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Cross-feature Trained Machine Learning Models for QoT-Estimation in Optical Networks

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Abstract. The ever-increasing demand for global internet traffic, together with evolving concepts of Software-defined network (SDN) and Elastic-optical-network (EON), not only demands the total capacity utilization of underlying infrastructure but also demands dynamic, flexible, and transparent optical network. Generally, worst-case assumptions are utilized to calculate the quality of transmission (QoT) with provisioning of high-margin requirements. Thus precise estimation of the QoT for the lightpaths (LP) establishment is crucial for reducing this provisioning margins. This article proposes and compares several data-driven Machine learning (ML) models to make an accurate calculation of QoT before the actual establishment of LP in an unseen network. The proposed models are trained on the data acquired from an already established LP of a completely different network. The metric considered to evaluate the QoT of LP is the Generalized Signal-to-Noise Ratio (GSNR) which accumulates the impact of both Non-Linear Interference (NLI) and Amplified Spontaneous Emission (ASE) noise. The dataset is generated synthetically using well tested GNPY simulation tool. Promising results are achieved, showing that the proposed Neural network (NN) considerably minimizes the GSNR uncertainty and consequently, the provisioning margin. Furthermore, we also analyze the impact of cross-features and relevant features training on the proposed ML models' performance.

Keywords: Machine learning, Quality of Transmission estimation, Generalized SNR.

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1 Introduction

In the last decades, optical transmission systems revolutionized the telecommunication industry to meet the rapidly increasing global internet traffic demands. In the last few years, internet traffic has been growing continuously¹ with the evolution of new technologies and bandwidth-intensive applications, such as video-on-demand, Full High Definition (FHD) or 4K, cloud computing and the Internet of Things (IoT). This increasing trend of global internet traffic requires the maximum utilization of the remaining capacity of the already working network infrastructure. Around this direction, the fundamental key enabler technologies are coherent technology for optical transmission and DWDM for spectral usage of fiber propagation. In addition to these, the network dis-aggregation paves a path for the technologies such as EON and SDN. The distinctive features of SDN and EON offers versatile and dynamic resource provisioning in optical networks for both control and data plane.^{2,3} EONs provide flexible spectral assignment in the data plane and boost the network's capacity while lowering network cost. This adaptability results in much more complex LP provisioning than conventional fixed-grid wavelength-division multiplexing (WDM) networks. On the other hand, the SDN controller in the control plane handles the operating points of different network components independently, which consequently enables the customized network management.

Today's optical networks have started evolving to partial dis-aggregation, with a full dis-aggregation goal eventually. The prime step towards network dis-aggregation is the consideration of optical-line systems (OLSs), which link the network nodes. In the current reference frame,

21 the capacity of OLS controllers to function at the optimum working point determines the QoT
22 degradation.^{4,5} The precise accomplishment of this working point leads to achieve lower margin
23 and higher traffic rates for traffic deployment. Therefore, it is compulsory to utilize the QoT-E
24 for accurate estimation of LP performance – the *path computation* – before its deployment. In
25 the current context, QoT is effectively evaluated by the GSNR, which comprises the accumulated
26 effect of NLI and ASE noise.⁶ Exploiting the transceiver characteristics, the GSNR describes the
27 feasibility of the path as well as deployable rate. Typically, the network elements suffer a variation
28 on their working point (insertion losses, noise and gain figure, ripples in amplifiers, etc.). This
29 implies uncertainty in QoT-E that needs a system margin to avoid out-of-services.

30 In the present investigation, we suppose a Domain Adaption (DA) approach. The DA approach
31 uses only the available data from *source domain "S"* (e.g., well-deployed in-service network),
32 where the network operator has the sufficient knowledge about the working point of network nodes
33 and provide useful information related to the QoT prediction in the *target domain "T"* (e.g., a
34 newly deployed or unseen network), i.e., the kind of a network where the system administrator
35 does not have the sufficient information of the operating point of network components. This work
36 aims to minimize the margin in the GSNR estimation of the *target domain*. This decrease in the
37 GSNR uncertainty enables the network controller in *target domain* to accurately establish the LP
38 with reduced margin. Generally, the controller can acquire an accurate description of the system
39 parameters i.e., *network status*. The QoT-E exploit several analytical approaches that can measure
40 the GSNR with a very good precision as shown in.⁷ The use of an analytical approach is not
41 reliable without the *exact* knowledge of system parameters, as it is essential to acquire system
42 parameters in the current context of DA. The present work-frame regarding DA concludes that the
43 use of analytic approach is not recommended in such an agnostic scenario to estimate the QoT of
44 LP prior to its deployment.

45 To overcome this challenge, we opted to use data-driven ML approach as an alternative way,
46 which has already been proved very effective in several different contexts of managing optical net-
47 works; look at⁸⁻¹¹ for performance monitoring of optical network operations. A comprehensive
48 assessment of ML practiced in optical networks is described in.¹² In particular, moving towards a
49 distinct interest of this investigation, i.e., estimation of QoT-E of LP before its actual deployment,
50 few very effective ML-based approaches, for instance, the cognitive case-based reasoning (CBR)
51 method, is presented in.¹³ The experimental results related to¹³ obtained with real field data are
52 described in.¹⁴ In,¹⁵ ML based approach is presented to control OLS in an open environment. An
53 approach based on Random forests (RF) is presented to utilize the already accumulated database
54 in¹⁶ to decrease unreliability in design margins and network parameters. A neural network (NN)
55 model is trained to measure the Q-factor for multicast communication scenario in.¹⁷⁻¹⁹ Numer-
56 ous ML based approaches are proposed in^{20,21} for QoT-estimation of LP . In,²² a binary classifier
57 based on RF is proposed to estimate the bit-error-ratio (BER) of LPs before their establishment.
58 Authors in²³ trained three classifiers, i.e., RF, support vector machine (SVM) and K-nearest neigh-
59 bor (KNN) for QoT estimation. The performance of all these approaches is evaluated in terms
60 of accuracy. Furthermore, the investigation presented in,²³ concluded that the SVM shows good
61 accuracy but performs worst in terms of computational time. The authors in²⁴ used NN to char-
62 acterize the integrated circuits consequently used for their full and accurate softwarization. In,²⁵
63 the authors evaluated the performance of two DA approaches for ML assisted QoT-E of an opti-
64 cal LP for a fixed/variable number of available training samples from the source/target domain.
65 The authors studied two networks characterized by different topologies but utilizing identical fiber

66 type and communication devices and assessed the performance of two DA approaches depending
67 on the number of available train realizations from the target domain. The results in²⁵ stated that
68 the DA-based approach worked better than standard ML techniques. The authors in,²⁶ not only
69 proposed ML for QoT-E but also reported the statistical closed-form approach to the QoT margin
70 setting. In,²⁷ CNN based QoT estimator is proposed for unestablished LPs for DA scenario. Fi-
71 nally, the authors in²⁸ analyzed the QoT-E accuracy delivered by a few Active Learning (AL) and
72 DA methods on two different network topologies. The results presented in²⁸ announced significant
73 improvements using an AL approach with some extra samples acquired from the target domain.

