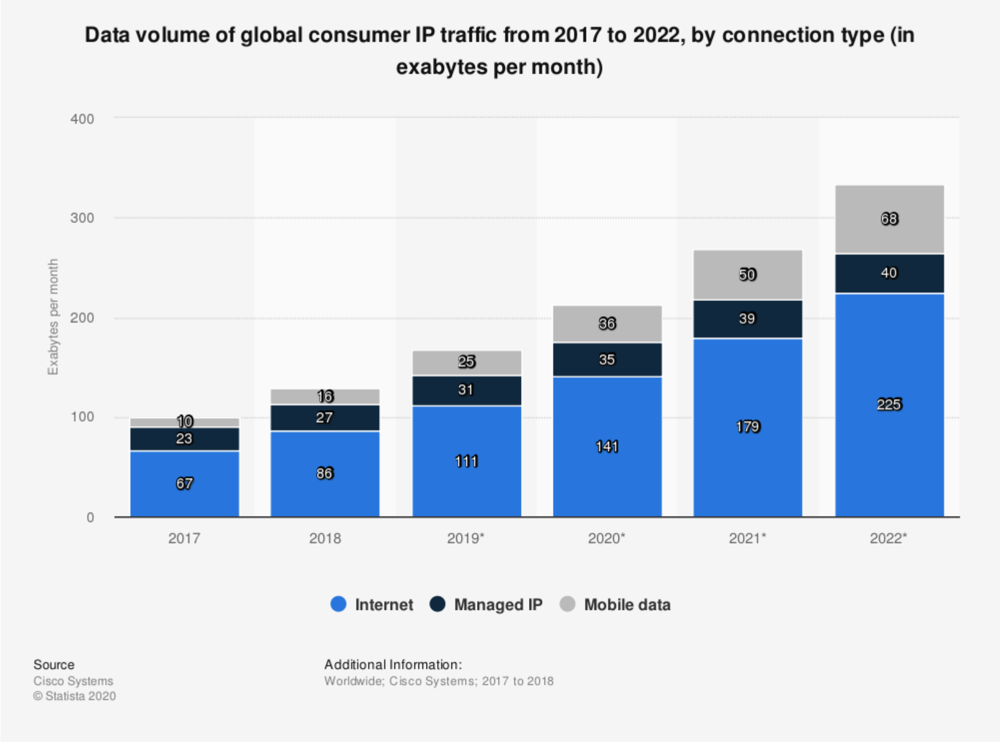
Applications and Design of Arbitrary Gain-Profile Raman Amplifiers

A. CARENA[1], A.M. ROSA BRUSIN[1], UIARA C. DE MOURA[2], F. DA ROS[1], D. ZIBAR[2]

1. OPTCOM Optical Communications Group – Politecnico di Torino, Torino – ITALY
2. DTU Fotonik – Technical University of Denmark, Lyngby – DENMARK

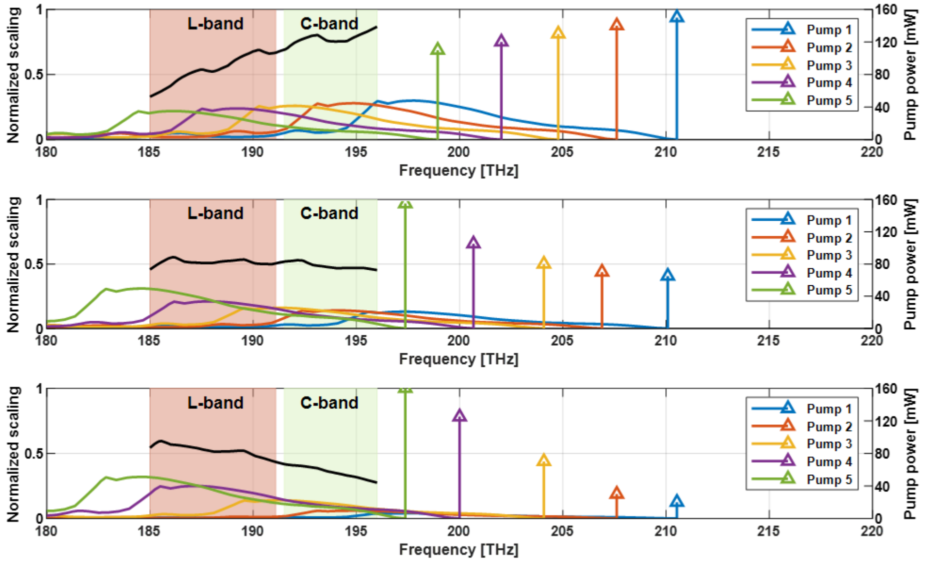
BACKGROUND: TRAFFIC INCREASE

- Internet data traffic always increases
  - More devices connected
  - New bandwidth hungry services and applications
  - Introduction of 5G will exacerbate the situation
- To face this continuous growth a promising solution to increase optical system capacity is to extend transmission band
  - From C-band towards L-band and beyond
- Optical amplification beyond C-band is a challenge
  - Doped fiber amplifiers
  - SOA
  - Raman amplifier



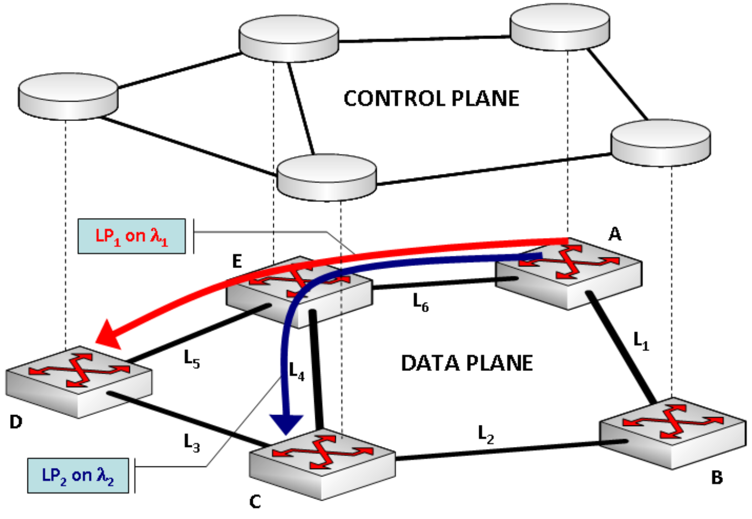
RAMAN AMPLIFICATION

- Raman amplification can complete this challenge
  - Availability of amplification in any bands
  - Broadband amplification in multi-pump configuration
  - Flexible and programmable gain by properly adjusting pump powers and frequencies
    - Arbitrary gain profiles compensating for tilts and ripples in hybrid solution
    - It allows to avoid Gain-Flattening Filters
  - Lower noise figure than other amplification solutions because it is a distributed gain



SCENARIO: DYNAMIC NETWORKS

- Reconfigurable optical networks allow and to dynamically adapt to traffic demand
- Network control plane must implement efficient resource allocation
  - Physical layer awareness is fundamental for the evaluation of Quality of Transmission
- Network elements, as the optical amplifier, must be abstracted to allow fast reconfiguration
  - Real-time models of Raman amplifiers are needed



OUTLINE

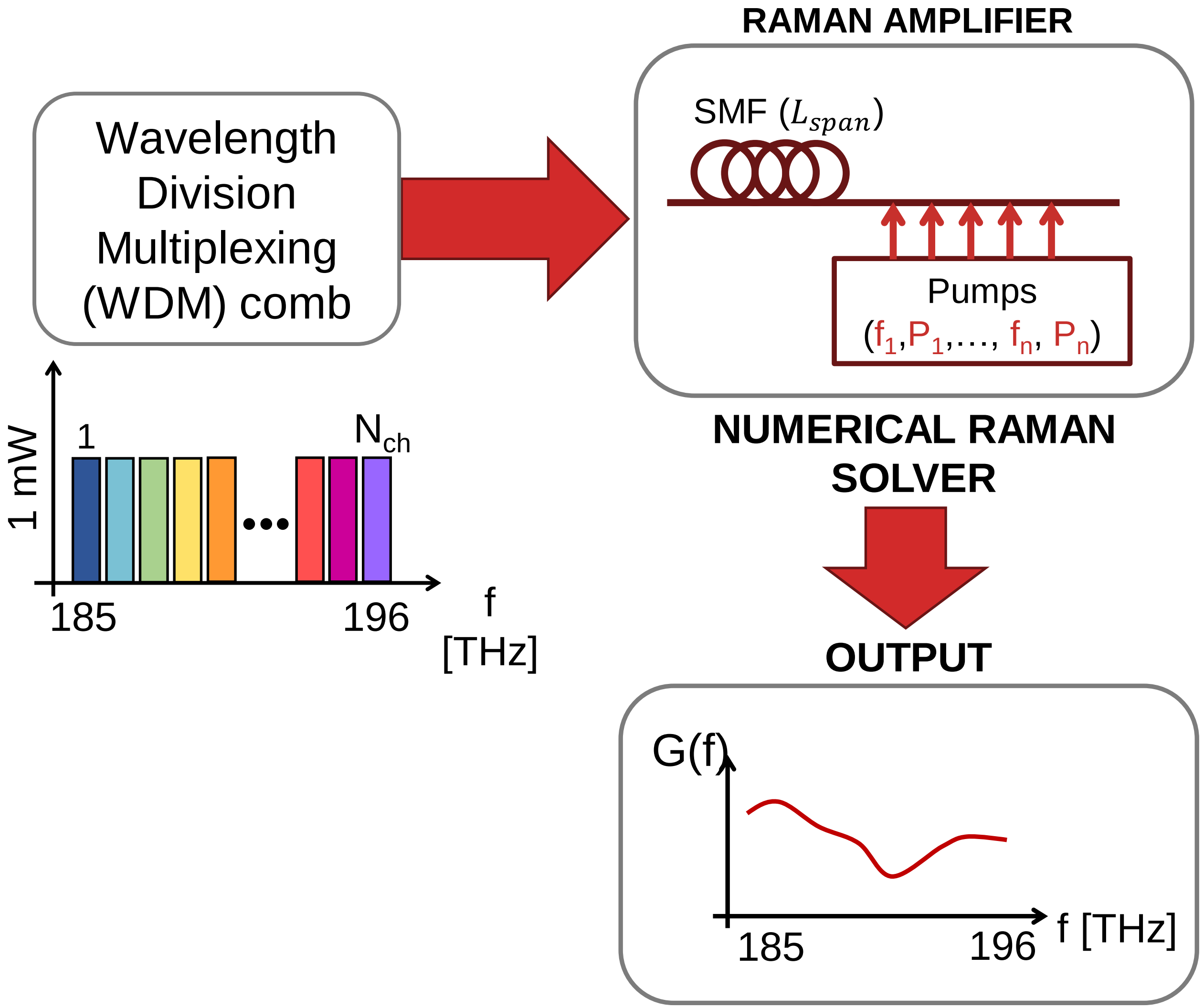
1. Raman amplifiers and Machine Learning
2. Previous works
3. Load Aware Raman amplifier analysis
4. Load Aware Raman amplifier design
5. Conclusions

1.

