fixed global code rate
$R_0^{GLOBAL} = R_0^{PHY} R_0^{HL}$ ⟷ **Useful Data Rate = raw data-rate** x R_0^{GLOBAL}

CROSS-LAYER APPROACH : Overview

CODING and **INTERLEAVING** possible at both **PHY LAYER** and **HIGHER LAYERS**



The PHY and HL coderates inherently related through definition of global coderate:

Fixed global code rate
$R_0^{GLOBAL} = R_0^{PHY} R_0^{HL}$ ⟷ **Useful Data Rate = raw data-rate** x R_0^{GLOBAL}

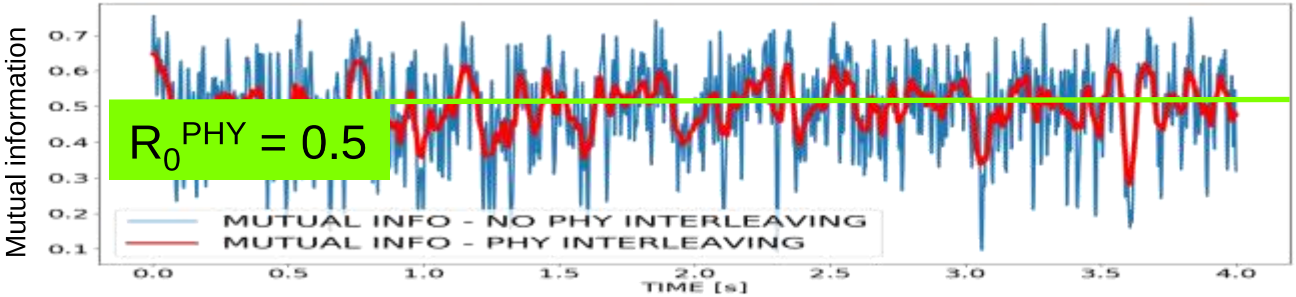
Tx PHY memory = PHY interleaver depth x **raw data-rate**

Tx HL memory = HL interleaver depth x **raw data-rate** x R_0^{PHY}

→ Advantage to HL

$R_0^{GLOBAL} = R_0^{PHY} R_0^{HL} = 0.3$

PHYSICAL LAYER

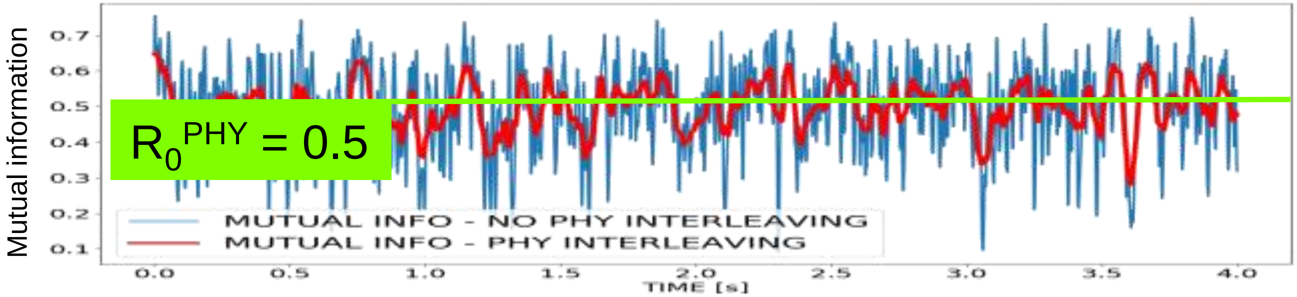


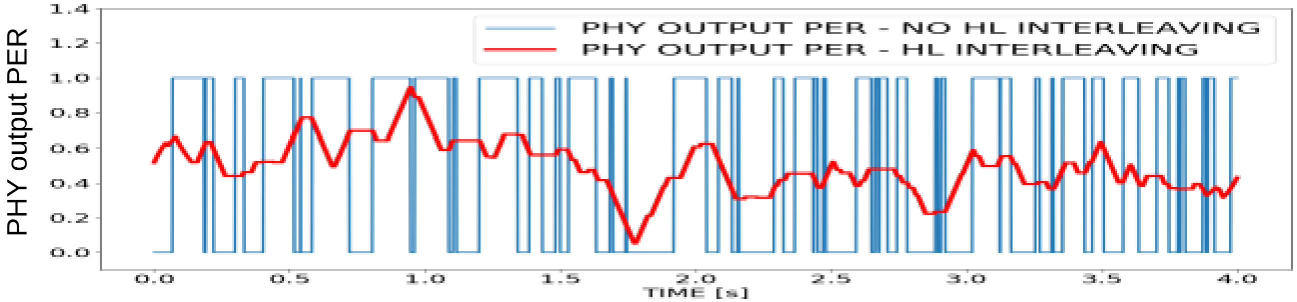
CROSS-LAYER APPROACH : Modeling

$R_0^{GLOBAL} = R_0^{PHY} R_0^{HL} = 0.3$

PHYSICAL LAYER

HIGHER LAYERS
DATA LINK | NETWORK | TRANSPORT





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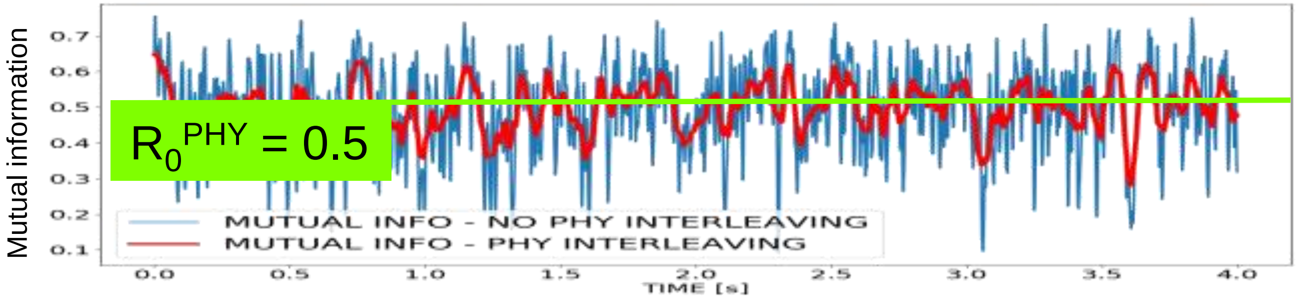
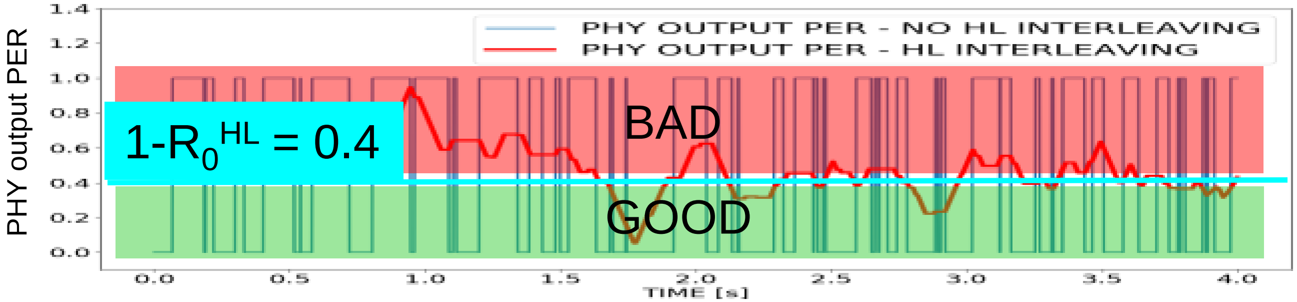
PHYSICAL LAYER