74 The notable difference between the past literature and the present work is that we proposed
75 several ML techniques considering the DA approach for the system margin minimization of the T
76 network using the mimicked data of GSNRs response to specific traffic configurations of LPs of
77 the S network in an open environment. We also evaluate and compare ML models' performance
78 by using cross-feature training and relevant features training approaches for GSNR prediction.
79 The generation of the dataset is achieved *synthetically* by perturbing the nominal working point of
80 network components. In the present practice, the synthetic dataset is created against two different
81 networks characterized by different topologies utilizing the identical fiber type and communication
82 devices but are different in terms of the most delicate parameters of amplifiers, i.e., noise figure,
83 amplifier ripple gain and fiber insertion losses. Regarding these two companion networks, the first
84 one is supposed as S network, a type of network where the operator has a complete description of
85 network elements' operational parameters. The other network is considered as T network, which
86 is intrinsically a type of network where the operator has only a basic description of the operational
87 parameters of network elements.

88 The rest of the paper is organized as follows: Section 2, briefly explains the physical layer's
89 abstraction to efficiently implement a multi-layer optimization, simultaneously with the argument
90 that an accurate QoT-E has a fundamental role in minimizing the system margin. Moreover, we
91 also pitched several potential methods to obtain information about OLS attributes, each providing
92 a diverse decline of the GSNR uncertainty. Section 3, explains the background of ML techniques
93 used for QoT estimation of un-established LP. In Section 4, the simulation conducted to model an
94 open OLS composed of cascaded amplifiers and fibers is described. The data generation and the
95 technique used for refining the dataset before applying to ML models are reported. The dataset
96 is generated synthetically against two different networks using the open-source GNPpy simulator.
97 The two mimicked datasets are perturbed by varying EDFA noise figure, ripple gain and insertion
98 losses. In Section 5, we reported the configuration parameters for the proposed ML techniques,
99 which are used in the context of the DA approach by exploiting the dataset of the already well-
100 deployed S network. The proposed ML techniques predict the GSNRs of LPs of the T network
101 before its actual deployment with significant accuracy. Moreover, we also define the characteriza-
102 tion of features and labels of the proposed ML models and the metric used to evaluate them. Later,
103 in Section 6, we produced detailed results. Finally, the conclusion and future research work are
104 illustrated in Section 7.

105 2 Overview of Optical Transport Network

106 Generally, an optical network consists of Optical Network Elements (ONE) connected through
107 bidirectionally fiber links, where traffic demand is added/dropped or routed, as shown in Fig. 1a.
108 The amplifiers are placed after a specific span length using the Erbium-Doped Fiber Amplifiers

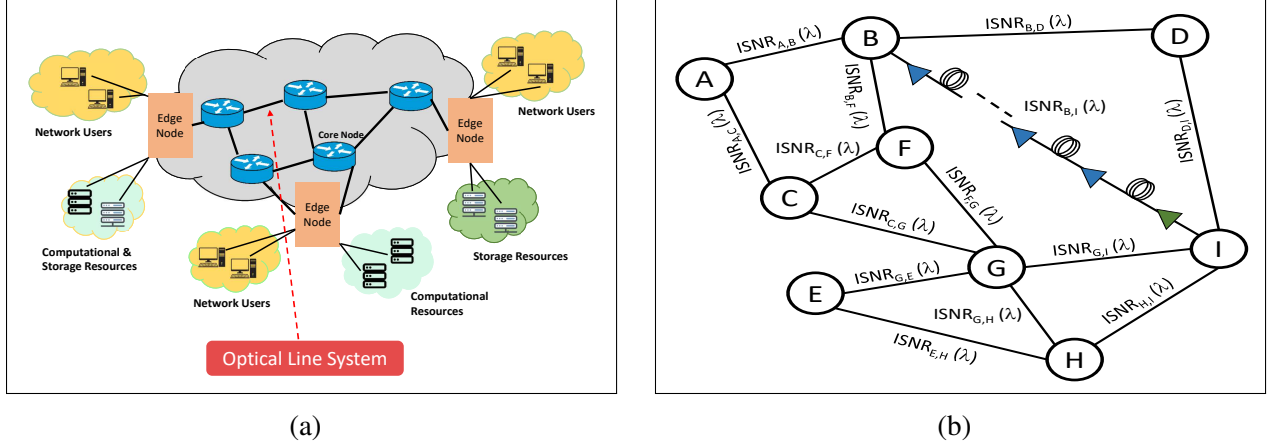


Fig 1: (a), Architecture of Optical Network (b), Optical Transport Network

109 (EDFAs) technique/Raman amplification or optionally used in combination. In the present state-
 110 of-the-art optical network, ONE connected through fibers are generally expressed as an OLS and
 111 a particular controller with the specific characteristic feature to configure the operating point of
 112 every amplifier traversing through the link, and the spectral load is provided at the input of every
 113 fiber span. Further to this, the transport layer adding/dropping or routing services is delivered using
 114 Reconfigurable Optical Add/Drop Multiplexers (ROADM). The DWDM, spectral usage technol-
 115 ogy according to the ITU-T recommendations,²⁹ can exploit either the fixed or flexible spectral
 116 grid that characterizes the spectral slots for both grid architectures.^{30,31} Utilizing either grid archi-
 117 tecture, LPs are deployed, where LPs are the logical abstraction of feasible links between node-to-
 118 node given the traffic demands. Furthermore, against every deployed LP, a Polarization-Division-
 119 Multiplexing (PDM) is exploit to propagate from particular source to its specific destination. Along
 120 with the transmission, LP suffers different propagation impairments like amplifier noise added as
 121 an ASE, fiber propagation, and filtering penalties applied by ROADM. Also, the fiber propagation
 122 has been extensively demonstrated that the fiber propagation on an uncompensated optical coher-
 123 ent transmission system impairs the QoT of deployed LPs by introducing amplitude and phase
 124 noise.^{4,32–34} This introduced phase noise is efficiently counterbalanced by the receiver's DSP mod-
 125 ule, using a carrier phase estimator algorithm. This particular set of noise can only be considered
 126 for very high symbol rate communication designed for short distance.³⁴ In opposite to this, the
 127 amplitude noise, typically described as the NLI, always impairs the performance. It is a Gaussian
 128 disturbance that accumulates with the receiver's ASE noise. Finally, the ROADMs filtering penalty
 129 also decreases the QoT level, which is generally estimated as an extra loss.