RAMAN AMPLIFIERS

AND MACHINE LEARNING

THE RAMAN AMPLIFIER



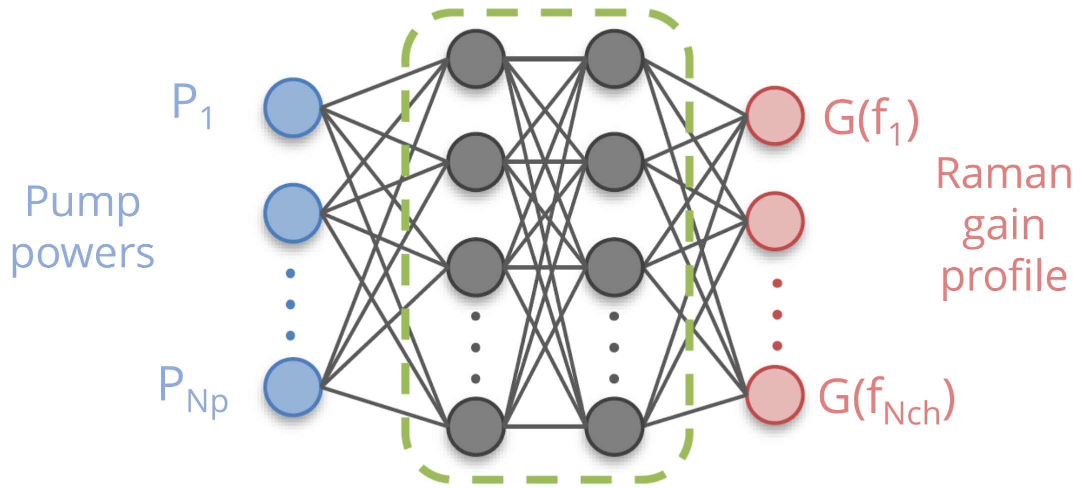
$$\frac{dP_s}{dz} = -\alpha_s P_s + C_R(\lambda_s, \lambda_p)\left[P_p^+ + P_p^-\right] P_s \qquad (1)$$

$$\pm\frac{dP_p^\pm}{dz} = -\alpha_p P_p^\pm - \left(\frac{\lambda_s}{\lambda_p}\right) C_R(\lambda_s, \lambda_p)\, P_s\, P_p^\pm \qquad (2)$$

$$\pm\frac{dP_A^\pm}{dz} = -\alpha_A P_A^\pm + C_R(\lambda_A, \lambda_p) P_p P_A^\pm + C_R(\lambda_A, \lambda_p)[1 + \eta(T)] h\nu_A B_{ref} P_p \qquad (3)$$

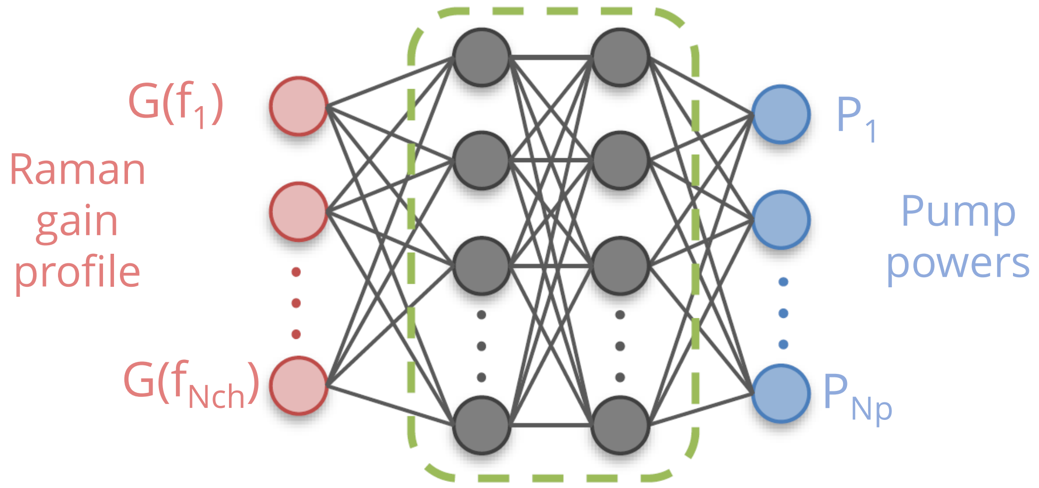
[1] J. Bromage, '*Raman Amplification for Fiber Communications Systems*', Journal of Ligthwave Technology, vol. 22, no. 1, pp. 79-93, 2004.

DIRECT PROBLEM



$\boldsymbol{x}$ $\quad y = f(x) \quad$ $\boldsymbol{y}$

INVERSE PROBLEM



$\boldsymbol{y}$ $\quad x = f^{-1}(y) \quad$ $\boldsymbol{x}$

2.

PREVIOUS WORKS

LS-SVR based RA design

IOP Publishing Journal of Optics
J. Opt. 20 (2018) 025702 (6pp) https://doi.org/10.1088/2040-8986/aaa2a6

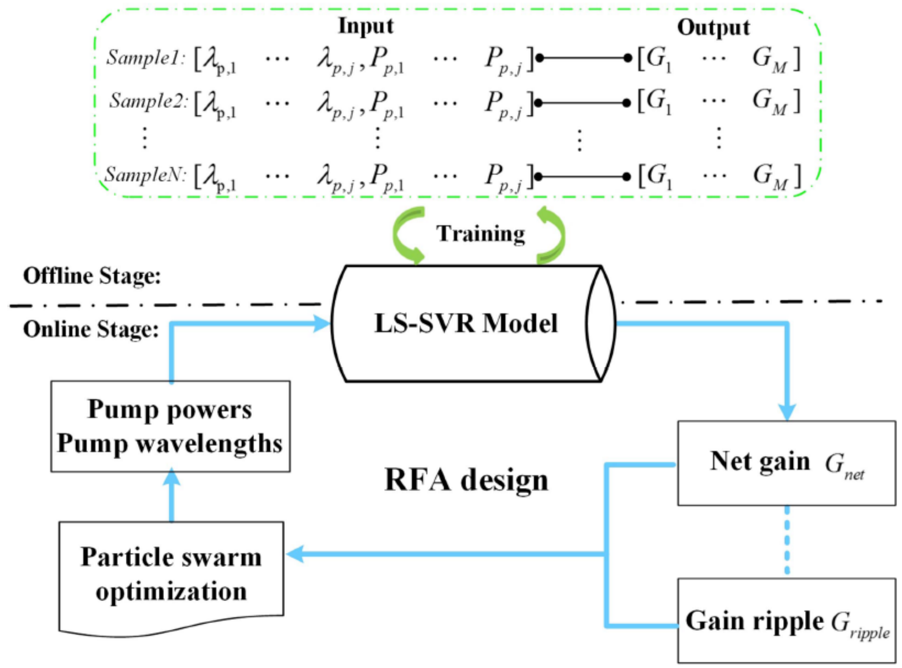
Efficient design of gain-flattened multi-pump Raman fiber amplifiers using least squares support vector regression

Jing Chen, Xiaojie Qiu, Cunyi Yin and Hao Jiang

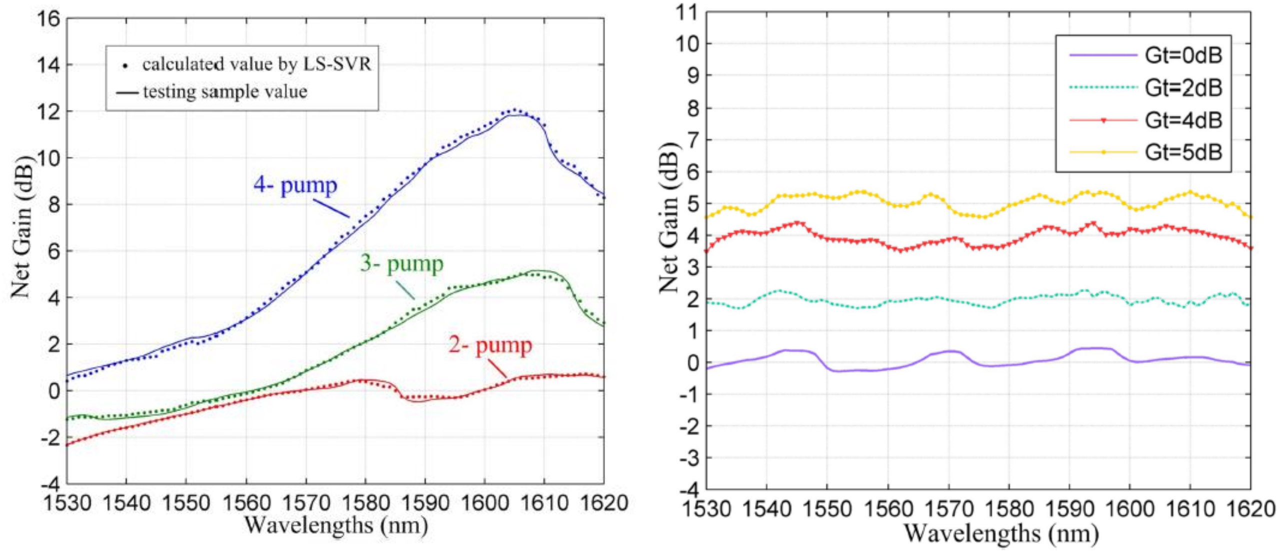
College of Electrical Engineering and Automation, Fuzhou University, Fuzhou 350116, People's Republic of China

