A Machine Learning-Assisted Quantum and Classical Co-existence System

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Abstract: A machine learning framework is presented for the coexistence of C-band quantum and classical channels over the same fibre with various fibre lengths, co-existence powers, channel allocations, and identifying the region where co-existence is viable.

1. Introduction

Quantum technologies have recently witnessed a rapid revolution from technology concept demonstration to various field-trial experiments and commercial demonstrations/deployments. Quantum key distribution (QKD), one of the most mature applications, offers ultimate security for classical communications by exploring the quantum mechanism of superposition indistinguishability and no-cloning theorem. After the first QKD implementation, significant improvement has been achieved for high-speed QKD [1] and long-distance QKD [2]. Beyond that, there is a growing focus on distributing entangled photons over distant users and establishing entanglement-based quantum communication networks accordingly to achieve scalability and support applications beyond QKD [3,4]. However, building quantum networks that support the prepare-and-measured QKD technologies or entanglement distribution is not a trivial task. To reduce the deployment cost, the quantum channels are usually required to co-exist with the classical channels in the standard telecom infrastructure. Coexisting classical with quantum channels in the C-band has been demonstrated in [5–7]. However, classical poses a huge impact on the quantum channels due to Raman scattering noise, resulting in a reduced secret key rate (SKR). In [8, 9], researchers have demonstrated the co-existence of C-band classical and O-band quantum channels with > 16 dBm classical power, with negligible impact of Raman scattering on O-band. Nevertheless, very limited frequency modes are supported in O-band by off-the-shelf components, thus these efforts cannot provide scalable solutions for a considerably high number of quantum channels which shall be added and dropped at different network locations. For enhanced scalability and extended transmission distance, both quantum and classical channels should coexist within the C-band, leveraging its lower loss and superior support for frequency modes through dense wavelength-division multiplexing techniques.

To the best of our knowledge, a comprehensive study considering the number of classical channels, different levels of co-existed power, channel allocation schemes, and various fibre lengths for quantum and classical channels co-existence has not been investigated. In this work, we experimentally investigate these impacts through a total of 16654 combinational data sets. Additionally, we propose a machine-learning framework for Raman scattering noise prediction and verify its accuracy with a limited number of data using transfer learning. The proposed framework is compatible with both prepare-and-measure QKD and entanglement distribution systems, while in this work, we integrated it into an emulated entanglement distribution system to provide insight into the regions where co-existence is feasible.

2. Experiment Setup and Machine Learning Framework

An experimental testbed has been established, as depicted in Fig.1a, to investigate the impact of the quantum and classical channels co-existence scheme on both channels. The experiment includes different channel allocation schemes across 11 classical channels, variations in the co-existed classical power, and differing lengths of co-existence fibre. The 11 classical transmitters (Tx), each providing a 100 GHz PM-QPSK signal, can be controlled on and off with varying launch power. The classical signals are multiplexed and then connected to an optical switch, providing the flexibility to connect to different lengths of fibre, namely 0, 1, 2, 5, 15, 25 and 50 km.

The quantum channel to be studied is selected at 193.20 THz (1551.72 nm) and the 11 classical channels operate at frequencies from 192.80 THz to 193.00 THz (5 channels) and from 193.40 THz to 193.65 THz (6 channels), spaced at 50 GHz as shown in Fig.1a. After transmission, the classical channels and quantum channels are separated by a demultiplexer (DEMUX). The classical channels are first amplified via an EDFA (indicated by a yellow triangle) and then received by the receivers (Rx), while the quantum channel can be detected by a single-photon avalanche diode (SPAD) as shown inside the Bob. The experiment aims to study the quantum and classical coexistence system thus the results are compatible with any quantum system.

The maximum per-channel co-existed power is set to -15.7 dBm, with all the channels spectrally pre-equalised to the same height, resulting in a total maximum co-existence power of -6.49 dBm. The co-existence power can be further controlled via the Variable Optical Attenuator (VOA). In the experiment, we explore Tx with attenuation of 3, 6, 9, 13, 17, and 20 dB respectively, corresponding to -15.7, -18.7, -21.7, -25.7, -29.7 and -32.7 dBm of