130 2.1 QoT-Estimation Metric

The QoT-E metric for a particular LP routed by definite OLSs from source node to destination node is given by the well-acknowledged GSNR measurement, which combines both the aggregated effect of ASE noise and NLI disturbance. Generally, GSNR is defined as:

$$GSNR = \frac{P_{Rx}}{P_{ASE} + P_{NLI}} = (OSNR^{-1} + SNR_{NL}^{-1})^{-1} \quad (1)$$

where $OSNR = P_{Rx}/P_{ASE}$, $SNR_{NL} = P_{Rx}/P_{NLI}$, P_{Rx} is the signal power of the particular channel at the receiver, P_{ASE} is the power of the ASE noise and P_{NLI} is the power of the NLI. Analyzing

the transceiver’s back-to-back characterization, the GSNR accurately provides the BER, as BER has been extensively stated in different vendor demonstrations with the use of industrial products.⁶ The non-linear effects, while fiber propagation generates P_{NLI} , which relies on the spectral-load and the power of the distinct channel.⁴ In these circumstances, it is pretty much clear that there is an optimal spectral load for each specific OLS that maximizes the GSNR.⁵ Examining the LP propagation effects against a specific pair of source and destination, we provide an abstract view of the operation as a combined impact of every single ONE that adds up the QoT impairments. Simultaneously, given a specific pair of source and destination encounters the cumulative impairments of previously traversed OLSs along with ROADM effects. Each crossed OLS adds a specific amount of NLI and ASE noise. For the purpose of QoT, the abstraction of OLS can be achieved by a single parameter known as SNR degradation which generally depends upon the frequency ($\text{GSNR}_i(f)$), if the OLS controllers can retain the OLS running at the ideal operation point. Therefore, an optical network can be generally abstracted as a weighted graph (W), where W = (vertices (V), edges (E)) corresponds to the specific networking topology. The V represent ROADM network nodes, while the E represent OLSs having $\text{GSNR}_i(f)$ as weights on the consequent edges, shown in Fig. 1b. Specifically, for a given LP from the source node I to destination node F that passes through intermediary nodes B, the QoT is:

$$\text{GSNR}_{\text{IF}}^{-1}(f) = \text{GSNR}_{\text{IB}}^{-1}(f) + \text{GSNR}_{\text{BF}}^{-1}(f) . \quad (2)$$

131 Following network level abstraction, LPs deployment can be feasible for a specific source node to
 132 destination node with the reduced margin, which relies on the *GSNR* of a particular source to the
 133 destination path.

134 2.2 Methods for QoT Estimation

135 This section describes the various possible approaches for acquiring knowledge about the charac-
 136 teristics of an OLS, with each allowing the distinct GSNR measurement. In the initial approach, the
 137 data obtained from ONE, for example, static description of elements (e.g., connector loss, noise
 138 figure amplifier gain, etc.), is utilized to achieve precise QoT-E vendor-specific systems. Con-
 139 cerning this specific method, several analytical approaches are available to assess the GSNR and
 140 characterize the OLS elements. Nevertheless, this strategy based on static data may not be reliable
 141 as the ONE experiences continuous performance degradation owing to the aging effect, heading to
 142 gradually un-reliable QoT-E after a specific period.

143 The next method is utilizing the telemetry data to examine the network status instantly. Assum-
 144 ing an agnostic operating of OLS in an open environment; the controller of OLS largely rely on
 145 the telemetry data achieving from the EDFAs and the Optical Channel Monitor (OCM). This spe-
 146 cific technique is feasible for an accurate QoT prediction by utilizing the network’s current state’s
 147 telemetry. In opposite to the former method, this technique does not depend on the static param-
 148 eters of ONE. Thus, it eliminates the unreliability in the QoT-E precision introduced because of
 149 device aging factor as discussed in the earlier technique. However, this unique technique dilemma
 150 is that the response of GSNR, particularly the OSNR part, significantly relying on the configuration
 151 of spectral-load, leading to substantial unreliability in the QoT margin.¹⁵

152 The final method examines the dataset that obtains the QoT responses against arbitrary spectral-
 153 loads of S network. As mentioned earlier, the generation of dataset is performed during the oper-
 154 ating period of the S network by estimating the OLS response with regard to GSNR for numerous

155 spectral-load arrangements. This specific case comes up with a perfect playing field to employ
 156 ML. An ML technique utilizing a dataset comprised of spectral-load samples of an S network for
 157 training and complies a correct QoT-E for every generated spectral-load section of T network. In
 158 distinction to the former method, where just telemetry data is explored, this procedure employs the
 159 QoT-E centered on the GSNR reaction to particular spectral-load arrangements of S network, used
 160 for an accurate GSNR prediction of T network. Additionally, this arrangement does not require
 161 any information about physical parameters of the OLS as compared to the first technique. There-
 162 fore, this approach gives an excellent playground to utilize the ML-DA method. In this activity, we
 163 focus on the third procedure, which is based upon the ML method. This approach uses the GSNR
 164 related to the individual spectral-load configurations of the previously established S network for its
 165 training and predicts the QoT of T network.

166 3 Background on Machine Learning Models

167 This section briefly explains the ML techniques we have applied for QoT estimation of un-established
 168 LP. Generally, ML has a wide range of applications in optical communications and networking.³⁵
 169 ML model learns from previous knowledge of the network and then uses that learned knowledge
 170 to make predictions. Recently, QoT prediction of an unestablished LP with ML models has gained
 171 a lot of attention^{12,15,16}. In this work, six ML models are employed to estimate the QoT of an un-
 172 established LP, and also domain adaptation (DA) capability of these models is assessed. In the
 173 following, we briefly present a short overview of these employed ML models.

174 3.1 Decision Trees

We propose using the Decision Tree (DT) model to assess the feasibility of un-established LP in
 the DA scenario, i.e., transferring the source data distribution learned from a known network to
 another related target network with a different distribution. DT constructs a tree based on the deci-
 sions made by exploring dataset features in different aspects. It has three essential parameters; the
 maximum number of splits, minimum leaf-size, and minimum parent-size. We applied a greedy
 approach to data to minimize the cost function and obtained the optimum values for these parame-
 ters. A standard regression cost function representing the mean absolute error is used, which is as
 follows:

$$E = \frac{1}{N} \sum_{i=1}^N (y - y') \quad (3)$$

175 Here y , denotes the ground truth (actual value) while y' represents the predictive value i.e., GSNR
 176 in our case. N represents the total number of samples. We sum overall the samples in our dataset
 177 to get the total error, then we keep on splitting the tree until an optimal value is reached.

178 3.2 K -Nearest Neighbours

179 K -nearest neighbors (KNN) is a type of supervised non-parametric ML model. KNN attempts to
 180 classify the data sample into a particular category by utilizing training dataset. We applied this
 181 model to make predictions based on feature similarity by calculating the distance between new
 182 data point and training data points. The hyper-parameters required for KNN are:

- 183 • Number of nearest neighbors (K)

184 • Distance metric

185 In our simulation environment, we kept $K = 5$ and used Euclidean distance to calculate the
186 distance between the test point and training samples.

187 3.3 Random Forest

188 It is a type of ML model that uses ensemble learning which is based on the bagging tree technique.
189 In this technique, each tree runs independently, and at the end, the results of all the trees (without
190 giving importance to anyone specific tree) are averaged to give the final output. In Random Forest,
191 each tree has a random set of training observations and a random subset of features used to form a
192 tree. If we only rely on the decision of a single tree, the scope of the output information is limited .
193 However, if we construct multiple such trees and average their output, our net information from the
194 output is much greater. We applied the Bagging technique where n different ensembles are created
195 to give different profound knowledge about the dataset because their outputs are not correlated.
196 When we average these ensembles, it effectively brings in the insights from each of them, and we
197 are left with a better generalization of the output. We also applied this technique to figure out the
198 important set of features to predict our label better.