E-mail: jiangh@fzu.edu.cn

LS-SVR MODEL



RESULTS



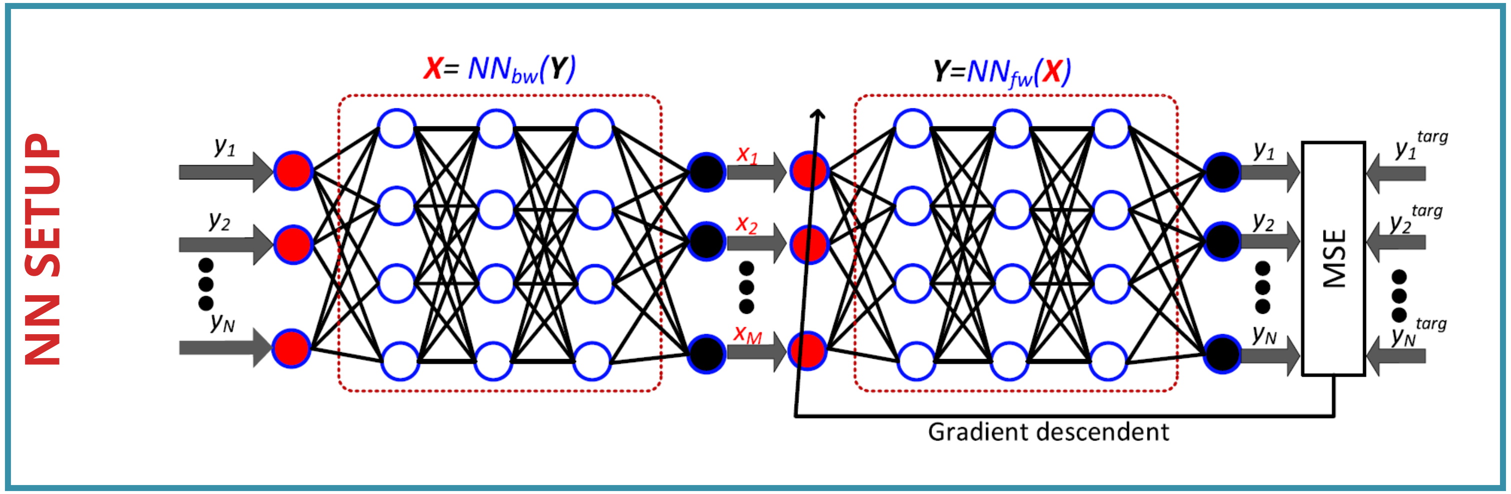
Jing Chen et al 2018 J. Opt. **20** 025702, https://doi.org/10.1088/2040-8986/aaa2a6

ML-based RA design

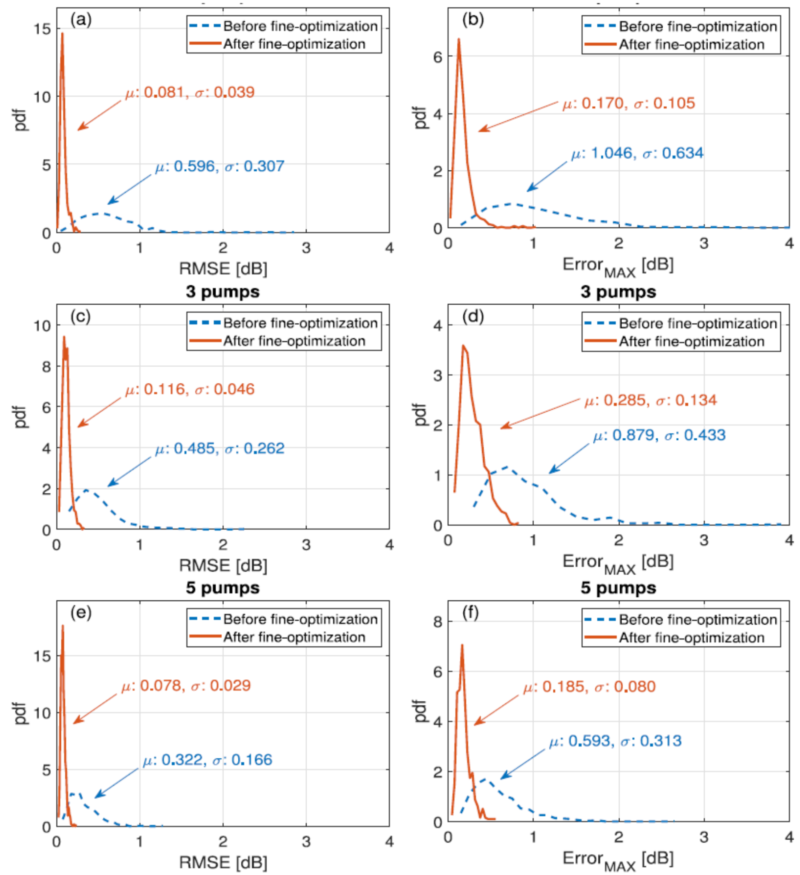
JOURNAL OF LIGHTWAVE TECHNOLOGY

Inverse System Design Using Machine Learning: The Raman Amplifier Case

Darko Zibar, Ann Margareth Rosa Brusin, Uiara C. de Moura, Francesco Da Ros, Vittorio Curri, and Andrea Carena



RESULTS



D. Zibar, A. Ferrari, V. Curri and A. Carena, “Machine Learning-based Raman amplifier design”, *2019 Optical Fiber Communications Conference and Exhibition (OFC)*, 2019.
D. Zibar , A. M. Rosa Brusin, U. C. de Moura, F. Da Ros, V. Curri, and A. Carena “Inverse System Design Using Machine Learning: The Raman Amplifier Case," in *Journal of Lightwave Technology*, doi:10.1109/JLT.2019.2952179

ML-based RA+EDFA design over C+L-band

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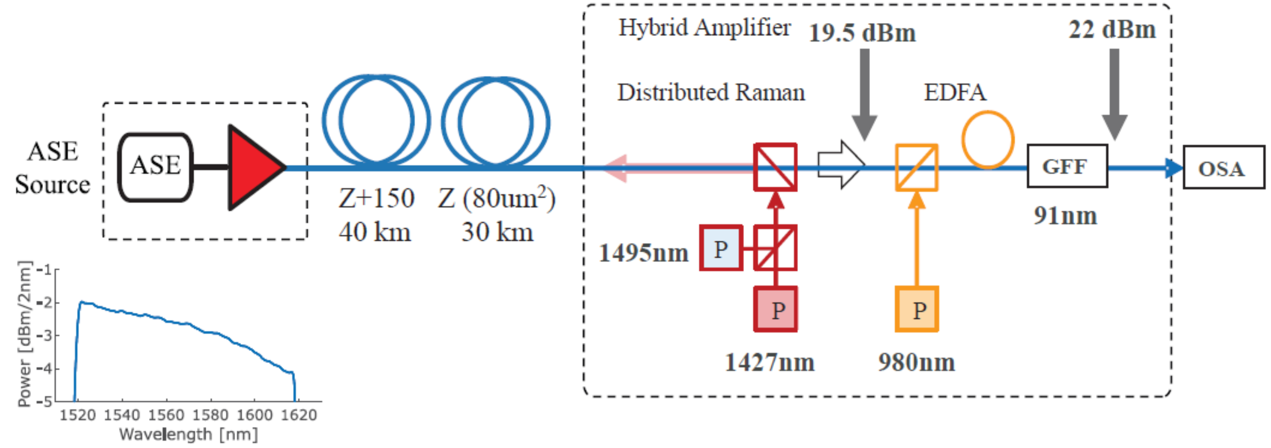
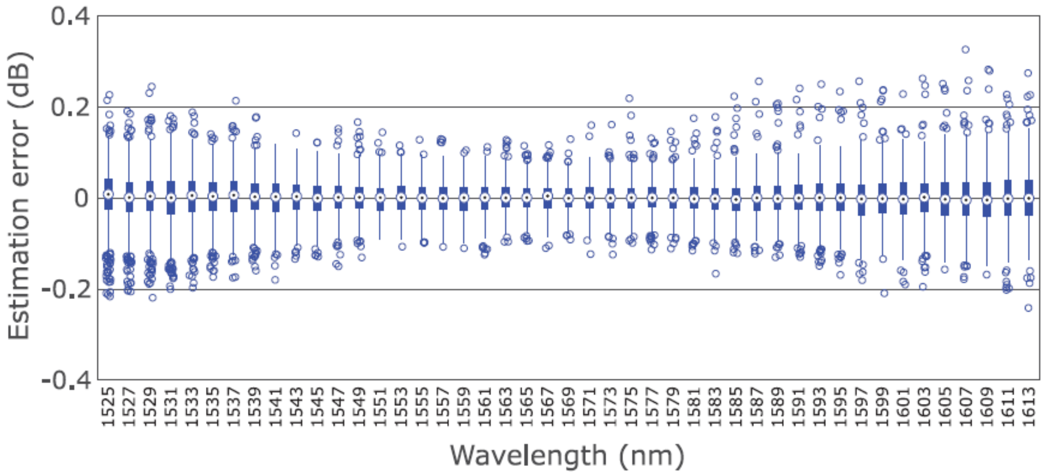
Machine Learning for Ultrawide Bandwidth Amplifier Configuration

Maria Ionescu*
Nokia Bell Labs Paris-Saclay, Nozay, 91620, France
**e-mail: maria.ionescu@nokia-bell-labs.com*

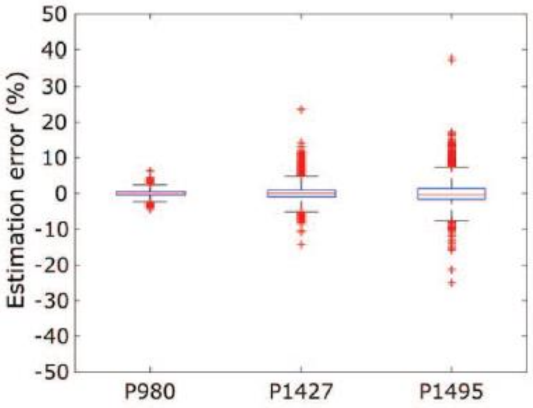
EXPERIMENTAL SETUP



RESULTS



Configuration	980 nm pump [mW]	1427 nm pump [mW]	1427 nm pump [mW]	1495 nm pump [mW]	1495 nm pump [mW]
(a) Best fit	529.7	225.5	226.7	235.7	237.1
(b) Human	500	230	230	230	230
(c) NN Model	519.1	223.5	224.2	246.8	245.7



M. Ionescu, "Machine Learning for Ultrawide Bandwidth Amplifier Configuration," *2019 21st International Conference on Transparent Optical Networks (ICTON)*, 2019, doi: 10.1109/ICTON.2019.8840453.