HIGHER LAYERS
DATA LINK | NETWORK | TRANSPORT





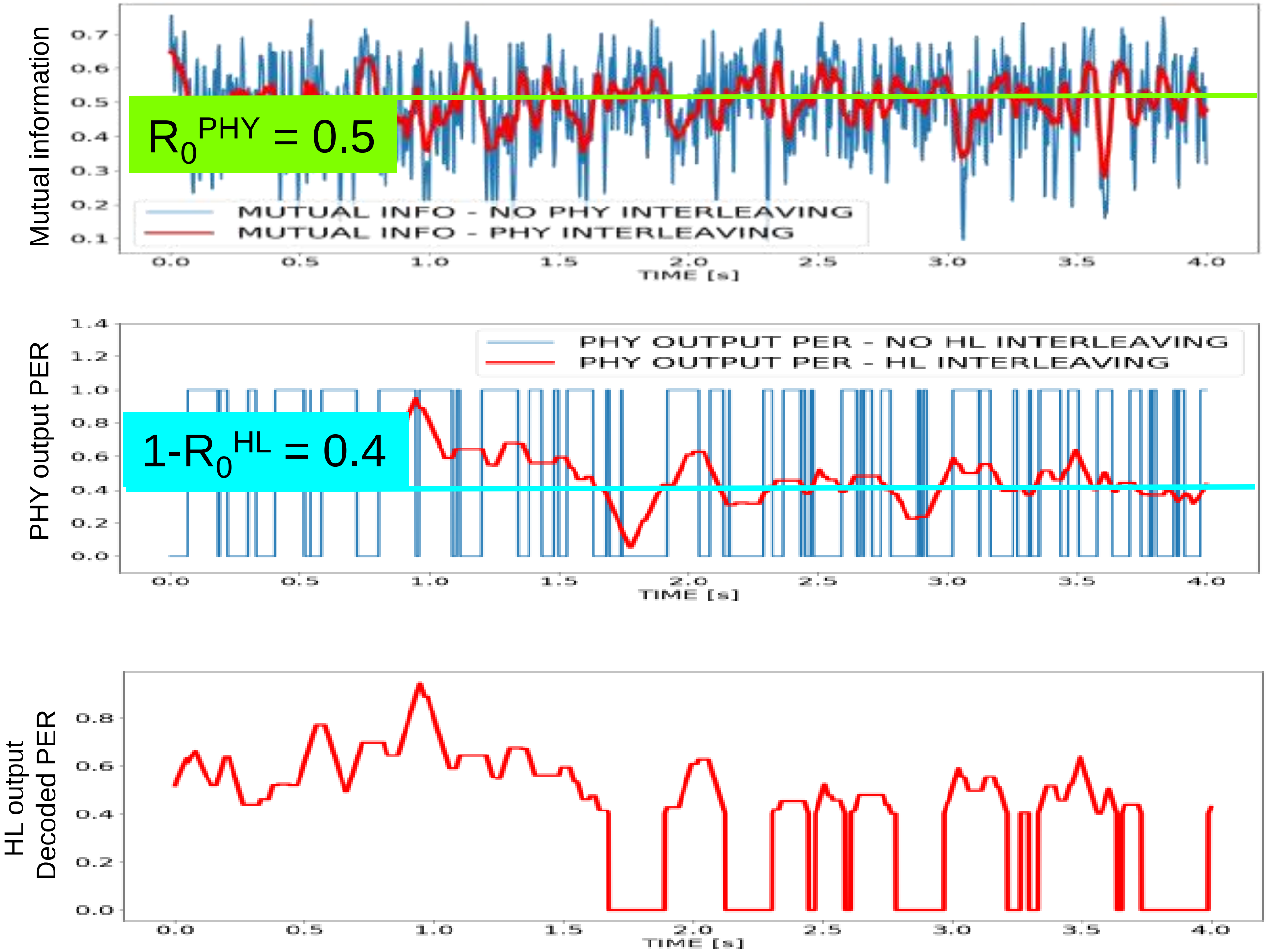
CROSS-LAYER APPROACH : Modeling

$$R_0^{GLOBAL} = R_0^{PHY} R_0^{HL} = 0.3$$

PHYSICAL LAYER

HIGHER LAYERS
DATA LINK | NETWORK | TRANSPORT

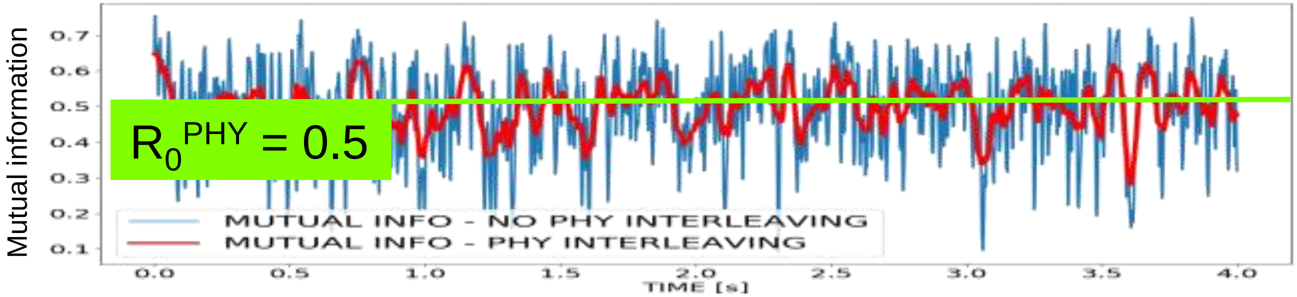
APPLICATION LAYER



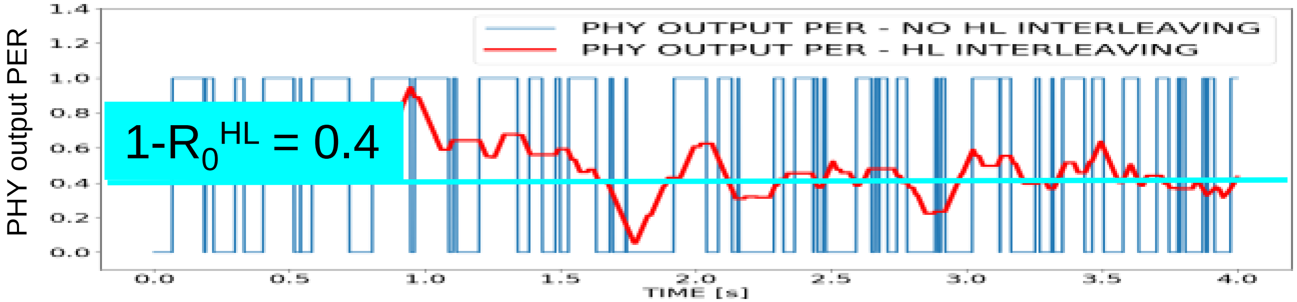
CROSS-LAYER APPROACH : Modeling

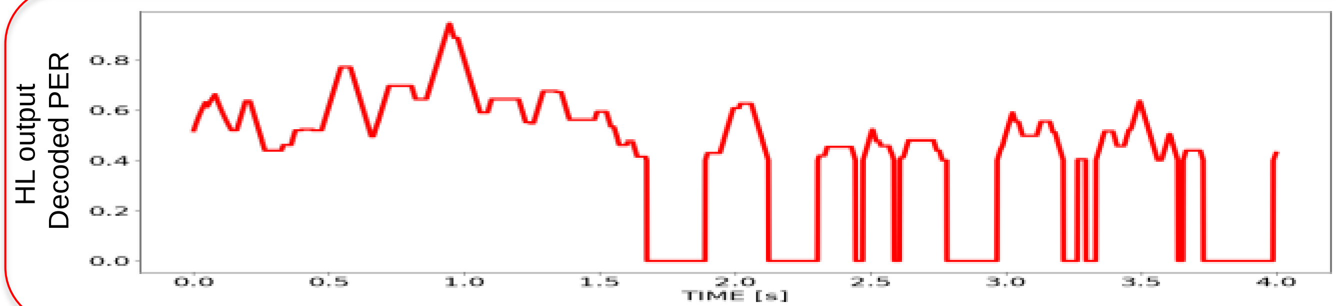
$R_0^{GLOBAL} = R_0^{PHY} R_0^{HL} = 0.3$

PHYSICAL LAYER



HIGHER LAYERS
DATA LINK | NETWORK | TRANSPORT



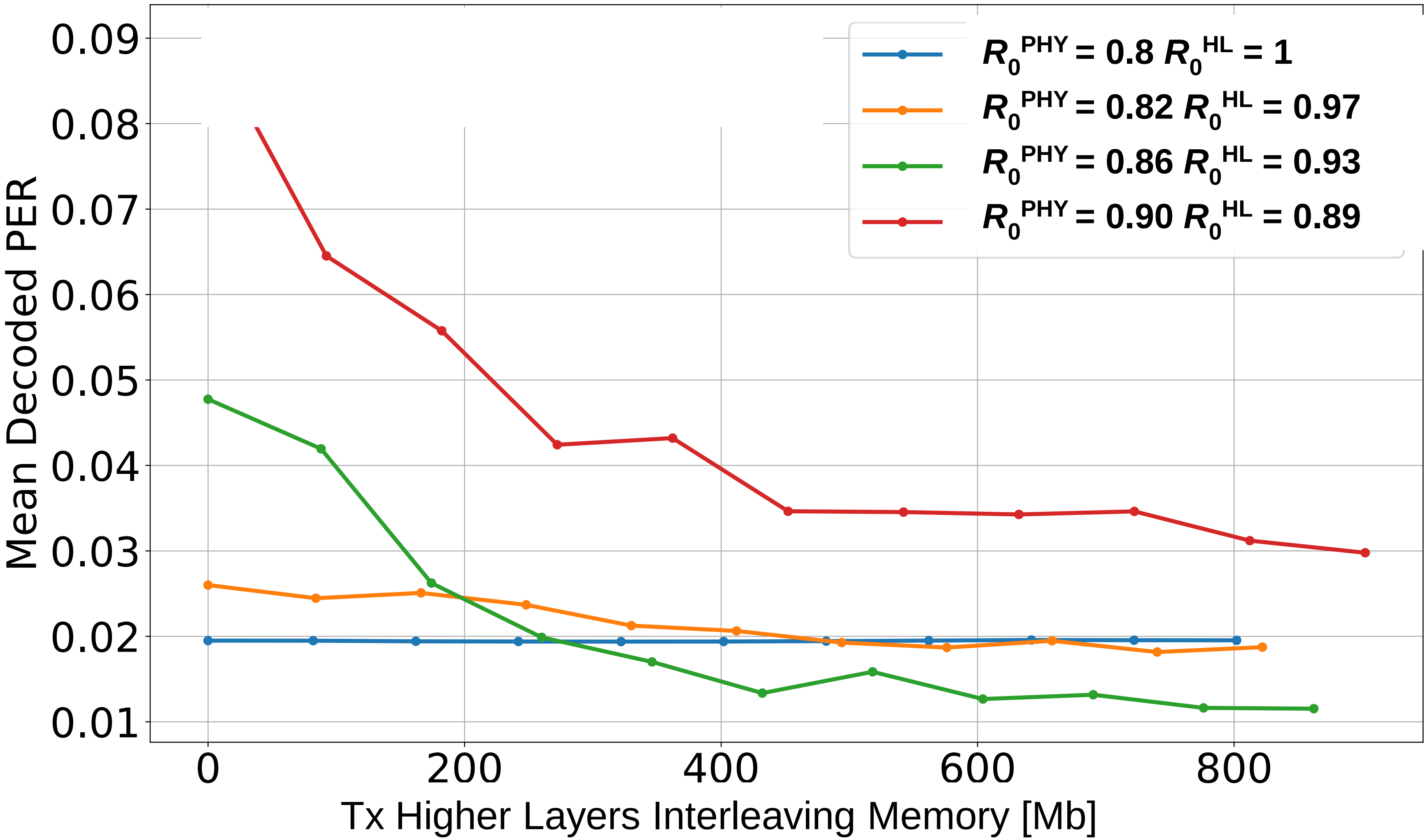


APPLICATION LAYER

FINAL PERFORMANCE METRIC : Average of decoded PER

CROSS-LAYER APPROACH : Benefits illustration
R_0^{GLOBAL} = 0.8 | Req. Power = -38 dBm | PHY interleaver 50 Mb