199 3.4 Linear Support Vector Regression

200 Linear Support Vector Regression (SVR) is a type of supervised ML model that works on the
201 same idea as Support Vector Machines (SVM). SVR is used to cater regression problems where
202 continuous output is predicted. The following essential parameters are used to configure SVR:

- 203 • **Kernel:** It is used to map data from lower dimension to higher dimension at lower compu-
204 tation cost. It is beneficial in finding the best hyper-plane. We applied linear Kernel to our
205 problem.
- 206 • **Hyper Plane:** It is a line used to predict the continuous output.
- 207 • **Decision Boundary:** Two parallel lines are drawn with ϵ distance from the hyper-plane to
208 define a margin.

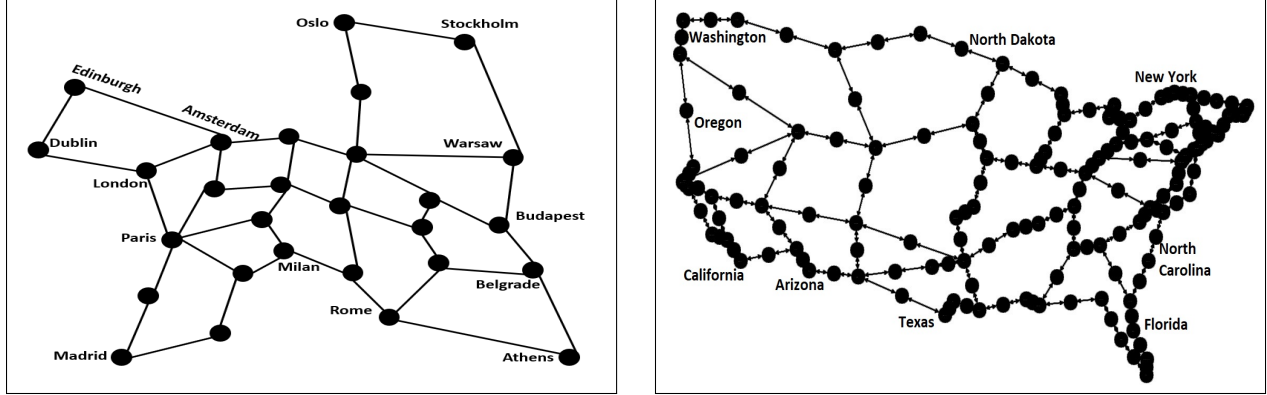
In SVR, we are trying to fit the maximum allowable error within a the tolerable range that is defined by the ϵ value. The goal is to find a function $f(x)$ that deviates by a value not greater than ϵ for each training point from the output prediction. The best fit line is the one with the maximum number of data points.

$$f(x) = xw + b \quad (4)$$

For the linear hyper plane, the equation that satisfies our support vector regressor to predict QoT of LP is given below:

$$\epsilon \leq y - xw - b \leq -\epsilon \quad (5)$$

209 To fit the maximum allowable error within a tolerable range, we define the value of $\epsilon=3$ in our
210 simulation environment.



(a) European Network

(b) USA Network

Fig 2: Networks Topologies

211 3.5 Neural Networks

212 NN is an ML model inspired by the human nervous system to process information. It comprises
 213 the input layer, hidden layers, and output layer, where the layers are sets of neurons. NN typically
 214 learns with a feedback process where the predicted output is compared with the actual output. The
 215 difference between them is then calculated. The error gradient is computed for every preceding
 216 layer using a back propagation algorithm to adjust the weights using a stochastic gradient descent
 217 algorithm. For QoT estimation, we applied the NN model with several tuned parameters to get an
 218 efficient model providing high accuracy.

219 3.6 Linear Regression

Linear Regression Model is a parametric ML model which uses a statistical technique to find
 the linear relationship between the input feature (x) and the output label (y). The mathematical
 representation for the Linear regression model is as follows:

$$y = B_0 + B_1x \quad (6)$$

220 where y is the output variable, B_0 is the intercept, B_1 is the co-efficient of each variable and x
 221 is the set of input features. The model estimates the values of intercept (B_0) and the co-efficient
 222 (B_1). Linear regression has a different kind of optimization strategy. In our work to estimate QoT,
 223 we applied the ordinary least square method that takes more than one input feature and requires no
 224 weighting function.

225 The hyperparameters for our employed ML models are given in Table 3.

226 4 Simulation Model and Synthetic Data Generation

227 This section describes the simulation model and the considered network topologies, the library
 228 used for physical layer abstraction and data generation, and the technique used for refining the
 229 dataset before applying it to ML models.

230 The proposed work simulates an open OLS composed of cascaded amplifiers and fibers. In the
 231 simulation setup, the grid size of 50GHz is considered to have 76 channels on the C-band. Due
 232 to computational resources limitation, only 76 channels are considered over the total bandwidth of

233 approximately 4 THz. The transmitter generates signals at 32 GBaud, shaped with a root-raised-
 234 cosine filter. The signal’s launch power is set to 0 dBm, which is kept constant by EDFA, operating
 235 at a constant output power mode of 0 dBm per channel. The noise figure of EDFA is varied uni-
 236 formly, in the range of 4.5 dB to 6 dB with a ripple gain variation uniformly with 1 dB variation.
 237 All the links are operated using a Standard Single-Mode Fiber (SSMF) having a typical span length
 238 of approximately 80 km. To these fiber impairments such as fiber attenuation (α) = 0.2 dB/km and
 239 dispersion (D) = 16 ps/nm/km are also considered. To create the simulation model realistic, the
 240 statistics of insertion losses are determined by an exponential distribution with $\lambda = 4$, as described
 241 in the study.^{36,37} The paths are computed using the Dijkstra algorithm, with the metrics used is
 242 the shortest distance path. For the computation of GSNR, the ASE noise is modeled as Additive
 243 White Gaussian Noise (AWGN) with bilateral Power Spectral Density (PSD), including both po-
 244 larization. The nonlinear impairments are modeled by the analytical perturbation model, such as
 Generalized Gaussian Noise (GGN) model.³⁸

Table 1: **Source-Destination pairs and Number of Spans of European Network**

Source	Destination	Number of Spans
Amsterdam	Berlin	8
Brussels	Bucharest	30
Frankfurt	Istanbul	34
Vienna	Warsaw	7
Paris	Rome	34

245

Table 2: **Source-Destination pairs and Number of Spans of USA Network**

Source	Destination	Number of Spans
Kansas City	Las Vegas	30
Milwaukee	Minneapolis	6