ML-based RA design over S+C+L-band

W1K.3.pdf

Experimental Prediction and Design of Ultra-Wideband Raman Amplifiers Using Neural Networks

Xiaoyan Ye, Aymeric Arnould, Amirhossein Ghazisaeidi, Dylan Le Gac and Jeremie Renaudier
Nokia Bell Labs, Paris-Saclay, France (aymeric.arnould@nokia.com)

EXPERIMENTAL SETUP

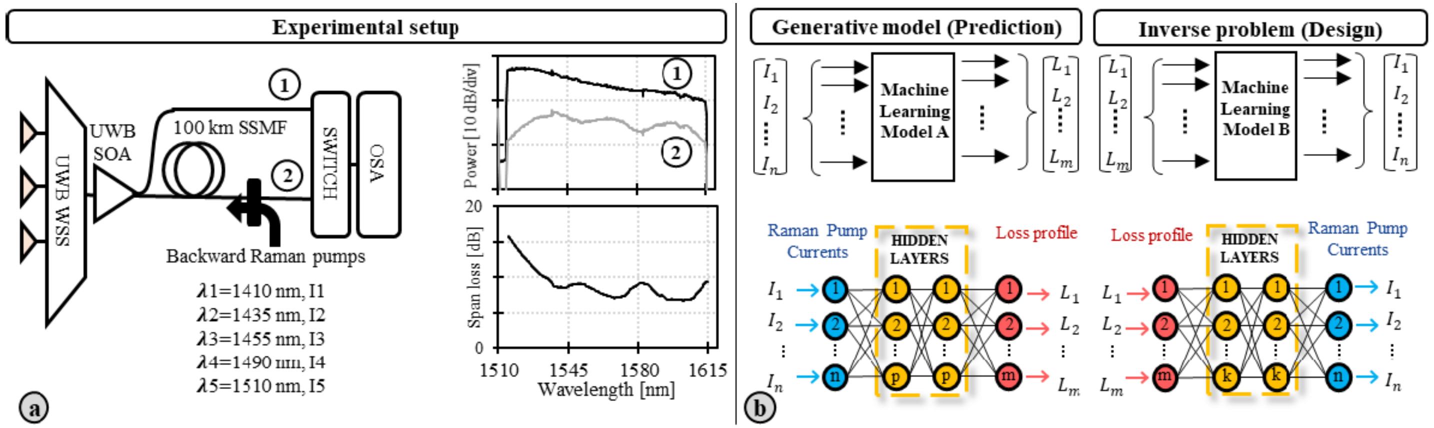
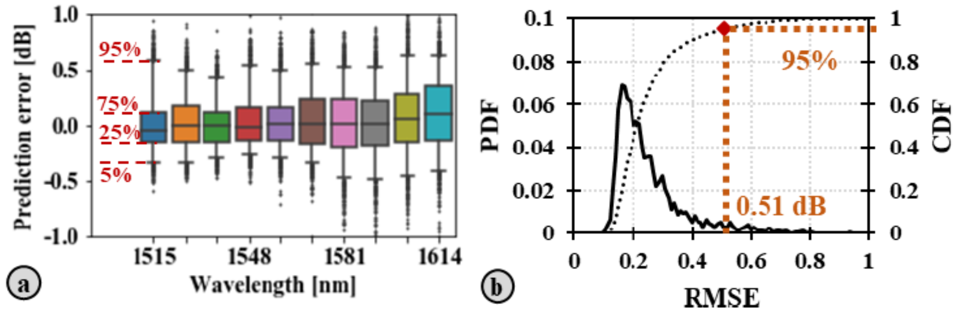
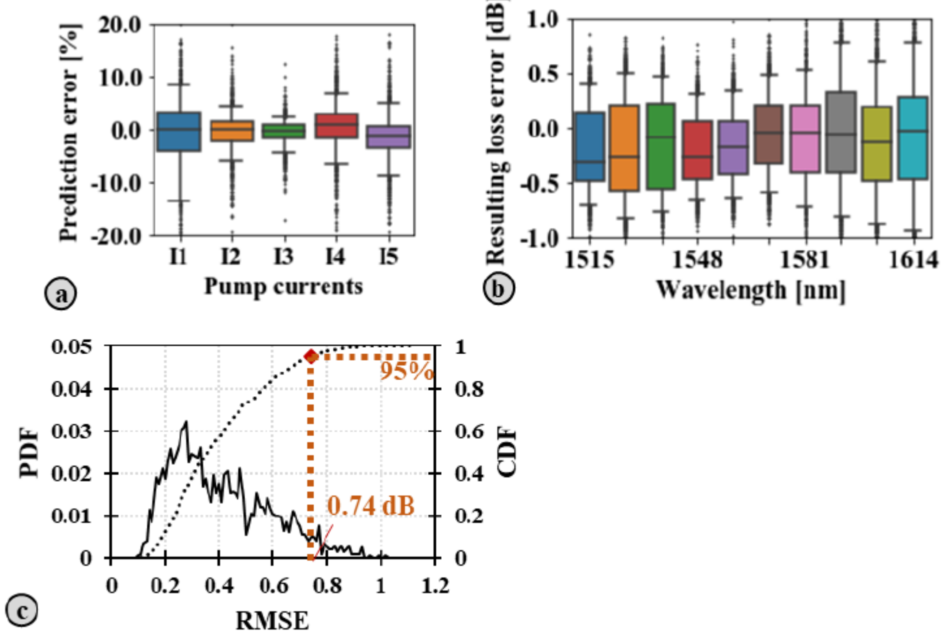


Fig. 1. (a) Single span characterization setup with 5 pumps Raman amplifier and SOA: span input and output power profiles are measured with the OSA (respectively labelled 1 and 2 in top inset) and span loss profile (bottom inset) is deduced. (b) ML models and artificial neural networks (ANN) architectures for span loss profile prediction (model A) and pump current value prediction (model B)

GENERATIVE MODEL RESULTS



INVERSE MODEL DESIGN RESULTS



X. Ye, A. Arnould, A. Ghazisaeidi, D. Le Gac and J. Renaudier, "Experimental Prediction and Design of Ultra-Wideband Raman Amplifiers using Neural Networks," *2020 Optical Fiber Communications Conference and Exhibition (OFC)*, 2020.