Average decoded PER against size of HL interleaving



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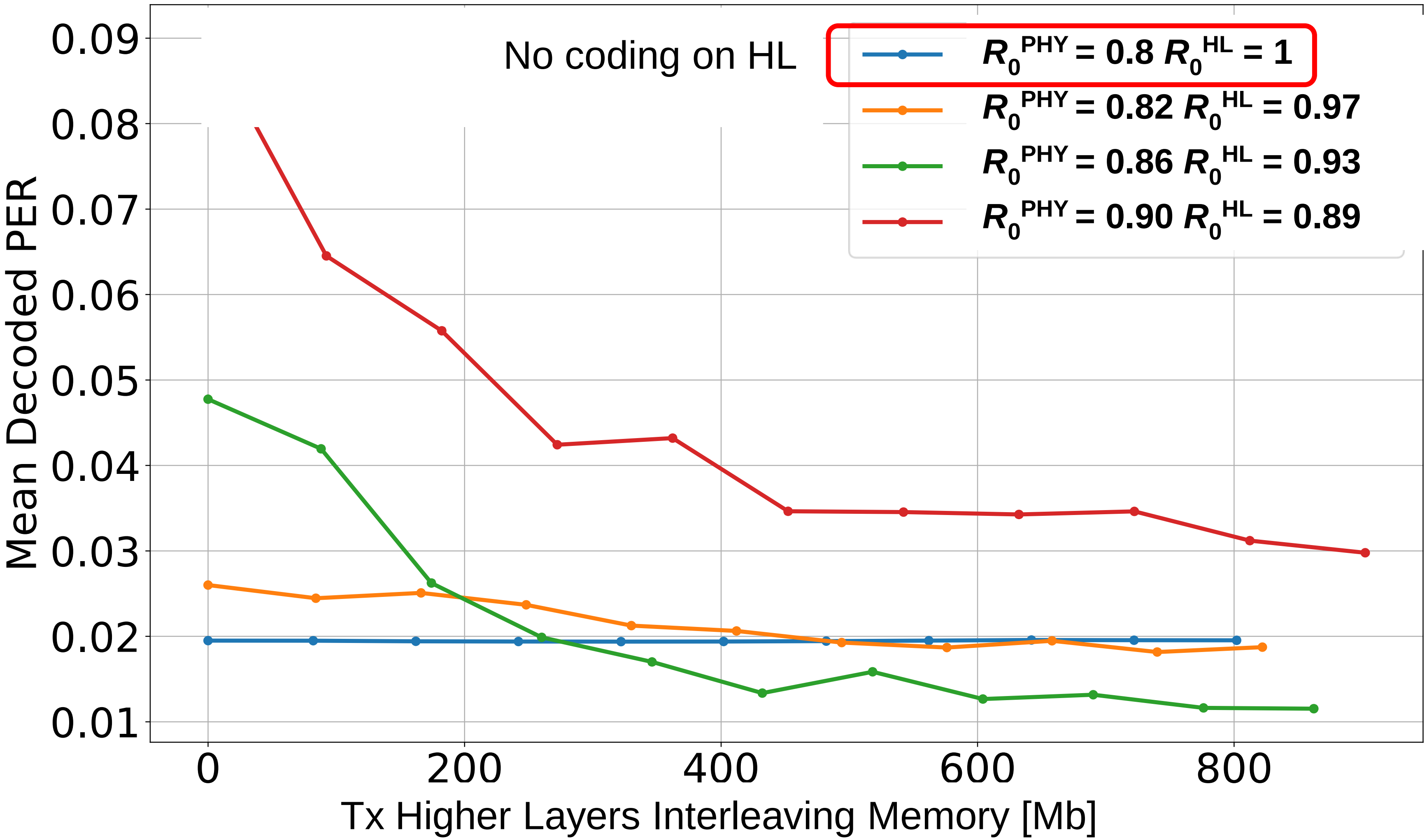

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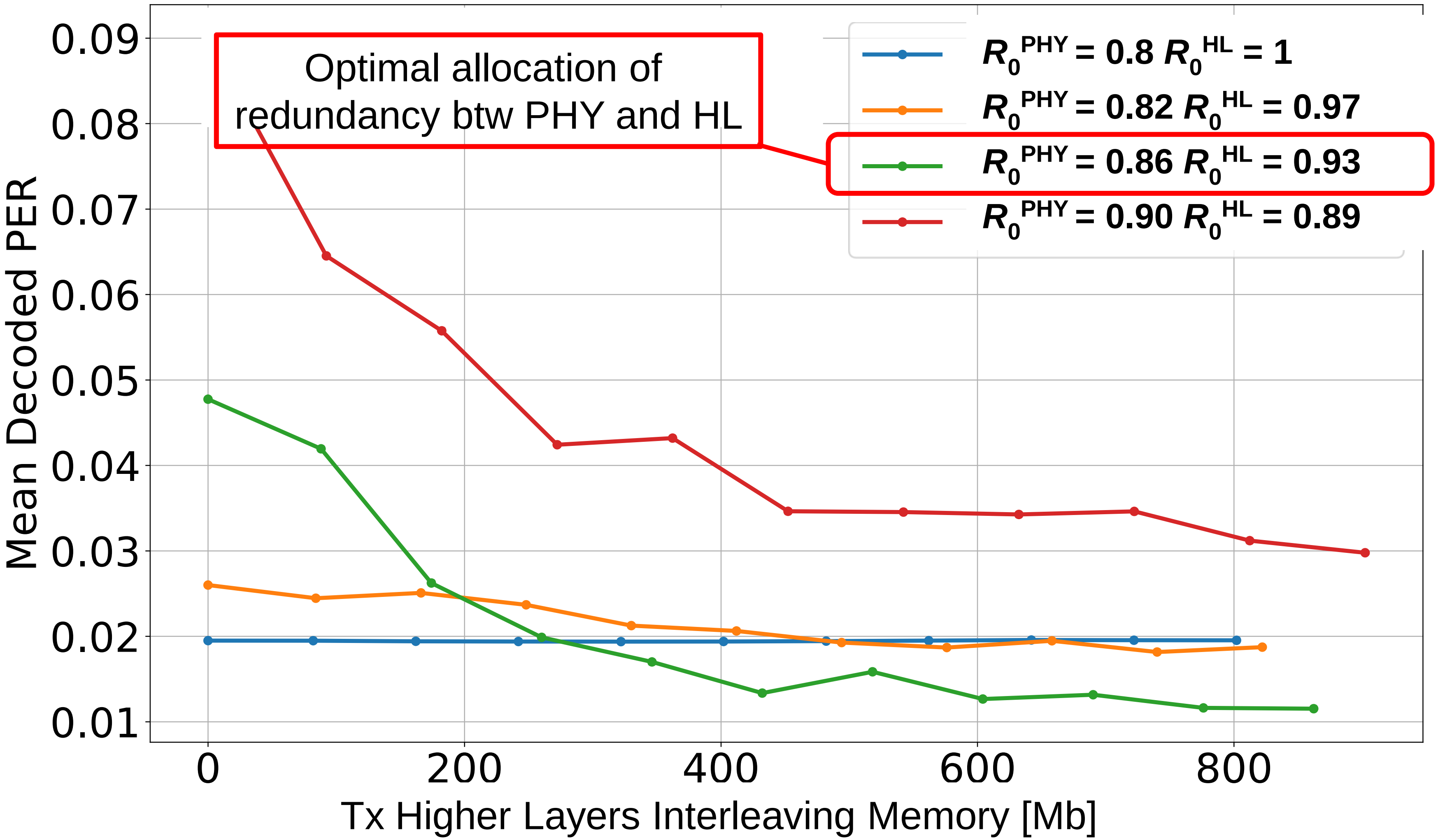
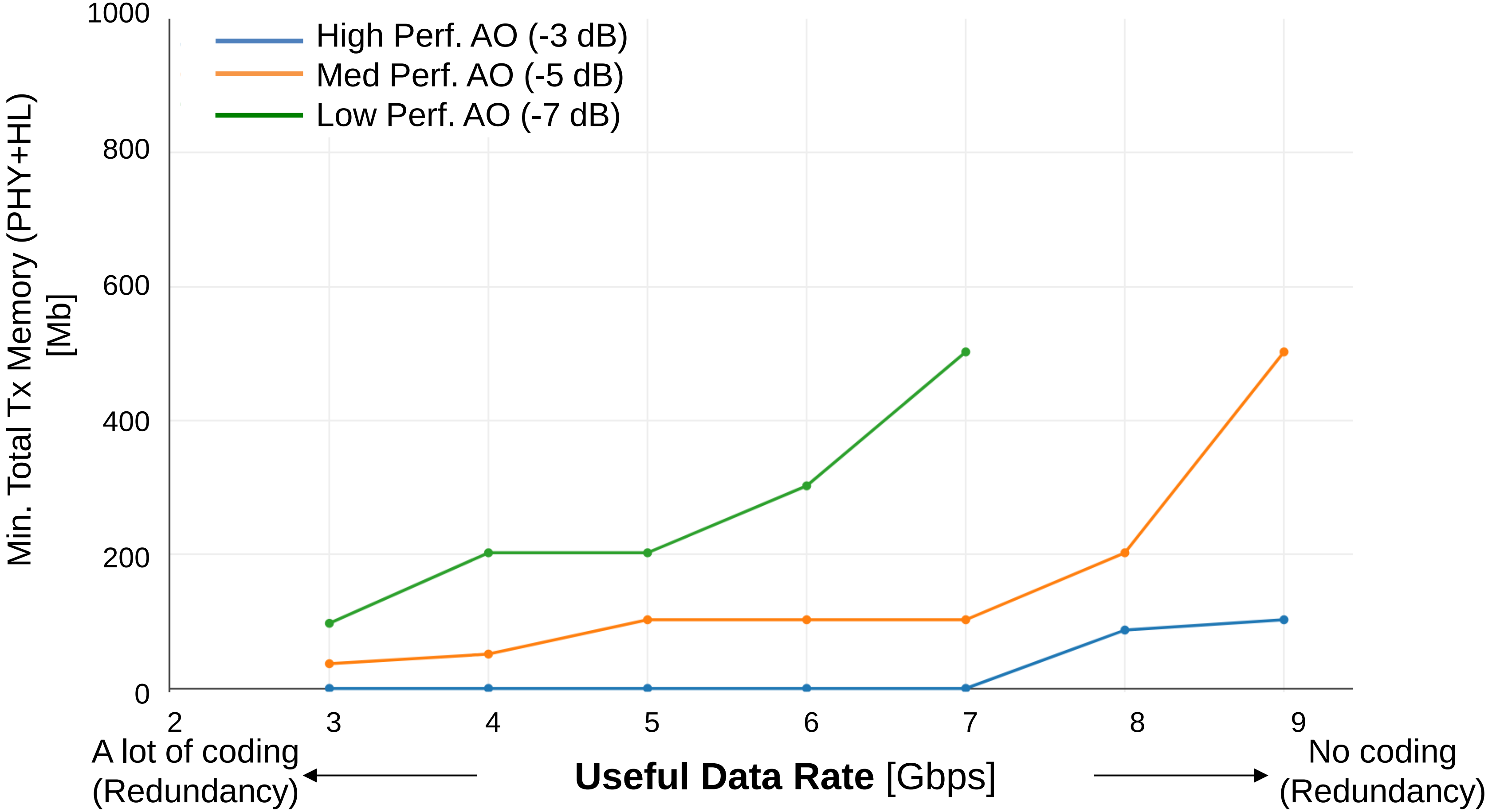


