Introduction to the JOCN Special Issue on Machine Learning Applied to QoT Estimation in Optical Networks

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This special issue contains a collection of invited and contributed papers, including a review article and eight research articles, on the application of machine learning to the estimation of quality of transmission in optical networks.

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Machine learning has gained traction in the optical networking community in the past few years, with numerous applications ranging from pure physical layer to (cross-layer) network optimization, as testified by the publication of a JOCN special issue on machine learning for optical communications in 2018 [1]. In particular, estimating quality of transmission (QoT), such as a connection's signal-to-noise ratio (SNR), bit-error rate (BER) or *Q* factor, has been a natural target for machine learning due to:

- its importance to network operators: QoT estimation is needed to inform basic network design decisions such as light path establishment, modulation format selection, and power allocation, possibly in real-time (e.g., in the case of restoration);
- its inherent (computational) complexity: traditional, physics-based methods trade accuracy for computation time to make them amenable to the design and operation of dynamic networks;
- the reliance of traditional models on uncertain or missing data, which can make even the most accurate model inaccurate.

For these reasons, dozens of articles have been published on the topic of QoT estimation using machine learning. In this special issue, the reader will find a review article including a taxonomy for these papers: "Machine Learning Techniques for Quality of Transmission Estimation in Optical Networks."

Counter-intuitively, although formulae to quantify the linear amplifier spontaneous emission noise in amplifiers such as Erbium Doped Fiber Amplifiers (EDFAs) have existed for decades, the highly nonlinear wavelength and load dependence of the linear noise power makes linear noise power estimation difficult, and particularly well-suited to estimation with data models and machine learning. This is exemplified by the invited paper "Machine-Learning-Based EDFA Gain Estimation," which uses an artificial neural network fed by a physical model for enhanced convergence speed, and enables accurate EDFA/EDFA cascade modeling to estimate end-to-end QoT of existing or new services.

Uncertainty in QoT estimation leads to undesirable (design) margins, where the amount of margin is ideally known, if not reduced; i.e., network designers not only require accurate *absolute* QoT estimates, but also want to know *how accurate* these QoT estimates are. Three articles, the first two of which are invited, tackle this problem: "Performance Comparisons Between Machine Learning And Analytical Models For Quality of Transmission Estimation In Wavelength-Division-Multiplexed Systems," "Towards Vendor-Agnostic Real-Time Optical Network Design with Extended Kalman State Estimation and Recurrent Neural Network Machine Learning," and "Machine Learning Regression For QoT Estimation of Unestablished Lightpaths." The first of these papers demonstrates that machine-learning based models are more robust to parameter uncertainty than analytical tools; however, the machine learning-based methods are also less easy to generalize to new, unobserved scenarios (e.g., new links or networks) due to their reliance on data for specific links or networks during training.

To overcome this generalization problem, it is possible to adapt a machine-learning algorithm trained on a "source" scenario to a "destination" scenario, with a small amount of training on the latter, using a technique called "transfer learning." In "Lightpath QoT Computation in Optical Networks Assisted by Transfer Learning," the authors apply such a technique to adapt deep neural network-based SNR models from one network to another. In the invited paper "Performance Studies of Evolutionary Transfer Learning for End-to-End

QoT Estimation in Multi-Domain Optical Networks," the authors apply transfer learning and autoencoders to estimate the BER of services across multiple domains while maintaining confidentiality of the per-domain monitoring data that is fed to the machine learning framework.

Although QoT estimation is typically applied to binary or discrete decision making (e.g., establish a service or not, select a modulation format), other applications exist. In particular, "Quality of Transmission Estimator Retraining for Dynamic Optimization in Optical Networks" applies QoT estimation for power equalization to improve the SNR of existing services.

Finally, unlike all previously mentioned articles, "Fast Signal Quality Monitoring For Coherent Communications Enabled By CNN-Based EVM Estimation" leverages machine learning to estimate QoT based on the received samples at coherent receivers, rather than from the network's physical parameters.

It has been a pleasure to guest-edit this special issue, as the papers are of high quality. We hope our readers will find inspiration in this rich research body to improve their network designs, reduce margins or make their networks more dynamic, thanks to machine learning.

Last but not least, we would like to issue special thanks to our Editor-in-Chief Jane Simmons, who took a very active role in shaping this special issue, and whose dedication and promptness ensured both quality improvement in many papers, as well as a timely publication of the special issue.

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