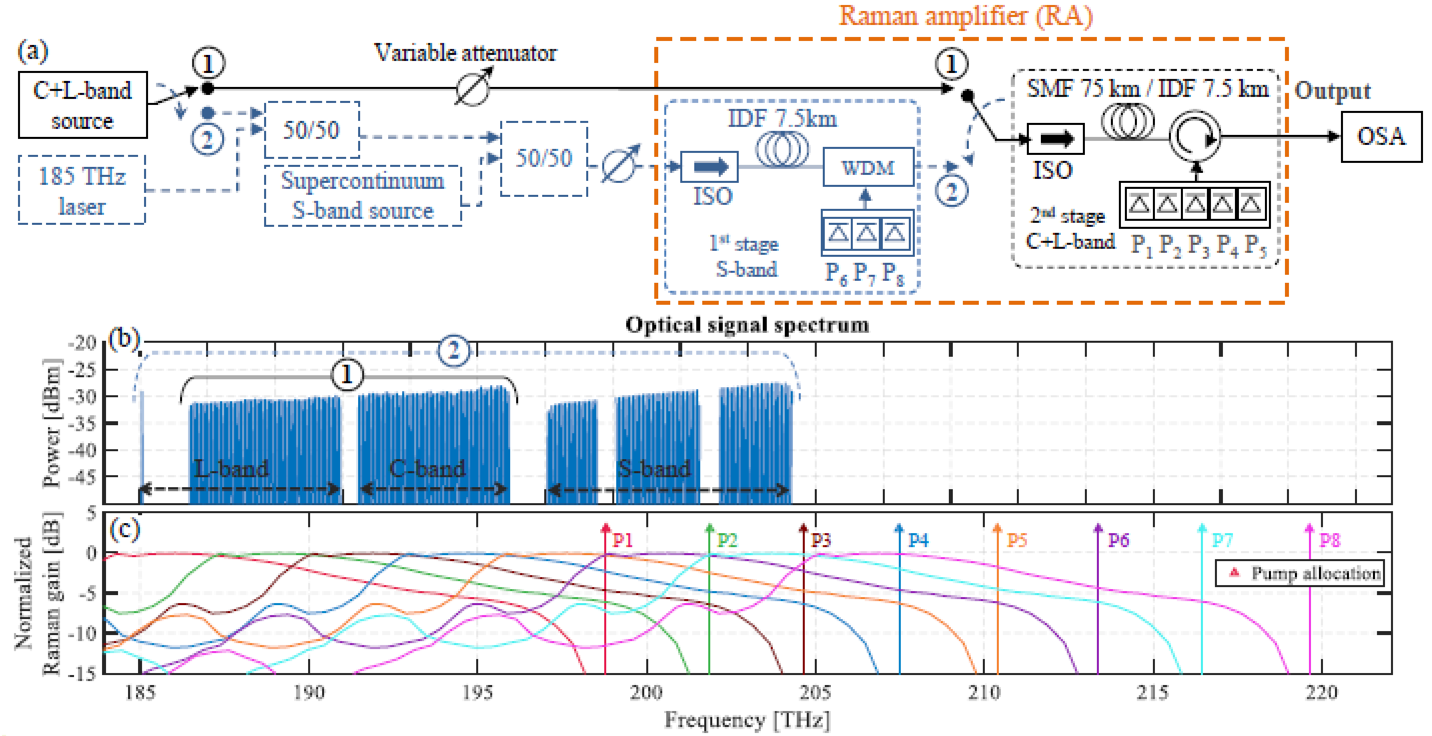
ML-based RA design over S+C+L-band

JOURNAL OF LIGHTWAVE TECHNOLOGY

Multi–band programmable gain Raman amplifier

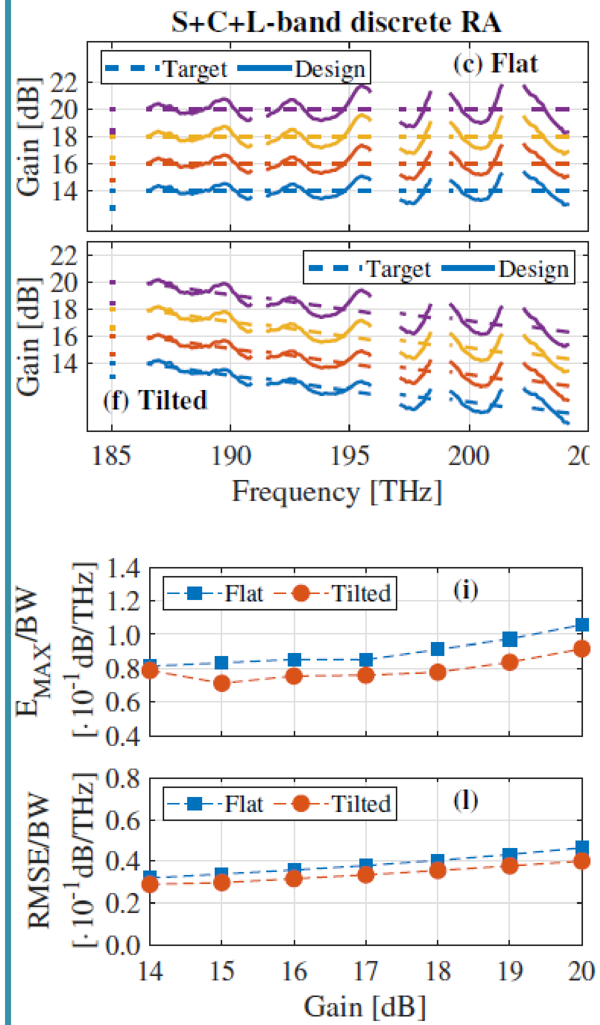
Uiara Celine de Moura, Md Asif Iqbal, Morteza Kamalian, Lukasz Krzczanowicz, Francesco Da Ros, Ann Margareth Rosa Brusin, Andrea Carena, Wladek Forysiak, Sergei Turitsyn, and Darko Zibar

EXPERIMENTAL SETUP



U. C. De Moura et al., "Multi-band programmable gain Raman amplifier," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2020.3033768.

RESULTS



(c),(f): Predicted and target flat and tilted (on–off) gain profiles with respect to frequency

(i): Maximum error of gain prediction with respect to total bandwidth

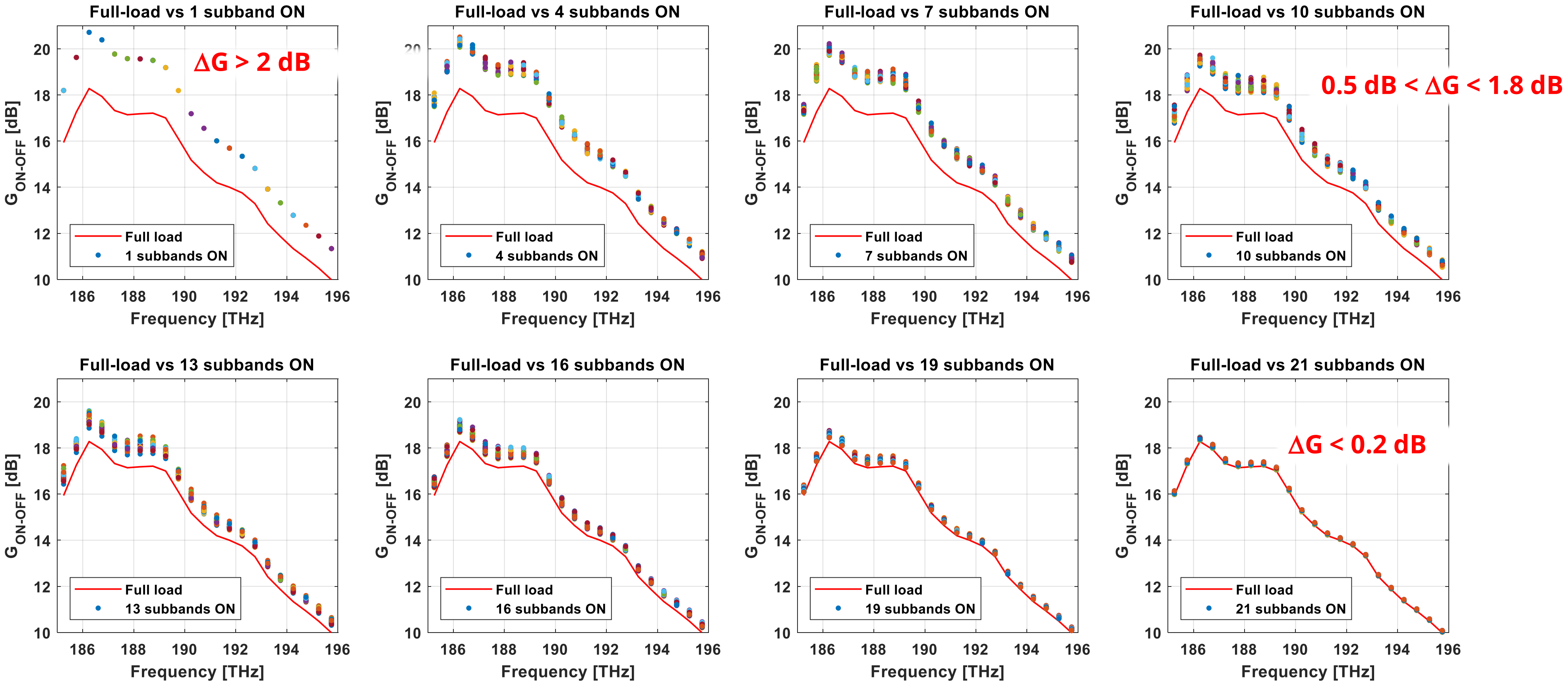
(l): Root-mean-square-error of gain prediction with respect to total bandwidth.

THE COMMON FACTOR

- All these works presented in previous slide have a COMMON FACTOR: they assume at the input of the Raman Amplifier FULL LOAD condition

- In dynamically reconfigurable networks, optical links operate with PARTIAL LOADS
  - Does this have an impact on the behaviour of the Raman amplifier?

EFFECT OF PARTIAL LOADS ON RA



Fixed pump powers and frequencies:

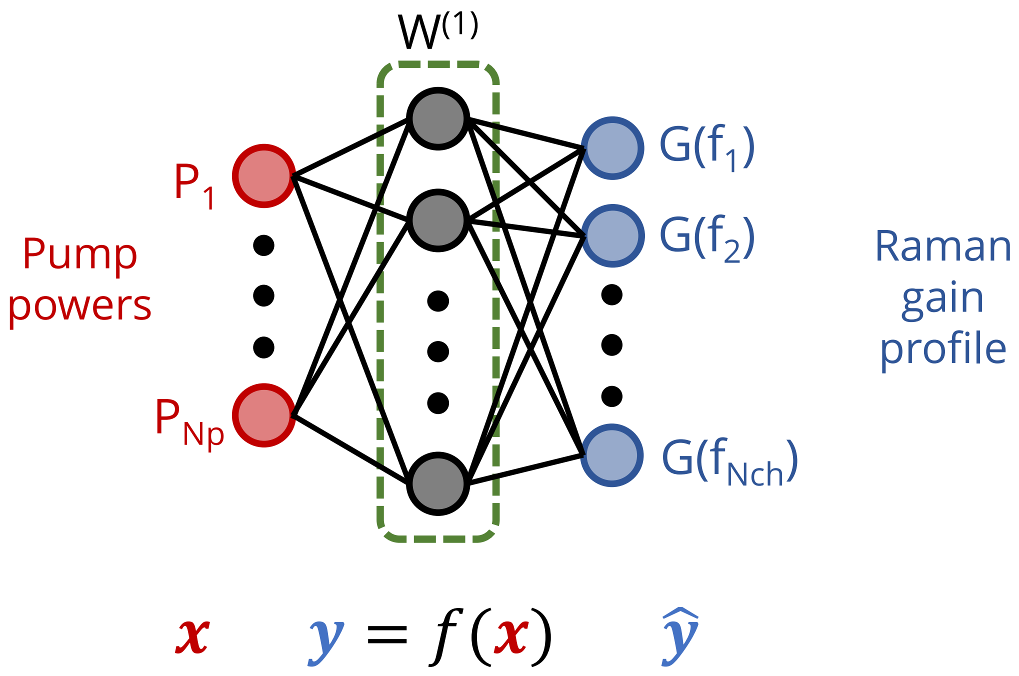
- f_p=[210.51 207.28 204.15 201.11 198.16] THz
- P_p=[246.7,237.7,194.2,192.7,168.8] mW

3.

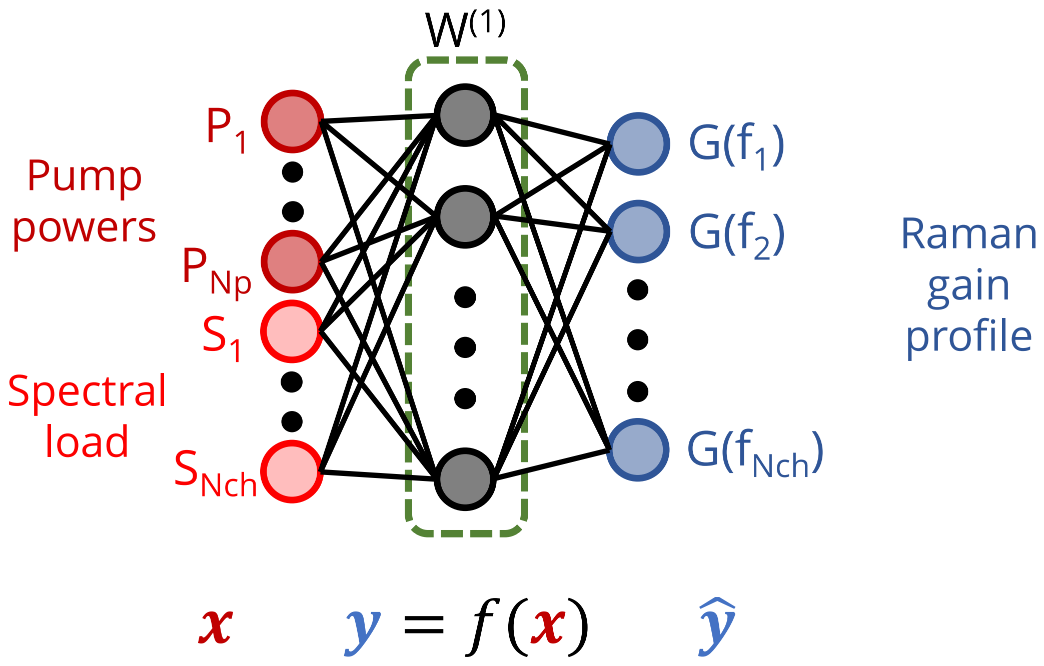
LOAD AWARE

RAMAN AMPLIFIER ANALYSIS

Load Unaware NN (LU-NN)



Load Aware NN (LA-NN)



SIMPLIFYING THE PROBLEM

- C+L bands: 220 frequency slots of 50 GHz
  - Partial load: each frequency slot can be ON or OFF
- In partial load scenario: 2^{220} possible combinations + pump powers arbitrariness

TOO LARGE!