RESOURCES OPTIMIZATION USING MINIMUM TOTAL MEMORY
TARGET PER = 10^{-4} | 10 Gbps LEO link
DPSK Receiver



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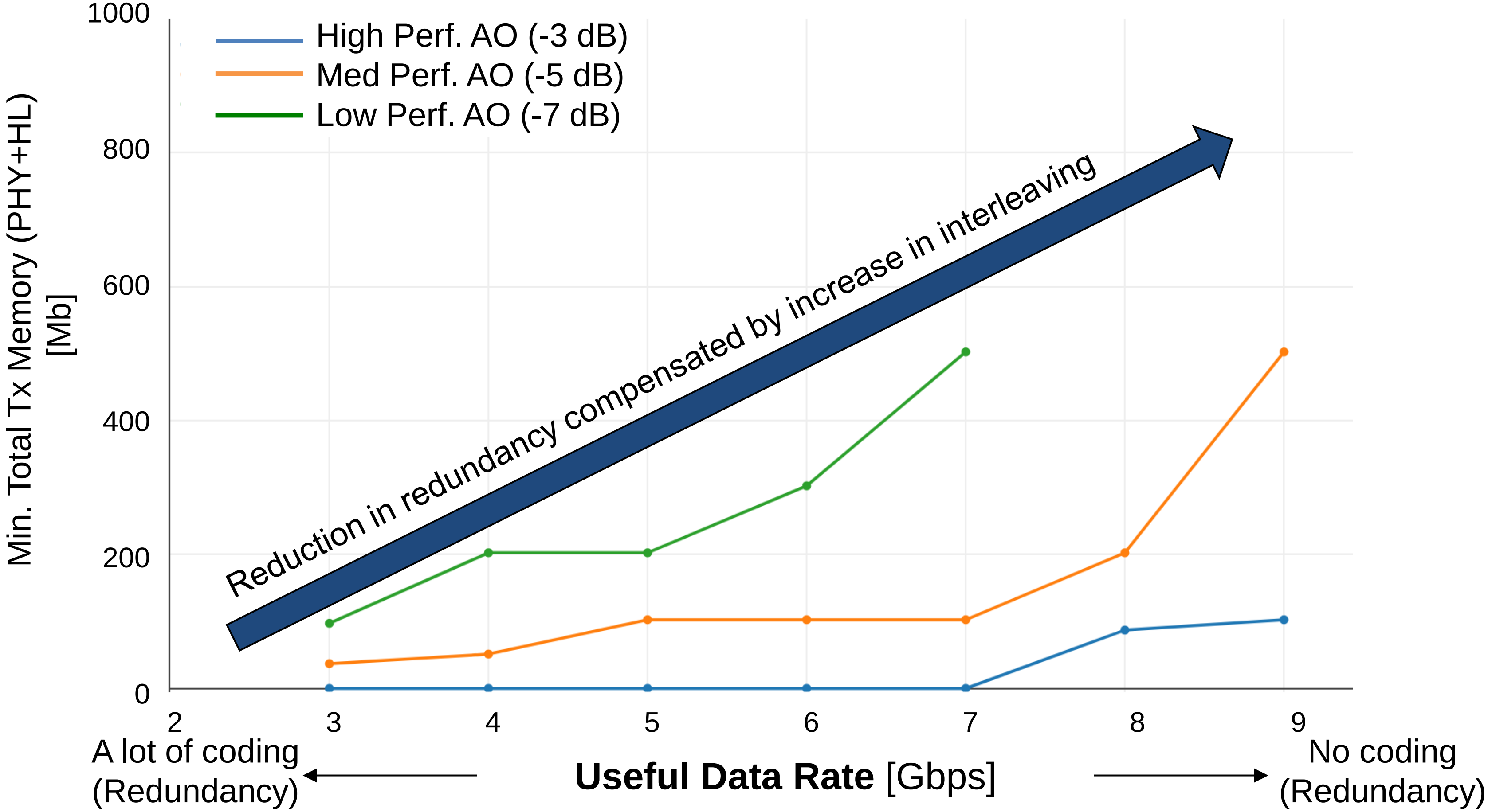
DPSK Receiver



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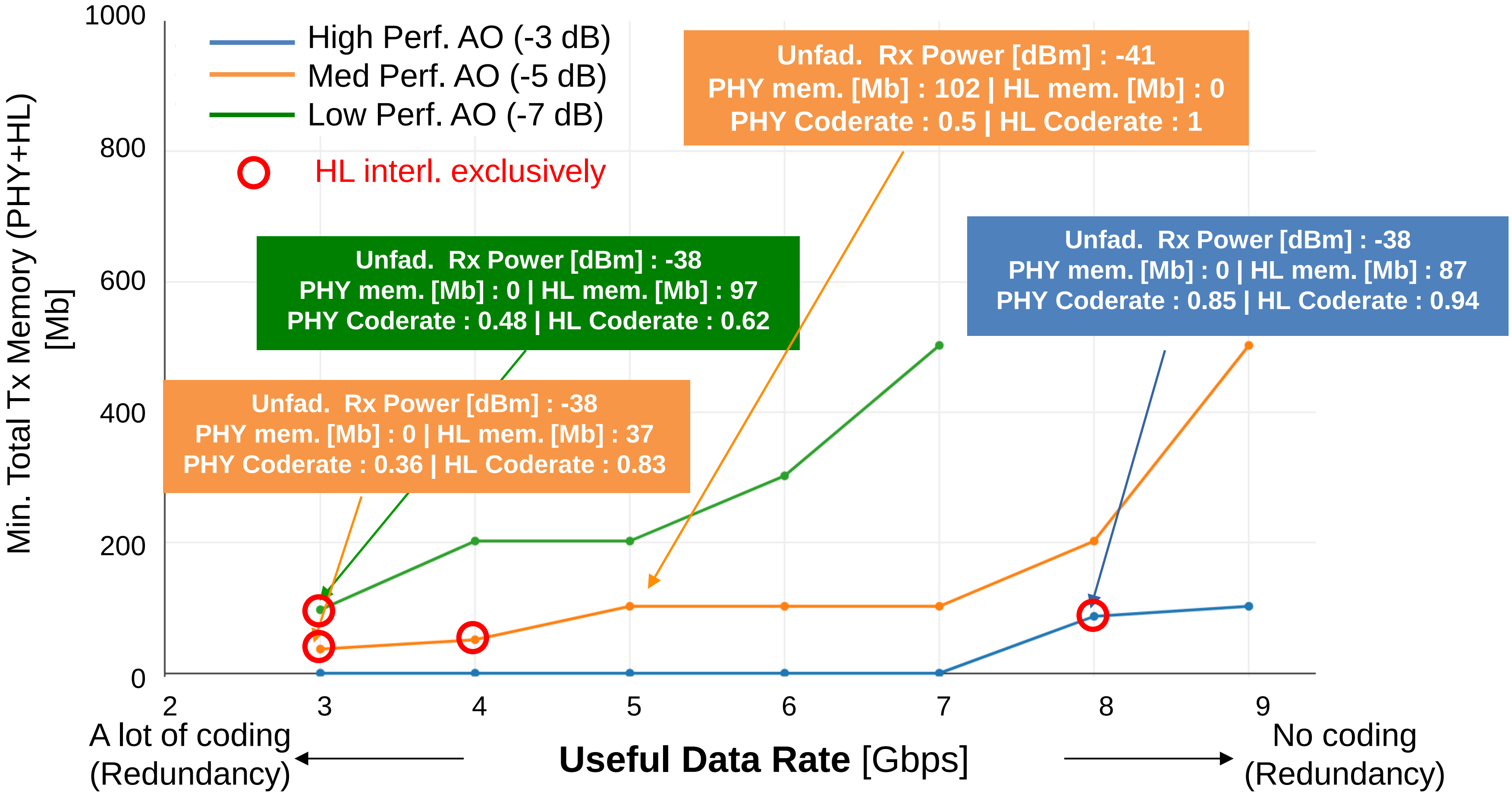