The dataset is generated synthetically mimicking the receiver’s signal power, NLI generation during the signal propagation against two different networks, and ASE-noise accumulation using the GNPpy simulator. The GNPpy is an open-source optimization library that is spectrally resolved and is formulated on GGN model.^{7,38} This simulator has been developed by Open Optical & Packet Transport–Physical Simulation Environment (OOPT–PSE) working group within the Telecom Infra Project (TIP). In,³⁸ GNPpy is validated on a real network for QoT estimation of the LPs. It exhibits outstanding accuracy for GSNR prediction. It provides an end-to-end simulation environment to develop the network model on physical layer. This library defines route planning in mesh optical networks and can include customized network elements in the network. The synthetic dataset is generated against two different network topologies; European (EU) network and USA network shown in Fig. 2a and Fig. 2b respectively. The EU Network is considered well-deployed and represents the S network while USA Network represents the T network. The two considered networks are the same in terms of fiber and ONE. However, they are different concerning the amplifier’s delicate parameters (noise figure and amplifier ripples gain) and fiber insertion losses. The dataset used in this work consists of 6 source-to-destination ($s \rightarrow d$) pairs of EU network and 11 $s \rightarrow d$ pairs of USA network shown in Table 1 and Table 2. The spectral load realization against each simulated link of a dataset is a subset of 2^{76} . In the considered spectral load realization for

Table 3: Hyperparameters of ML Models

ML Model	Parameter	Value
Decision Tree	Max no of splits	obs-1=5407
	Min leaf size	4
	Min parent size	10
	Split criteria	'mse'
	Purne	'on'
	Purne criteria	'mse'
KNN	k	5
	Distance metric	Euclidean
Random Forest	Method	'Bag'
	Min leaf size	4
	No of cycles	50
	No of Var to sample	1/3 of max splits
Linear SVR	ϵ	0.3
	kernal	'Linear'
Neural Network	No of hidden layers	3
	No of units	3
	Activation Function	'ReLU'
		'Linear'
	Learning rate	0.01
	No of epochs	1000
Linear Regression	Equation	Linear
	Method	Ordinary Least Squares

every $s \rightarrow d$ pair, we considered 3000 realizations of arbitrary traffic flow varying between 34% to 100% of overall operational bandwidth. Thus for EU network topology, 18,000 realizations are generated, and for the USA network topology, 33,000 realizations are generated. The considered dataset is then *normalized* to scale the values. We investigated the different normalization methods on the prediction performance of our machine learning models. Based on the value of the evaluation metric (mean absolute error), we believe that z scale normalization seems to be a good choice for our case. In the z score, the mean and standard deviation of against each input feature is used to normalize the vector of each feature.³⁹ It helps to reduce the effect of outliers from the data and overcomes the problem of dominant features entirely.⁴⁰ It is used as follows:

$$Z = \frac{X - \mu}{\sigma} \quad (7)$$

246 where μ and σ is the mean and standard deviation against each feature, the considered Z-score
247 normalization is applied to both the train and the test data.

248 5 Machine Learning Models Orchestration

249 This section describes the characterized features and labels of ML models and the metric used
250 to evaluate the ML models. Furthermore, the models, depicted in section 3, are simulated in this

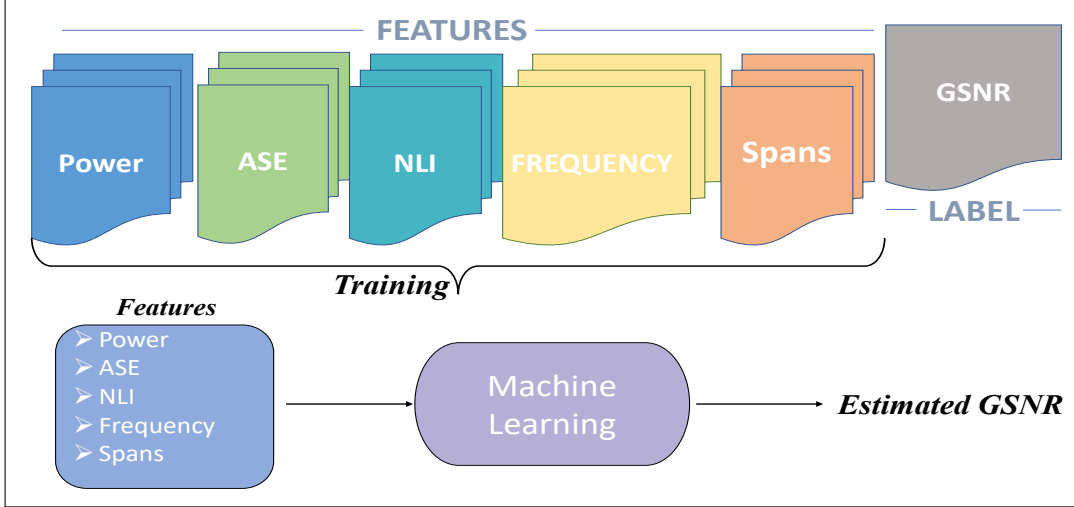


Fig 3: Machine Learning Module

251 section. The standardized dataset is divided into two sets: *train* and *test* set. The train set consists of
 252 four paths (12,000 samples) for the EU network, while the test set consists of the last one path (3000
 253 samples) of the EU network and two paths of the USA network (6000 samples). The parameters
 254 utilized to describe ML models' features include ASE, NLI, received signal power, span length,
 255 total distance and channel frequency of 76 channels, shown in Fig. 3. All the proposed models
 256 are evaluated using the Mean Absolute Error (MAE) metric to quantify the GSNR predictions of
 257 the ML models by taking the mean absolute difference of all the predicted values with the actual
 258 values. Moreover, the models described in Section 3 are simulated using MATLAB[®] platform and
 259 are configured using the simulation parameters given in the Table 3.

260 6 Results & Discussion

261 In this section, the performance comparison of six ML models in the Same Domain (SA) and
 262 DA scenario is reported. In the SA scenario, we trained the ML models on the EU network and
 263 tested it on other EU network paths. In the DA scenario, ML models exploit the knowledge of
 264 the EU network to estimate the output label (i.e., GSNR of LP) of the USA network. Moreover,
 265 we also perform feature engineering to find out the importance of features for GSNR prediction.
 266 Furthermore, the evaluation and comparison of models are also performed using the cross, and
 267 relevant features model training approaches for the specific label (i.e., GSNR of LP in our case).