SOLUTION

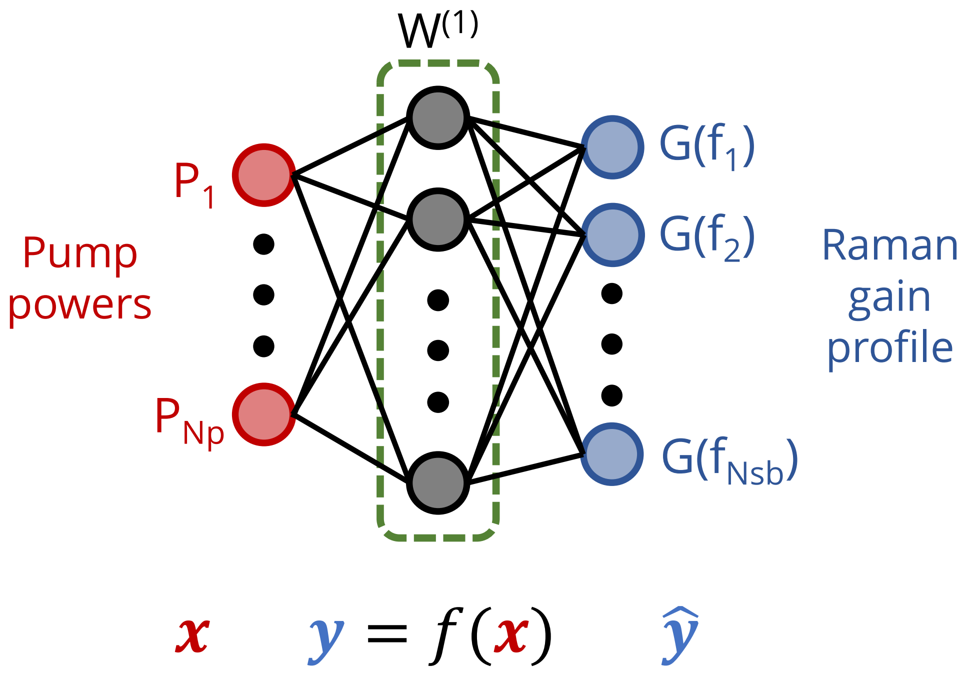
- 10 adjacent frequency slots grouped together to form a sub-band
- Each sub-band is 500 GHz wide and can assume two states: ON or OFF
- Total of 22 sub-bands over the entire 11 THz C+L-band
  - 12 sub-bands in the L-band
  - 10 sub-bands in the C-band

DATASET GENERATION

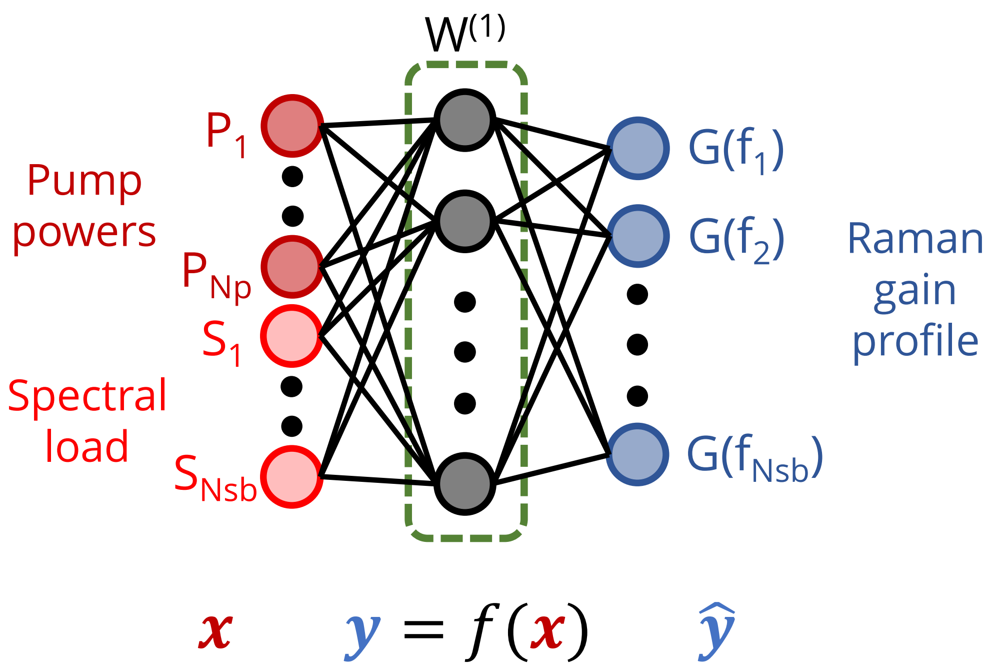
- General data
  - Five pumps
  - Fixed pump frequencies f_p=[210.51 207.28 204.15 201.11 198.16] THz
  - C+L band: $f \in [185,196]$ THz
  - 22 sub-bands: 500 GHz each
- We generate 11000 different **partial loads** configurations
  - To emulate all load conditions, we consider different classes (C, L and C+L) and sub-classes (number of sub-band ON) of elements with randomly selected sub-band positions
- Using the numerical Raman solver included in GNpy we generate the corresponding gain and noise profiles

MACHINE LEARNING FRAMEWORK

Load Unaware NN (LU-NN)



Load Aware NN (LA-NN)



- Training method: Random projection
- 1 hidden layers, 1980 neurons per layer, activation function: tanh
- Same approach can also be used to predict ASE noise profile generated by Raman amplifier

TESTING PROCESS

$$\left[P_1, P_2, \dots, P_{N_p}\right]$$

or

$$\left[P_1, P_2, \dots, P_{N_p}, S_1, S_2, \dots, S_{N_{sb}}\right]$$

LU-NN

LA-NN

NUMERICAL RAMAN SOLVER

TRAINED NEURAL NETWORK

Target profile G_{target}

Predicted profile G_{pred}

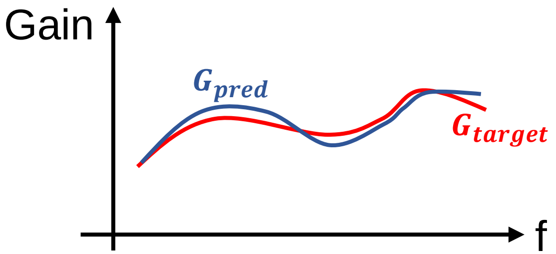
COMPARISON

Maximum error:

$$Error_{MAX} = \max_{i \in \{1, N_{sb}\}} \left| G_{pred,i}(f) - G_{target,i}(f) \right|$$

Root-mean-square-error (RMSE):

$$RMSE = \sqrt{\frac{1}{N_{sb}} \sum_{i=1}^{N_{sb}} \left(G_{pred,i}(f) - G_{target,i}(f) \right)^2}$$