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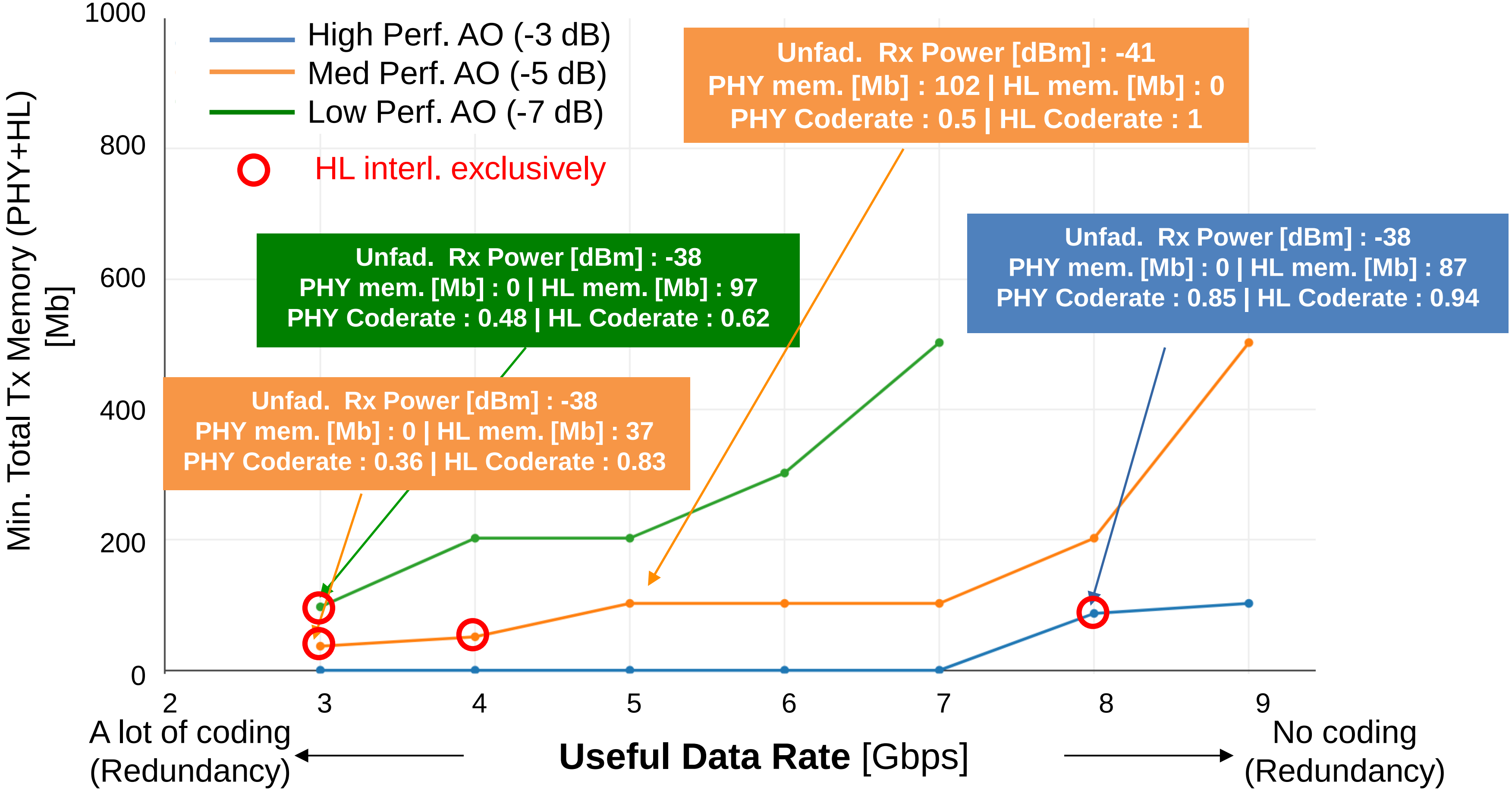
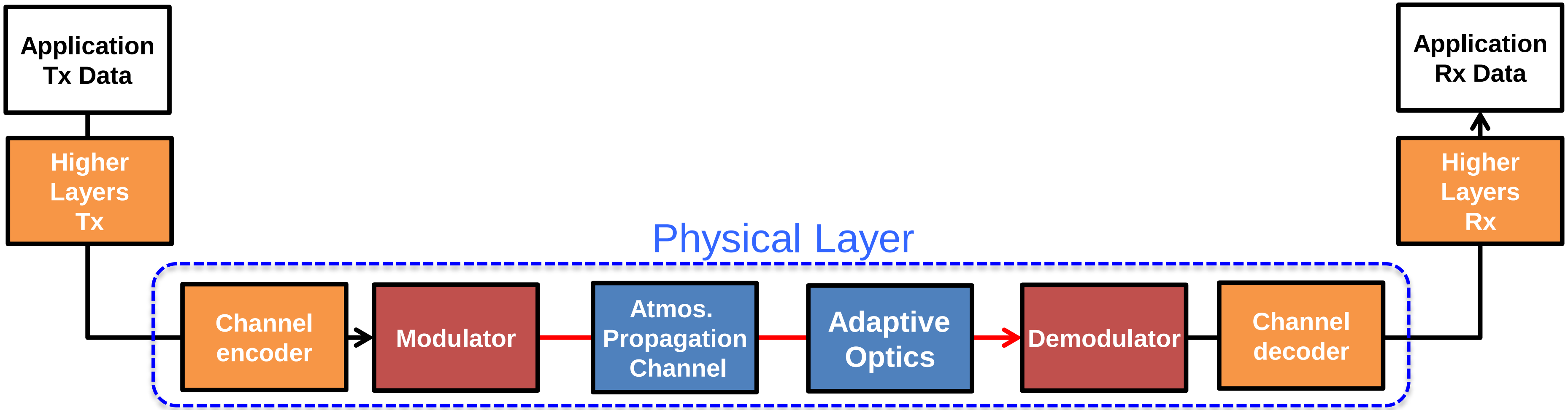


HL interleaving optimal in less challenging conditions

Physical turbulence mitigation techniques (AO) can have significant impact on overall system design optimization by driving hardware trade-offs (eg. ASIC vs RAM interleaver)

CONCLUSION
How to ensure reliable optical downlinks?