268 6.1 ML models trained on cross features

269 We first investigated the MAE using the SA approach, i.e., training an ML model on some paths
 270 of EU Network and then testing it on other paths. This section exploits all the available features
 271 of 76 channels to perform cross-feature training of ML models to estimate the GSNR of channel
 272 1. Using the paths reported in Table 1, the first four paths of the EU Network are used to train
 273 the ML models, and the last path is used for testing the models. The result of the test path, from
 274 Paris to Rome, is depicted in Fig. 4. It shows the results of all the proposed models, i.e., Actual
 275 and Predicted GSNR with mean (μ) and standard deviation (σ). Observing the statistics μ and σ
 276 in Fig. 4. it is depicted that the NN model trained on cross features shows excellent results in
 277 terms of GSNR prediction, whereas the KNN model is showing the worst prediction performance

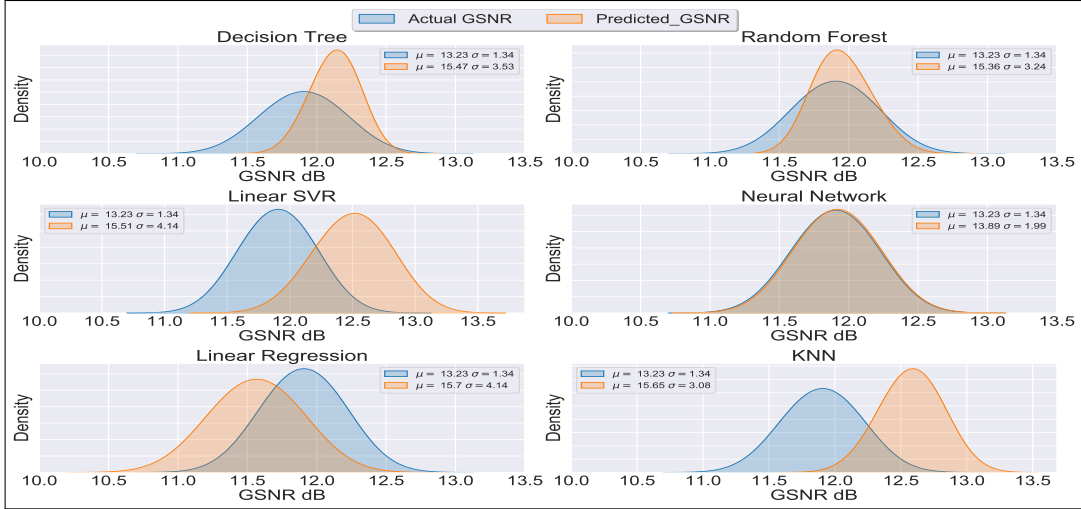


Fig 4: EU network path Paris to Rome: Cross features training.

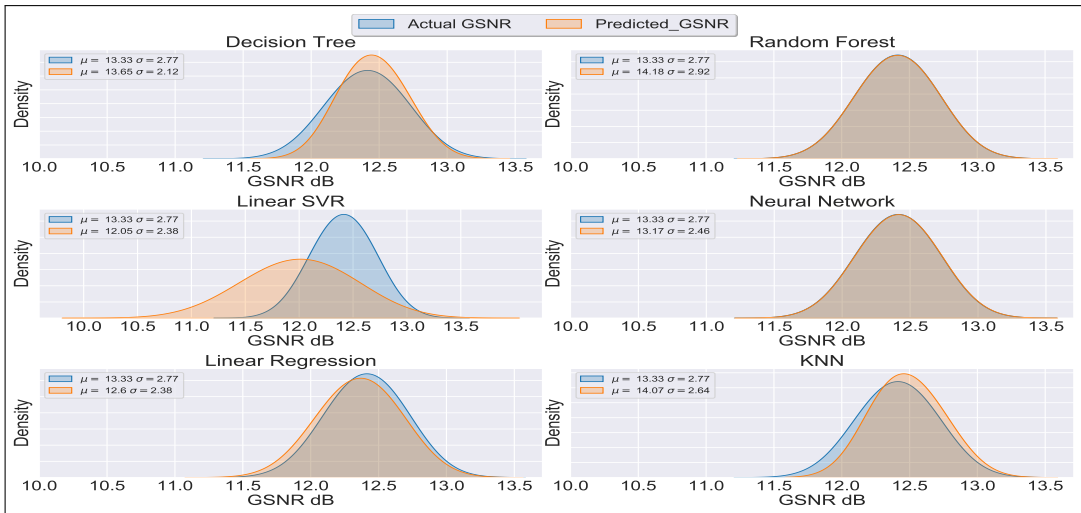


Fig 5: USA network path Kanas to Las-Vegas: Cross features training.

278 in comparison with all proposed models. NN's performance gets better each time we train it on
 279 training data because of the iterative learning approach, whereas in KNN, the training dataset is
 280 given once for it to work.

281 To evaluate the performance of the proposed ML models using the DA approach, i.e., training
 282 on four paths of EU network and testing on two paths of USA network are reported in Table 2. The
 283 outcome of the DA approach is shown in Fig. 5 and Fig. 6. It shows the proposed ML models'
 284 prediction performance against the two paths, i.e., Kanas City to Las-Vegas and Milwaukee to
 285 Minneapolis, of the USA network. Observing the statistics of μ and σ , it is pretty clear that the
 286 predictions with the NN model seem to follow the same distribution as the actual values, and
 287 it outperforms all other proposed ML models, whereas KNN is again performing worst among
 288 all the proposed models. Based on the performance of our NN model, we make the following
 289 observations. NN model still performs better in case of DA for the USA network because of its
 290 ability to learn complex hidden patterns, leading to better generalization. NN continuously adjusts
 291 weights at each input to further optimize results.

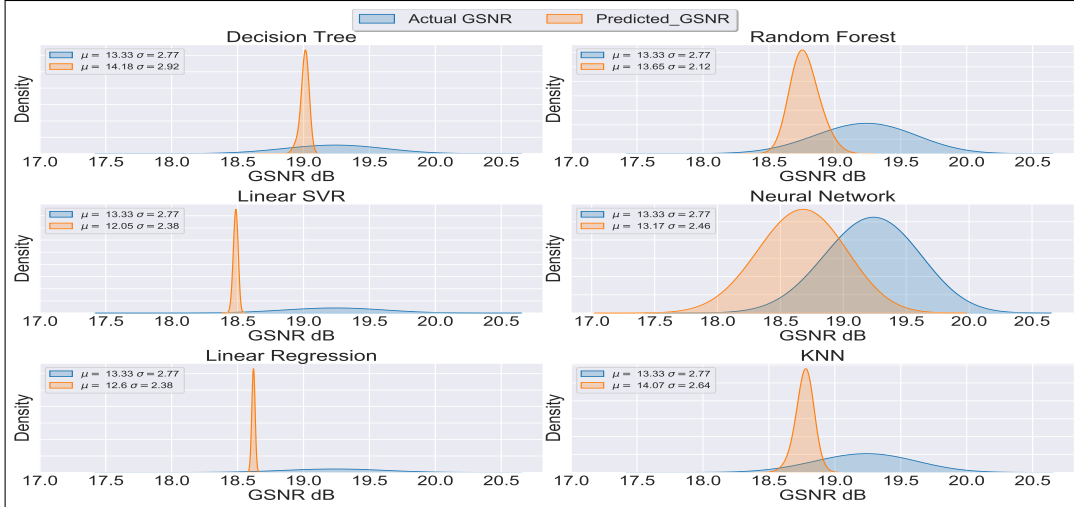


Fig 6: USA network path Milwaukee to Minneapolis: Cross features training.