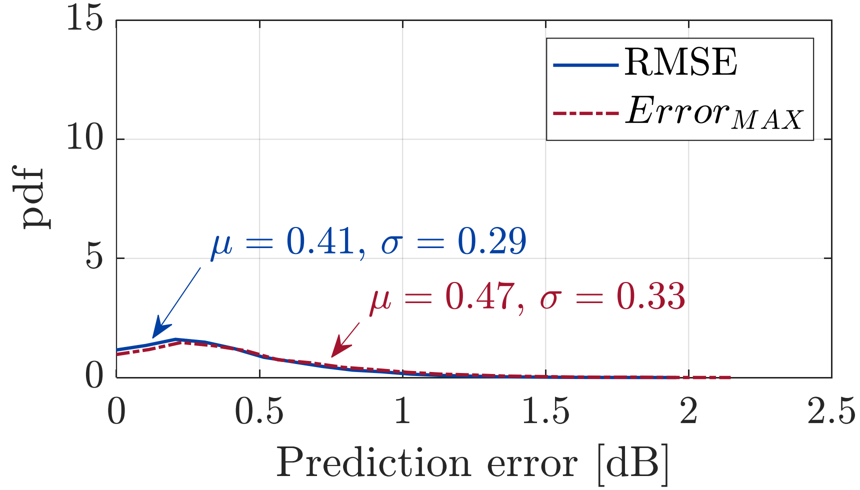


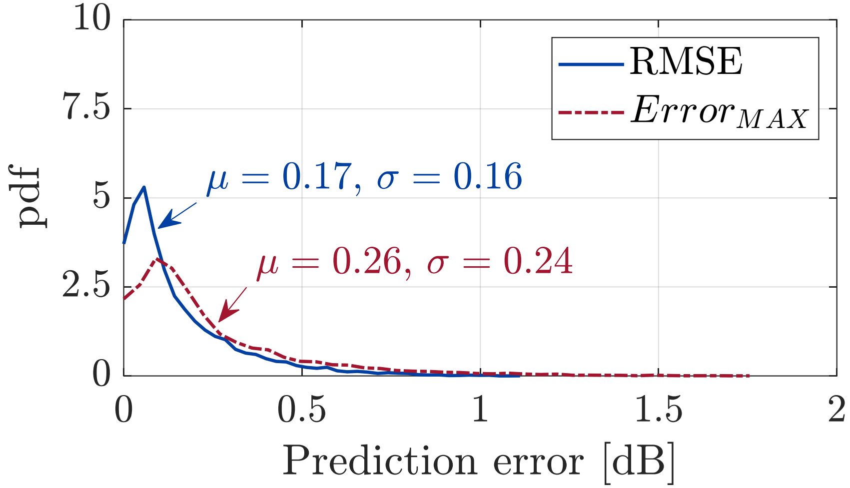
TESTING RESULTS: LU-NN vs LA-NN

RAMAN GAIN PREDICTION

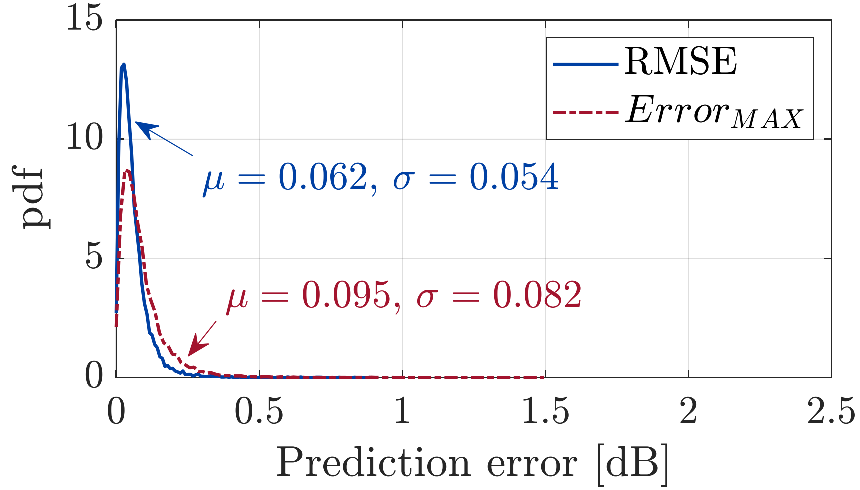
ASE NOISE PREDICTION

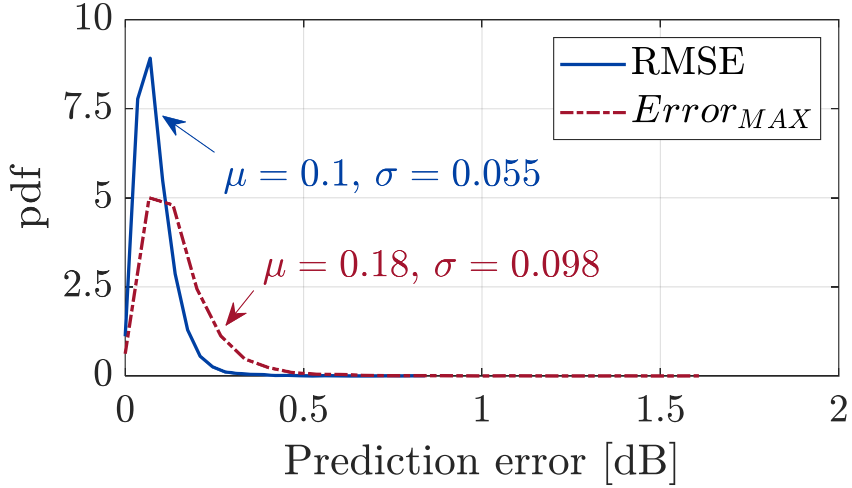
LU-NN





LA-NN

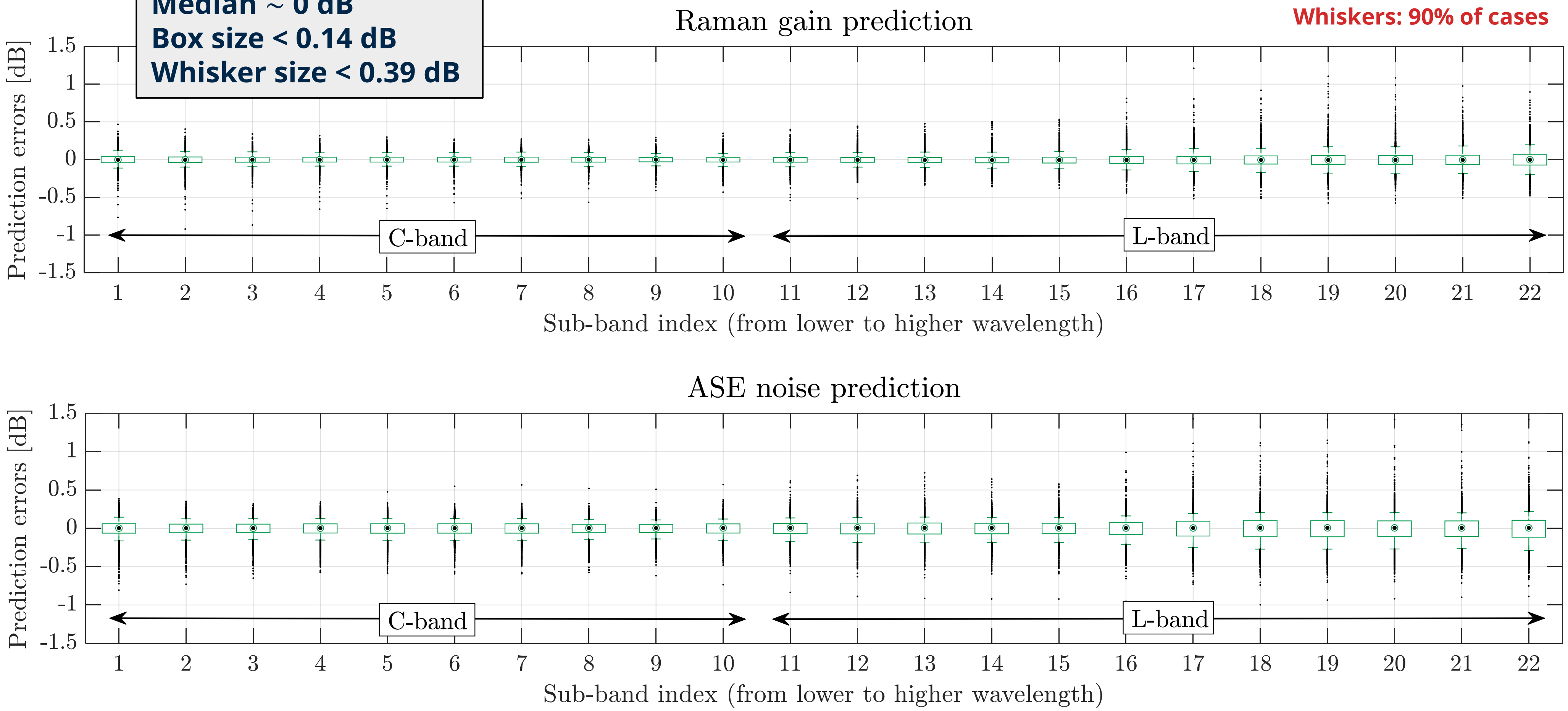




TESTING RESULTS: LU-NN vs LA-NN

Median ~ 0 dB
Box size < 0.14 dB
Whisker size < 0.39 dB

Box: 50% of cases
Whiskers: 90% of cases



A. M. Rosa Brusin, U. C. de Moura, V. Curri, D. Zibar and A. Carena, "Introducing Load Aware Neural Networks for Accurate Predictions of Raman Amplifiers," in *Journal of Lightwave Technology*, vol. 38, no. 23, pp. 6481-6491, Dec. 1, 2020, doi: 10.1109/JLT.2020.3014810.

4.

LOAD AWARE

RAMAN AMPLIFIER DESIGN

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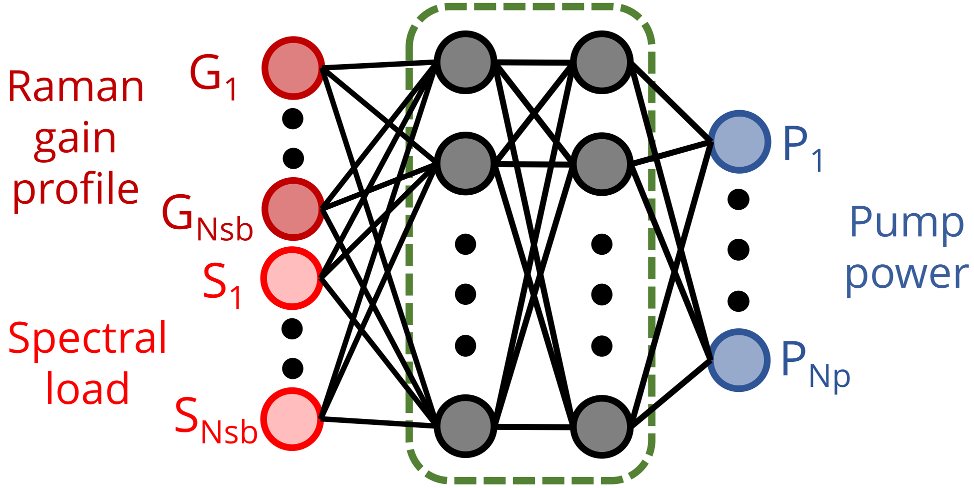
Load Aware NN (LA-NN)



$$\boldsymbol{x} \qquad \boldsymbol{y} = f(\boldsymbol{x}) \qquad \hat{\boldsymbol{y}}$$

- Training method: Levenberg-Marquardt
- 2 hidden layers, 40 neurons per layer, activation function: tanh

TESTING PROCESS

$[G_1, G_2, \ldots, G_{N_{sb}}, S_1, S_2, \ldots, S_{N_{sb}}]$

TRAINED LA-NN

Predicted pumps power P_{pred}

NUMERICAL RAMAN SOLVER

Predicted profile G_{pred}

G_{target}

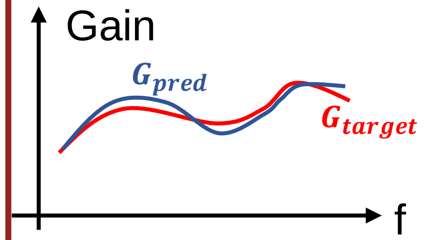
COMPARISON

Maximum error:

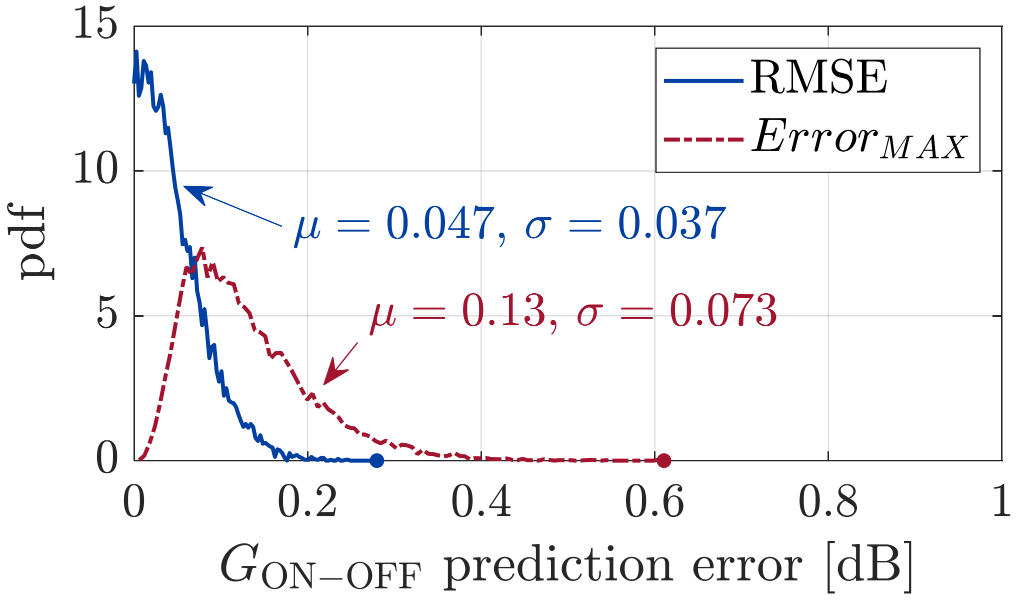
$$Error_{MAX} = \max_{i \in \{1, N_{sb}\}} \left| G_{pred,i}(f) - G_{target,i}(f) \right|$$