SIGNIFICANT RESULTS

- First accurate model of partially corrected coupled flux into SMFs
- Detailed investigation of required physical layer interleaving depth and ECC
- First application of cross-layer coding/interleaving scheme to sat. opt. transmissions
- Investigation of overall optimization of AO and data reliability mechanisms

RECOMMENDATION FOR FUTURE WORK

- **Experimental validation-** LEO Downlink planned (DLR's OSIRIS & ONERA's LISA)

- **Investigation of performance evolution over the duration of a whole link**

- **Input turbulence conditions not well known (except astron. observation sites)**

- **Transposition of approach to GEO uplink**

PUBLICATIONS AND COMMUNICATIONS

Peer-reviewed publication

- Canuet L., Védrenne N., Conan J-M. , Petit C., Artaud G., Rissons A., and Lacan J., **« *Statistical properties of single-mode fiber coupling of satellite-to-ground laser links partially corrected by adaptive optics* »** J. Opt. Soc. Am. A 35, 148-162 (2018)

International conferences

- Canuet L., Védrenne N., Conan J-M., Artaud G., Rissons A., and Lacan J., **"Evaluation of communication performance for adaptive optics corrected GEO-to-ground laser links"**, in proceedings of ICSO (International Conference on Space Optics) 2016, Biarritz, France

- Canuet L., Lacan J., Védrenne N., Artaud G., and Rissons A., "**Performance Evaluation of Coded Transmission for Adaptive-Optics Corrected Satellite-To-Ground Laser Links"**, in proceedings of ICSOS (IEEE International Conference on Space Optical Systems and Applications), November 2017 – Naha, Okinawa, Japan

- Canuet L., Lacan J., Védrenne N., Artaud G., and Rissons A., **"Cross-layer optimization for adaptive-optics corrected satellite-to-ground laser links"**, in proceedings of the 8th international symposium – OPTRO 2018 optronics in defense and security, 6-8 February 2018, Paris

ACKNOWLEDGEMENTS

Committee members

Pr. Peucheret
Pr. Belmonte
Pr. Kahn
Dr. Sodnik
Dr. Perlot

Advisors

Jérôme Lacan
Angélique Rissons
Nicolas Védrenne
Géraldine Artaud

ONERA

Jean-Marc Conan
Cyril Petit

CNES

Bouchra Benammar

Airbus DS

Sylvain Poulenard
Hervé Haag
Thomas Anfray

Thales AS

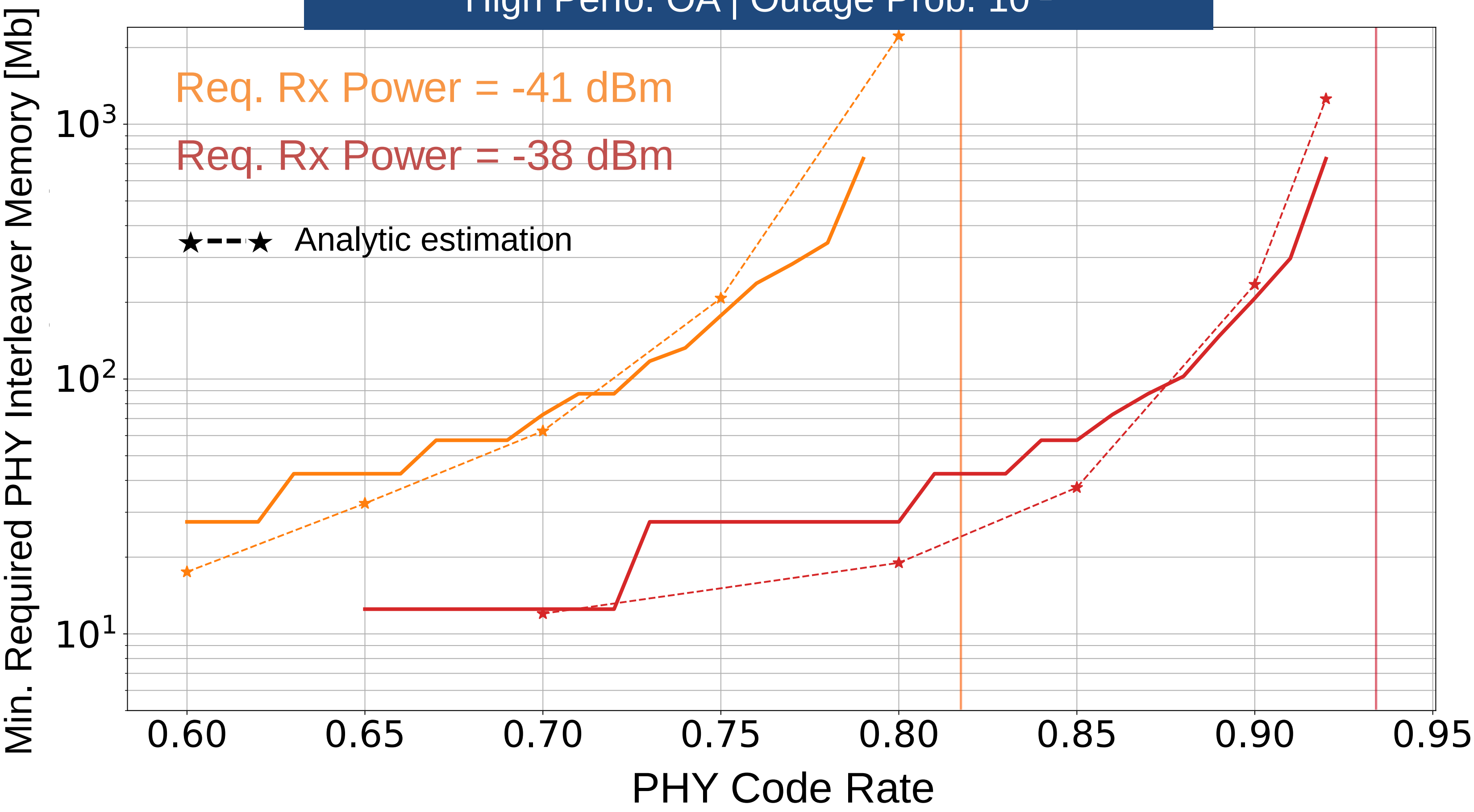
Michel Sotom
Arnaud Le Kernec

TéSA

Corinne Mailhes

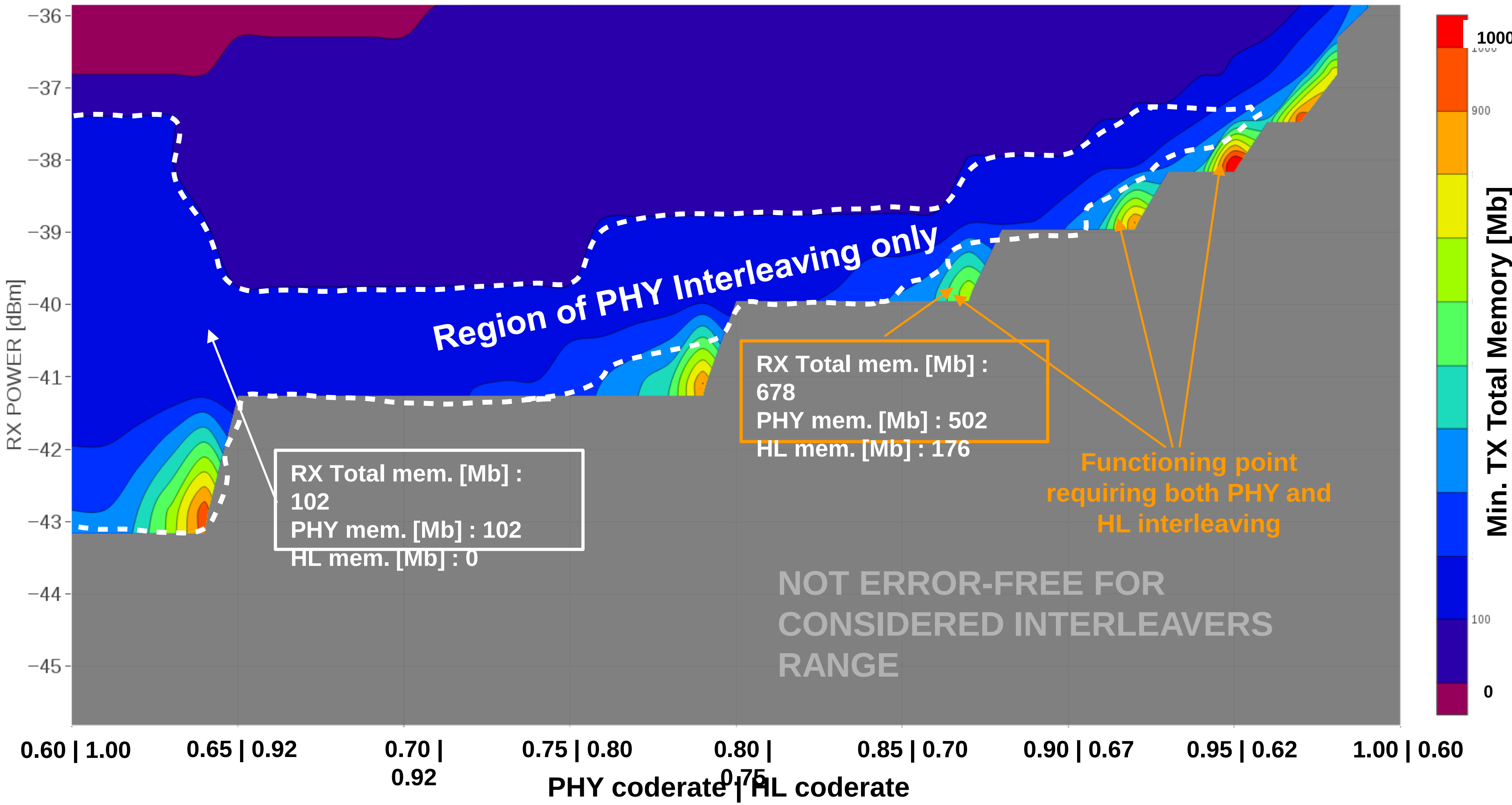
PHYSICAL LAYER TRADE-OFF ASSESSMENT
Minimum required interleaving depth

Minimum Required PHY interleaving depth
High Perfo. OA | Outage Prob. 10^{-2}



Analytic estimation based on statistical and temporal characteristics of coupled flux

MINIMUM MEMORY REQUIRED FOR ERROR-FREE TRANSMISSION
10 Gbps link | R_0^{GLOBAL} = 0.6 (6 Gbps throughput) | High Perf. AO