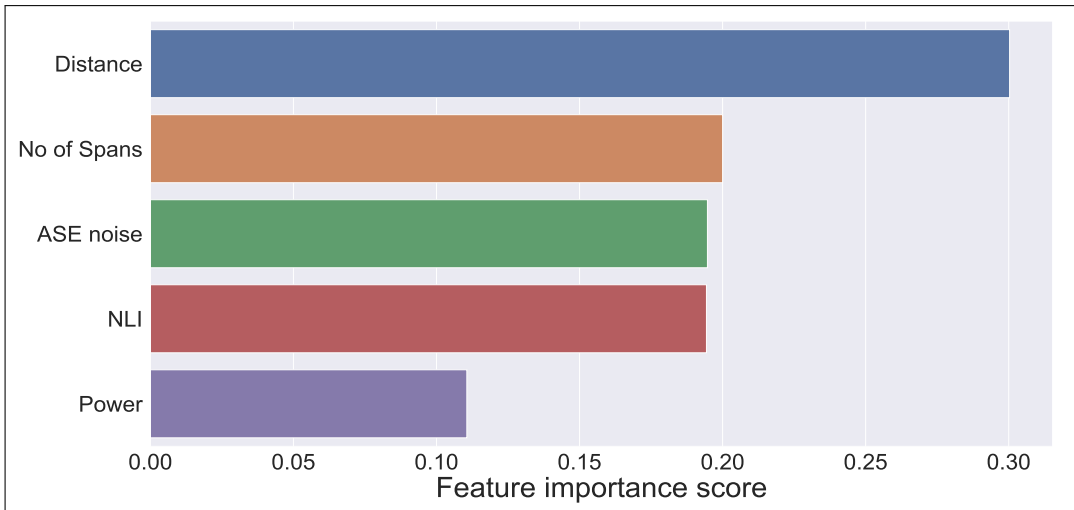


Fig 7: Features importance

292 6.2 ML models trained on relevant features

293 This section analyzes the impact of relevant features in predicting the GSNR of channel-1, which
 294 is supposed to be Channel-Under-Test (CUT). Firstly, we applied the Random Forest model to
 295 determine the feature importance for GSNR prediction. The Random Forest model helps in finding
 296 the features that have more impact on the prediction of the target label (i.e., the GSNR in our case).
 297 It performs well due to its property of randomly sampling the features and the data points. Fig. 7
 298 depicts the importance of features to the label (GSNR). On the y-axis, various used features are
 299 shown, while on the x-axis importance score is plotted. The results shown in Fig. 7 represent that
 300 the distance between source and destination is the most important feature followed by the number
 301 of spans, ASE, NLI, and power of the LP in predicting the GSNR of LP. We trained the ML models
 302 on all of these relevant CUT features and evaluated CUT's predictions against one test path of the
 303 SA (European) network and two DA (USA) network paths. First, we see the SA network results
 304 with a test path, i.e., Paris to Rome. The results of the actual and predicted distribution of the SA
 305 test path against all the proposed models are shown in Fig. 8. The statistics of μ and σ demonstrate

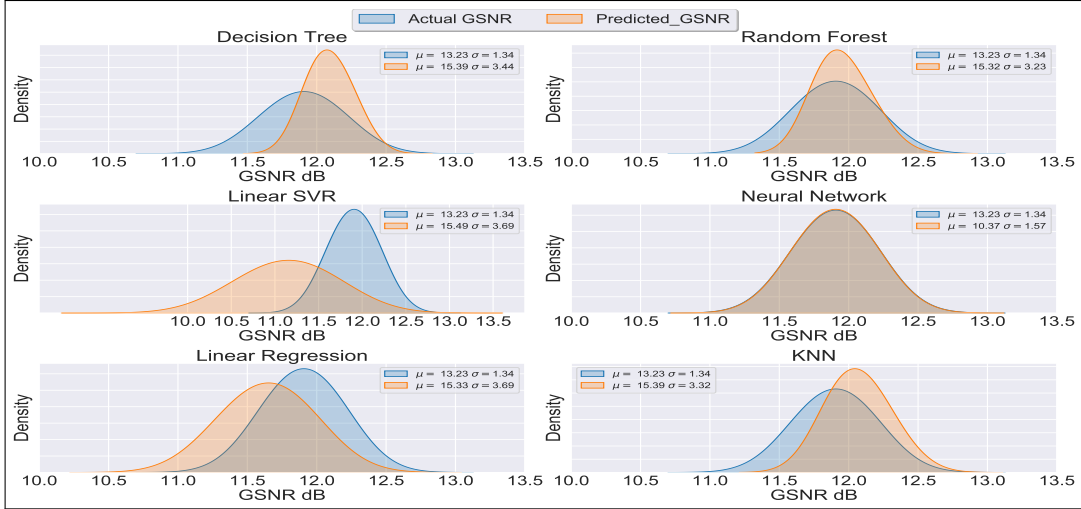


Fig 8: EU network path Paris to Rome: Relevant features training.

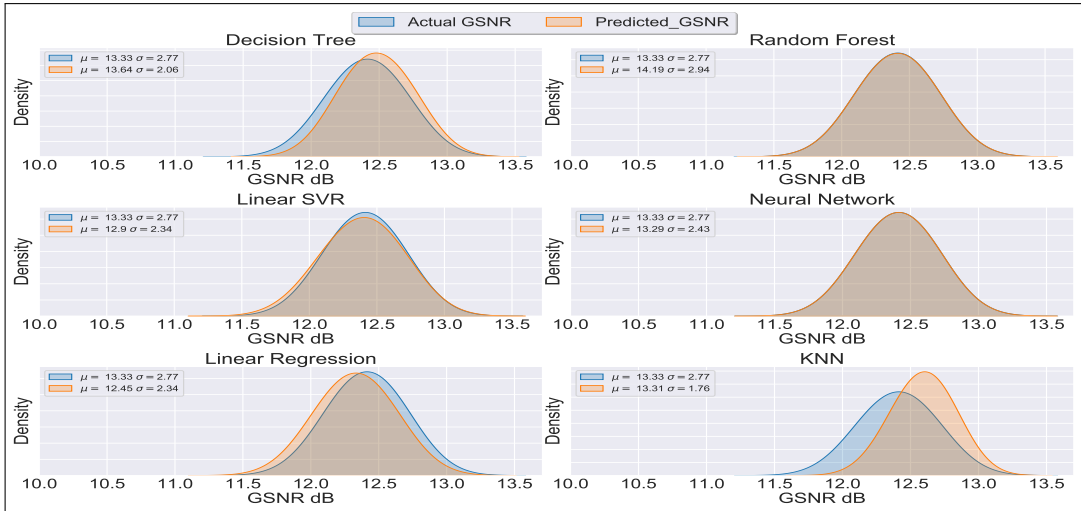


Fig 9: USA network path Kanas to Las-Vegas : Relevant features training

306 NN's excellent prediction performance against other models. Moreover, for the DA approach, the
 307 distribution of predicted vs. actual GSNR for the CUT on the two paths, i.e., Kanas to Las-Vegas
 308 and Milwaukee to Minneapolis is shown in Fig. 9 and Fig. 10. The results in both Fig. 9 and Fig.
 309 10 show that NN also performs best in the case of DA as compared to all the proposed models.