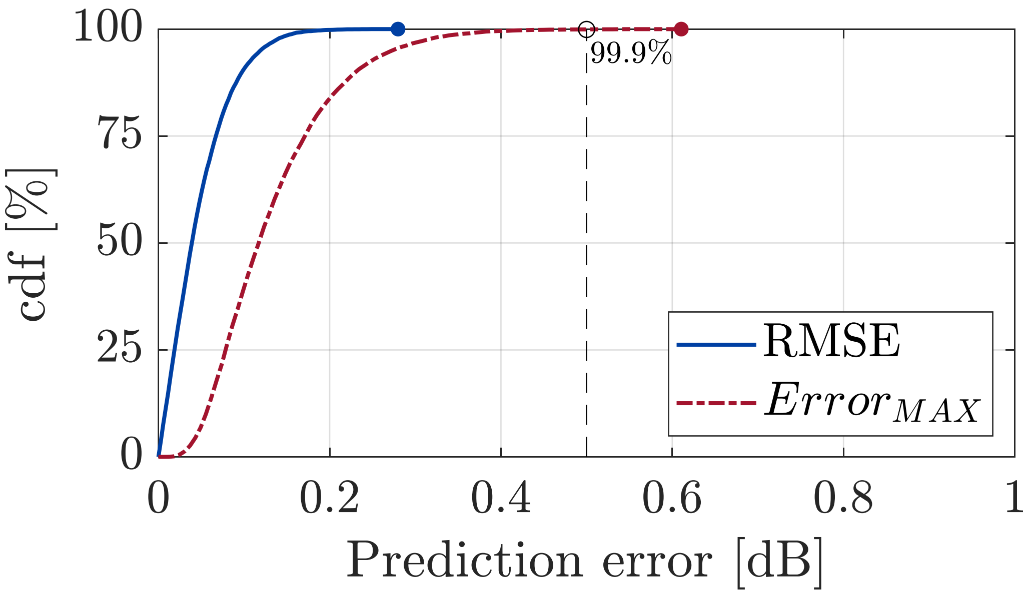
Root-mean-square-error (RMSE):

$$RMSE = \sqrt{\frac{1}{N_{sb}} \sum_{i=1}^{N_{sb}} \left(G_{pred,i}(f) - G_{target,i}(f) \right)^2}$$



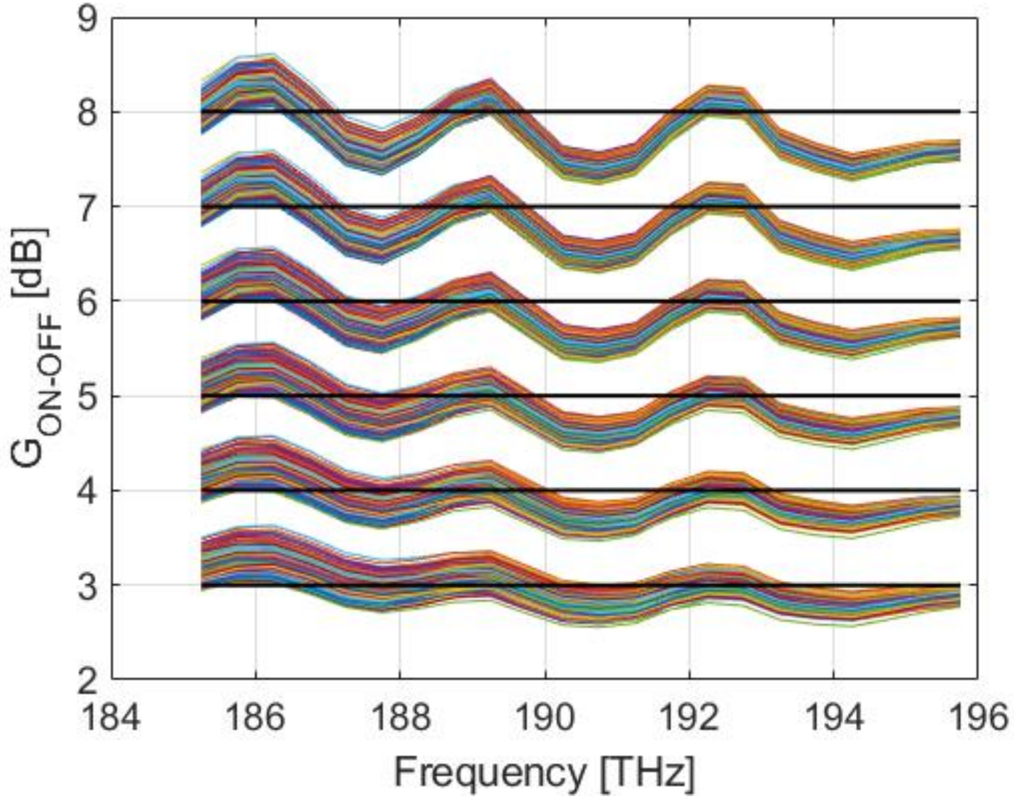
TESTING RESULTS: ARBITARY PROFILES





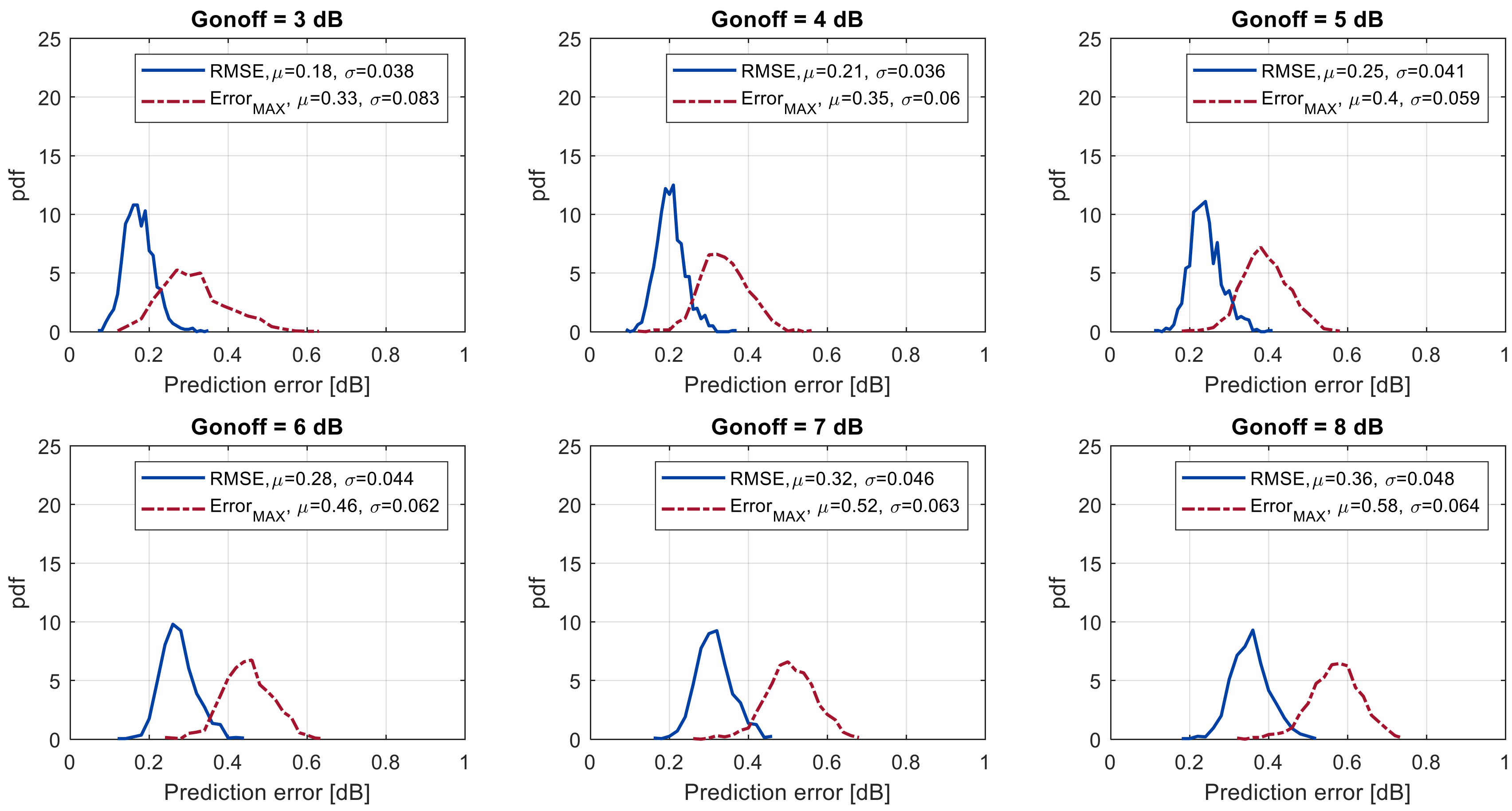
TESTING RESULTS: FLAT PROFILES

- 1000 different partial loads



TESTING RESULTS: FLAT PROFILES

- 1000 different partial loads



5.

CONCLUSIONS

CONCLUSIONS

- For ultra-wide band transmission, Raman amplification is an enabler to deliver arbitrary gain profiles at any wavelengths
- Machine Learning based methods allow for fast and accurate Raman amplifier analysis and design
- Load awareness is fundamental for applications in dynamically reconfigurable networks
  - Direct NN predicts gain and noise profile to be effectively used in network controller
  - Inverse NN predicts pump powers to design the required gain profile

Thank you for your attention!

andrea.carena@polito.it

Slides available at: https://www.optcom.polito.it/talks

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