ONERA
THE FRENCH AEROSPACE LAB

MINIMUM MEMORY REQUIRED FOR ERROR-FREE TRANSMISSION
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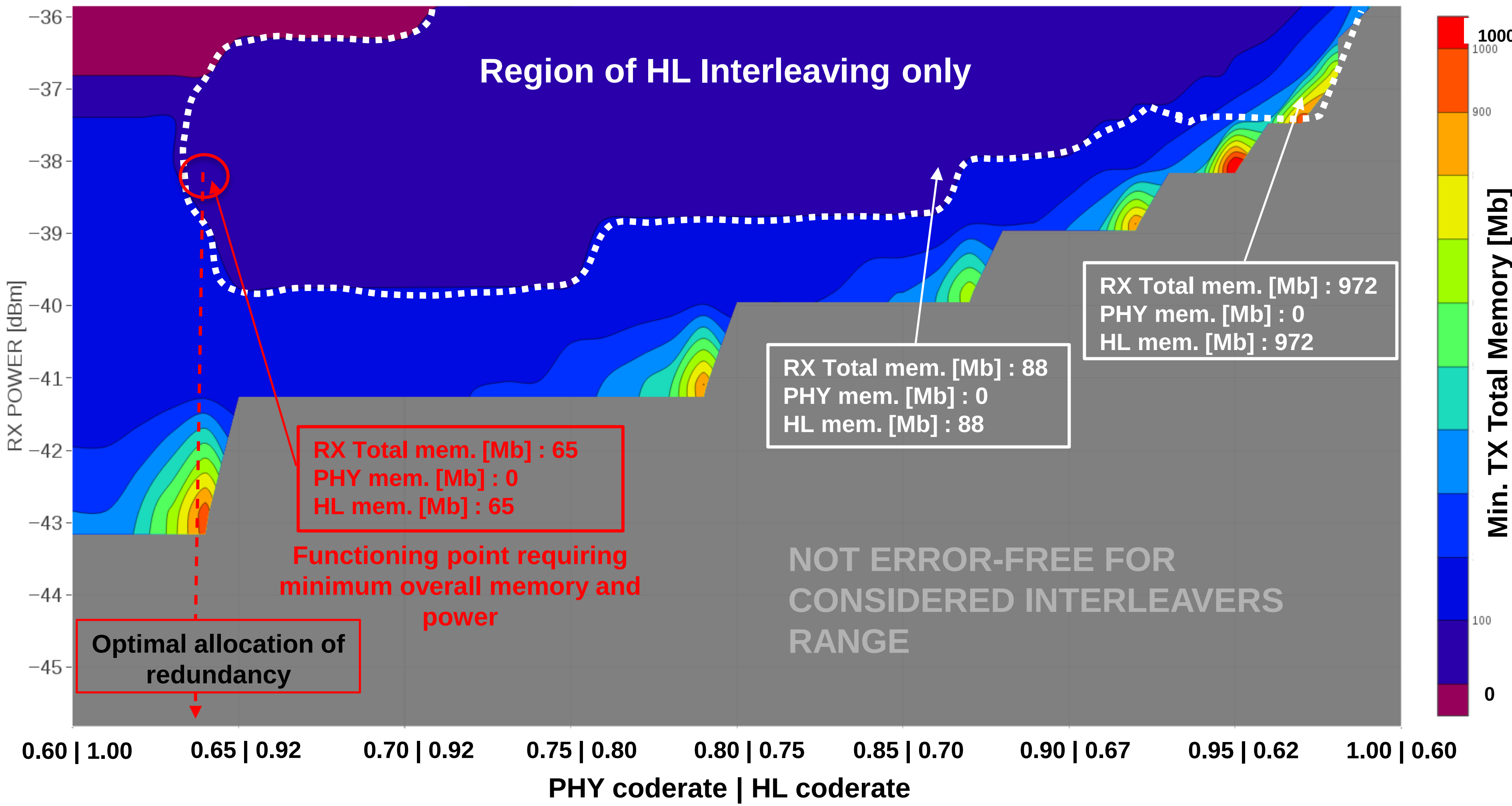
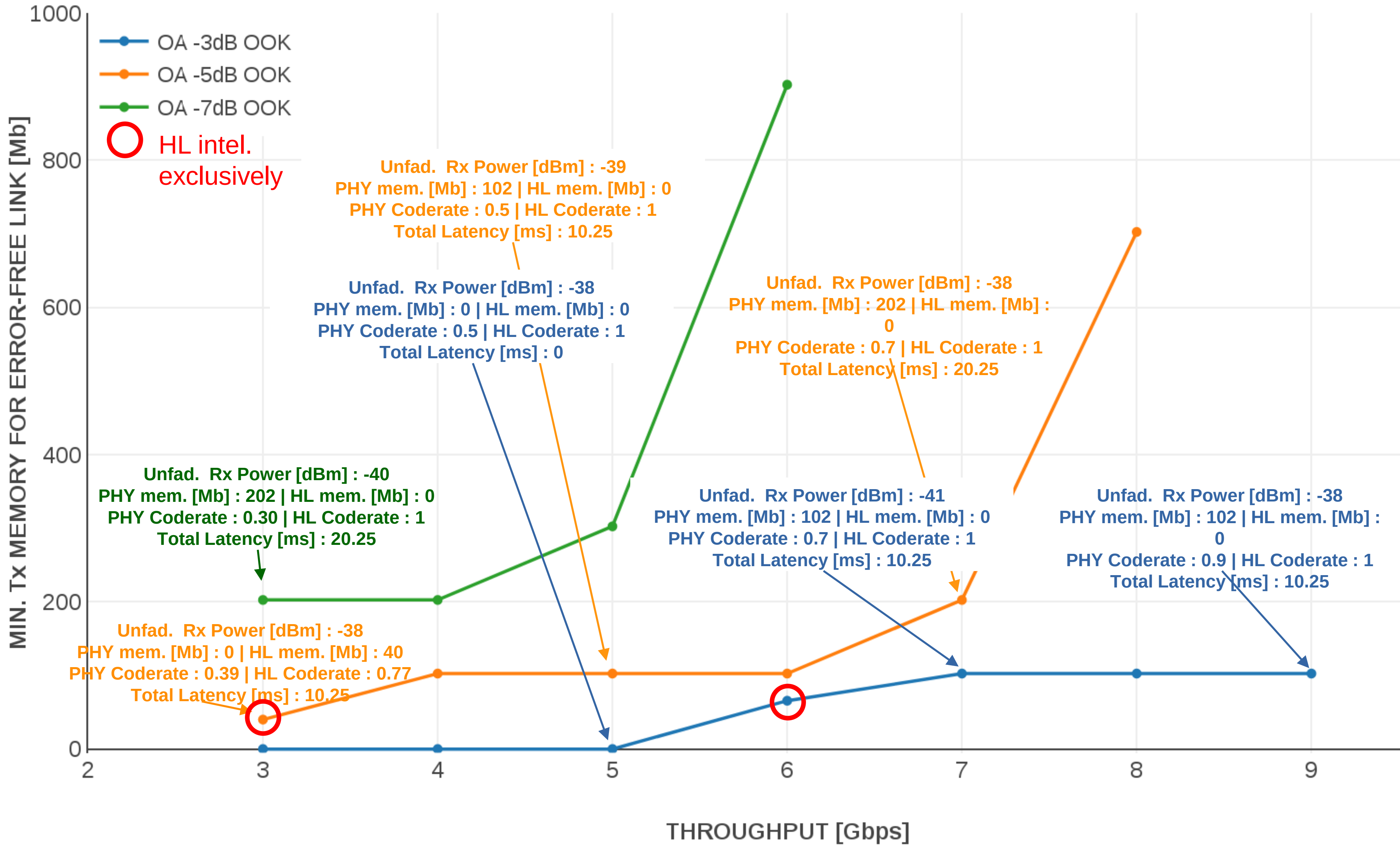


RESOURCES OPTIMIZATION USING MINIMUM TOTAL MEMORY
TARGET PER = 10^{-4}
OOK Receiver



PHYSICAL MITIGATION TECHNIQUES : APERTURE AVERAGING PLUS AO

Increase in Drx **=** **Aperture averaging of scintillation**	**+**	**Adaptive Optics** **=** **Real-time correction of phase fluctuations only**

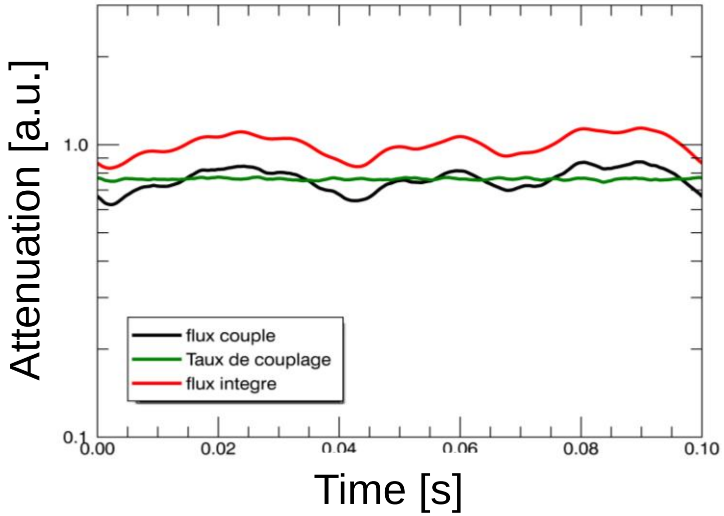
For a fixed Drx scintillation effects are imposed upon the detector