310 6.3 Cross feature vs. Relevant feature training

311 This section compares ML models based on MAE when trained on cross features and relevant
 312 features. Table.4 illustrates the MAE comparison of the EU and USA networks. For the given
 313 simulation scenario, Fig 4 demonstrates that the MAE of Decision Tree is reduced when trained
 314 on relevant features for both networks, but it does not perform well on USA network when trained
 315 on cross features due to its poor learning of underlying associations in the dataset. On the other
 316 hand, Random Forest leverages several decision trees for feature selection, hence its overall perfor-
 317 mance is better than the decision tree for both networks when trained on cross features and relevant

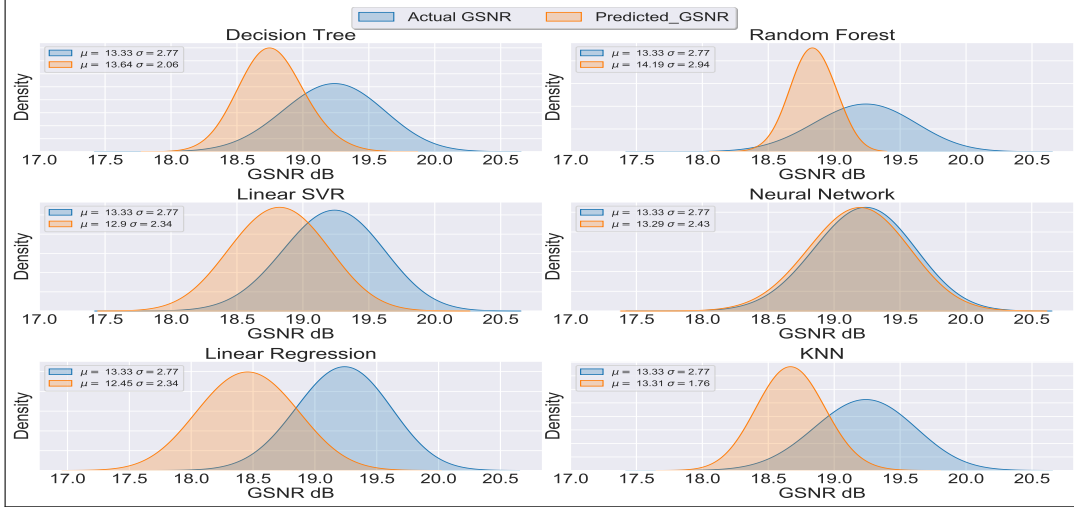


Fig 10: USA network path Milwaukee to Minneapolis :Relevant features training.

318 features. The performance of Linear SVR and Linear regression is almost similar and it gets bet-
 319 ter when relevant features are considered for training in both scenarios. On the other hand, the
 320 performance of NN for EU network is outstanding when trained on cross features and relevant fea-
 321 tures because of its cognitional ability to learn complex and hidden patterns very well. To further
 322 analyze the NN model's performance trained with cross features and relevant features, we tested
 323 it on the USA network, including more test data. When NN is tested on the USA network path
 324 with relevant feature training, it generalizes very well and gives an excellent performance for both
 325 networks. For the given scenario, KNN performs well when trained on relevant features of CUT
 326 because of its good capability to work on feature similarity. In the case of KNN model, the per-
 327 formance is degraded when trained on cross features and it failed to fit the underlying relationship
 328 in the dataset and depicts the worst generalization on the USA network as compared to all other
 329 models. The MAE of the KNN model is increased when trained on cross features particularly for
 330 the USA network because it does not properly approximate the relation between input and output
 331 of a dataset. Observing these results, we conclude that NN-based models have the potential to
 332 generalize well on an unseen network with good performance when trained on relevant features of
 333 CUT. To take the confidence level into consideration along with prediction error, we executed the
 334 simulation 10 times with 1000 epochs and computed prediction error each time for both the train-
 335 ing and testing data in the same as well as in the domain adaptation scenario. These simulations are
 336 performed using our best performing model, the neural network model trained on relevant features
 337 whose results, including the mean and standard deviation of Δ GSNR distribution, are reported in
 338 Fig. 8 and Fig. 9. The average mean absolute error of the prediction error in the training and test-
 339 ing dataset about the EU network is around 0.00127 dB and 0.00132 dB, respectively. Similarly,
 340 the standard deviation (confidence level) in the respective training and the testing dataset is around
 341 0.0000114 dB and 0.000018 dB. Moreover, to check the robustness of the model in the domain
 342 adaptation scenario, we also tested the trained model on the different network topology (i.e., USA
 343 network). The mean absolute error in prediction on the USA network is around 0.0053 dB, while
 344 the standard deviation (confidence level) is found to be 0.00015 dB. Overall, what we analyzed is
 345 that when relevant features are considered for training ML models, the performance gets enhanced.

346 Our best performing NN model provides a viable solution for practical implementation into
 347 SDN-based optical networks for real-time QoT estimation of LPs. It is executed on a system
 348 with an Intel®Core™i7 8550U 1.80 GHz CPU workstation equipped with 8 GB of RAM. The
 349 model’s computation time is 0.2 ms when trained on relevant features. With the use of cross-
 350 features, we are taking the features of all the relevant channels to make an appropriate decision
 351 about the lightpath deployment. It can be considered an important component for online network
 352 operating tools for QoT estimation in real-time. It can improve network efficiency as on the arrival
 353 of a lightpath request; it can estimate the QoT of a lightpath in real-time. In contrast, the typical
 354 techniques require extensive computational effort when applied to real-time scenarios. Its other
 355 application is in the design of Elastic Optical Networks (EONs), where its output will be used
 356 by Routing and Spectrum Assignment (RSA) decision tools to make the final decision about the
 357 lightpath deployment

Table 4: Comparison of MAE of EU and USA network

European Network			USA Network	
ML Model	cross feature MAE(dB)	relevant feature MAE(dB)	cross feature MAE(dB)	relevant feature MAE(dB)
Decision Tree	0.0745	0.0471	0.2277	0.1874
Random Forest	0.0089	0.0089	0.0597	0.0477
Linear SVR	0.0777	0.0532	0.3481	0.3103
Neural Network	0.0072	0.0013	0.008	0.0054
Linear Regression	0.08919	0.0612	0.3912	0.3606
KNN	0.1653	0.0758	0.6759	0.3886

358

359 7 Conclusion

360 We investigated different ML techniques to predict the QoT of LP of an unseen network before
 361 its deployment. The prior prediction of the QoT of LP in an un-seen network is an essential
 362 step for the optimal design of the network and reliable LP deployment with a low margin. The
 363 GSNR of LP is used as a QoT metric which comprises the effect of both NLI and ASE noise
 364 accumulation. Our simulation results show that NN performs best with an MAE of 0.001 dB for
 365 the European network and 0.005 dB for USA network when trained on relevant features and 0.007
 366 dB for European network and 0.008 dB for USA network when trained on cross features.

367 We performed feature engineering and observed that when the models are trained only on
 368 relevant features, the prediction performance is improved. The presented results clearly show that
 369 ML-based techniques, especially NN, significantly reduce the provisioning GSNR margin in both
 370 SA and DA scenarios. For future perspective, additional work is required considering broad range
 371 of system configurations to prove the effectiveness of this approach for real world applications.

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