↓

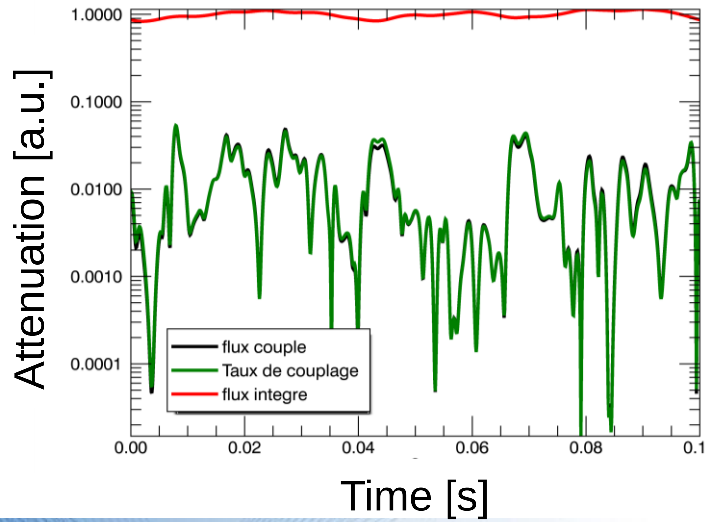
The design of the AO system must be done consequently

Trade-offs scintillation/phase fluctuations mitigation and therefore performances/cost

High perfs AO ➔ Limited by scintillation



Low perfs AO ➔ Limited by phase fluctuations



INSTANTANEOUS COUPLED OPTICAL POWER ATTENUATION

EM field of incoming wave

$$\Psi(\mathbf{r}) = A_0(\mathbf{r}) \exp\left(\chi(\mathbf{r}) + i\phi(\mathbf{r})\right)$$

Unperturbed amplitude — Log-amplitude — Phase (corrected)

Instantaneous coupled optical power attenuation

$$A_{SMF} = \left| \int_{-\infty}^{+\infty} P(\mathbf{r}) W(\mathbf{r}) \exp\left(\chi(\mathbf{r}) + i\phi(\mathbf{r})\right) d\mathbf{r} \right|^2$$

Pupil transmittance — SMF mode

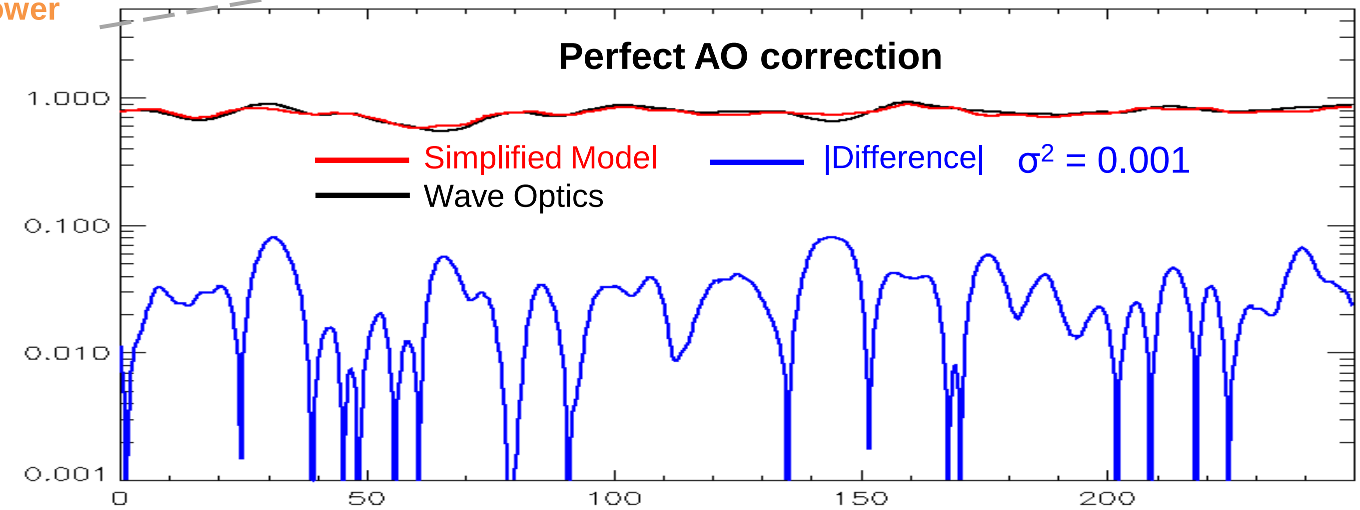
Neglecting amplitude spatial structures influence on coupling fluctuations:

Scintillation — Injection losses

$$A_{SMF} = \exp(-\sigma_\chi^2) \exp(2\chi_P) \left| \int_{-\infty}^{\infty} W(\mathbf{r}) \exp(i\phi(\mathbf{r})) d\mathbf{r} \right|^2$$

Average coupling losses

Collected power fluctuations



Rustic approx, justified for GEO downlinks (medium elevation, small perturbations)

INJECTION LOSSES STATISTICAL CHARACTERIZATION

Phase decomposition into Zernike polynomials

(= Orthonormal basis over a plane and circular domain)

$$\phi(\mathbf{r}) = \sum_{i=1}^{N} a_i Z_i \left(\frac{2\mathbf{r}}{D}\right)$$

Zernike coefficient #i

Zernike polynomial #i

Retro-propagated SMF mode in pupil plane

Set of Zernike polynomials not orthonormal

Phase decomposition after "re-orthonormalisation"

$$\phi(\mathbf{r}) = \sum_{i=1}^{N} b_i F_i \left(\frac{2\mathbf{r}}{D}\right)$$

Statistical properties (PDF) of each a_i : known analytically

*(Independent Gaussian variables **BUT** not identical)*

Temporal properties (PSD) of each a_i : known analytically

Transfer Matrix $\{a_i\} \rightarrow \{b_i\}$: known analytically

"Spatial variance" of the phase fluctuations in the focal plane

$$\sigma^2_{W_0}(\phi) = \sum_{i=2}^{N} b_i^2$$

Closed-form injection efficiency approximation :

Injection efficiency without aberrations

$$\frac{\rho_\phi}{\rho_0} \simeq \exp\left[-\sigma^2_W(\phi)\right]$$

INJECTION LOSSES STATISTICAL CHARACTERIZATION

Instantaneous coupled optical power attenuation

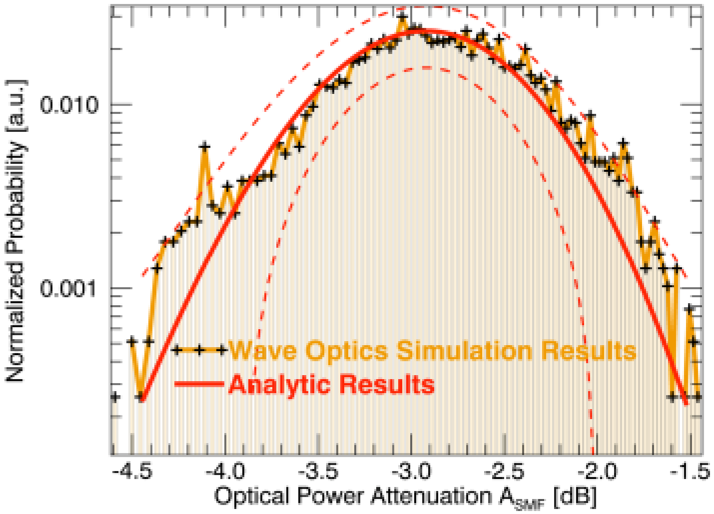
$$A_{SMF} = \exp(-\sigma_\chi^2)\exp(2\chi_P)\left|\int_{-\infty}^{\infty} W(\mathbf{r})\exp(i\phi(\mathbf{r}))d\mathbf{r}\right|^2$$

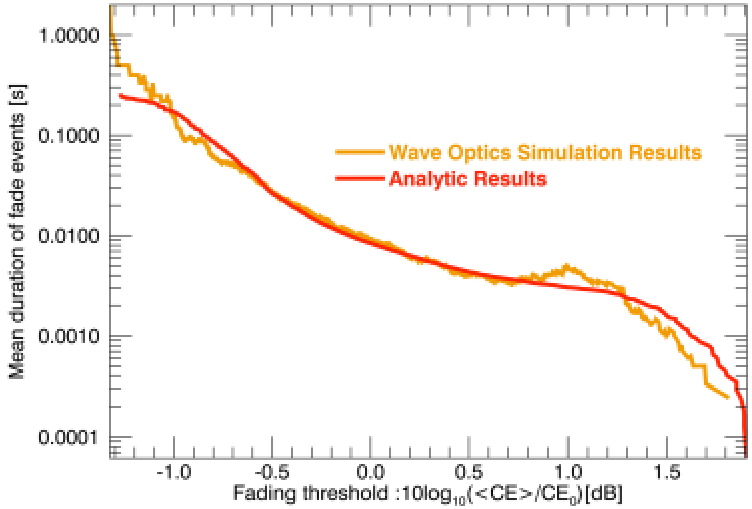
Scintillation — Typical Log-normal distribution

Injection losses — "Exponentiated sum of non-identical Gamma variates"

Statistical laws (PDF/CDF)
\+
Temporal properties (PSD, coherence time)

Analytic expressions





RESOURCES OPTIMIZATION USING MINIMUM TOTAL MEMORY
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