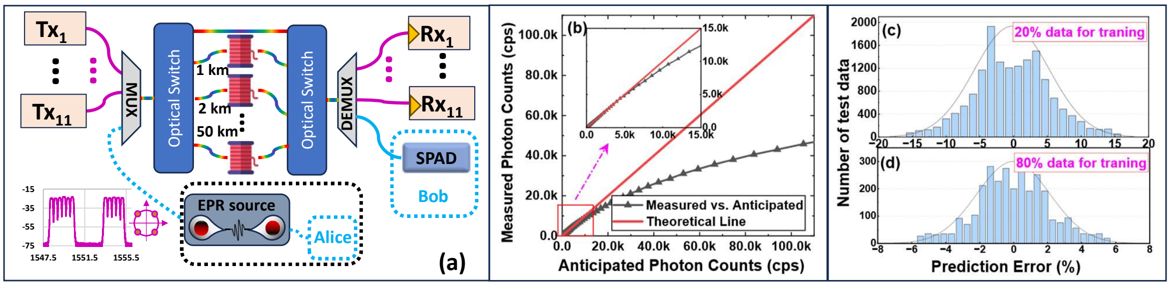

Fig. 1: (a) The testbed setup. (b) SPAD calibration data (c) The distribution of the prediction error.

per-channel power. With individual control of 11 channels on and off, there are in total of $2^{11} = 2048$ possible combinations of channel allocation schemes. We randomly select between 300 and 500 schemes for 6 different per-channel co-existence power and 7 fibre lengths, creating a total of 16,654 scenarios. The Raman scattering noise is then measured using a SPAD (ID Quantique ID230, the detection efficiency is set to 20% and dead time is 8 μs). The classical channels are evaluated to be successful if all support error-free transmission after forward error correction (FEC), otherwise, identified as a failure if an error occurs after applying FEC code.

It is unrealistic to account for every possible parameter combination like channel allocation, co-existence power and fibre lengths. Therefore, we proposed a machine-learning framework using an artificial neural network (ANN) to predict Raman scattering noise for unmeasured quantum and classical co-existence schemes. The ANN model consists of a 13-feature input layer (11 channel allocation + power + fibre length), two hidden layers each with 36 neurons and one output indicating the amount of Raman noise in the quantum channel. We further leverage transfer learning in the prediction to investigate the prediction accuracy by testing unexplored regions, such as new co-existence power or new fibre lengths to the existing experimental trained data set.

3. Result Analysis

To accurately obtain the Raman scattering noise, We initiated a calibration process for the SPAD to set off reduced detection efficiency effect for increasing levels of photon counts instead of merely considering detection efficiency to be a constant 20%. We performed calibration by attenuating a c-band continuous-wave laser to the single photon level via a VOA, then gradually reducing the attenuation to allow more photons into the detectors. In Fig.1b, the black curve with triangular represents the performance of the measured photon counts against the anticipated counts while the red line shows the theoretical value for an idea detector. The calibration function between the black curve and the red line was calculated, and an inverse function will be applied to Raman scattering photon count measurement in the classical and quantum co-existence experiments.

As mentioned above, we conducted the experiment with a total of 16,654 scenarios. Besides, a machine-learning framework is implemented to leverage the Raman scattering noise prediction via a limited data set. The prediction error using 20% of total data to predict noise counts of the rest 80% scenarios is plotted in Fig.1c. It can be observed that 68.2% of the predicted noise value falls within 5.6% prediction error. Increasing the ratio between training and prediction data to 80:20, it can narrow down the Raman scattering prediction error, achieving a precision of < 2.1% for 68.2% tested scenarios, as illustrated in Fig.1d.

Table 1: Raman scattering noise prediction accuracy

	[obtained dataset] → [prediction] (co-existence power in dBm per channel)			[obtained dataset] → [prediction] (different fibre lengths in km)		
	[-15.7, -18.7, -25.7, -29.7, -32.7] → [-21.7]	[-15.7, -21.7, -29.7, -32.7] → [-18.7, -25.7]	[-15.7, -25.7, -32.7] → [-18.7, -21.7, -29.7]	[0, 1, 2, 15, 25, 50] → [5]	[0, 1, 5, 25, 50] → [2, 15]	[0, 1, 2, 15, 25] → [50]
direct prediction precision	94.09%	95.54%	81.57%	95.03%	96.33%	Failure
Prediction precision with transfer learning	99.24%	98.53%	98.60%	97.33%	97.07%	96.10%

Although a considerably good precision can be achieved by applying 20% data in the training dataset, it contains the scenarios of all co-existence power and all the tested fibre lengths. However, sometimes it is not the case that different data combinations will be available. In many cases, it is of interest to study the unknown areas. For instance, when the training dataset consists of only a limited number of fibre lengths and co-existence power levels, it becomes essential to infer the Raman scattering noise for co-existence scenarios and different fibre lengths not covered in the training data. We investigate this by two approaches: 1) direct prediction: Using the existing data for the ANN model; 2) transfer learning: employing pre-trained ANN models with a few experimental data in the unexplored fibre lengths and co-existence power levels to update the model. In this work, we use 10% of experimental data with different fibre lengths and co-existed power levels for transfer learning. For example, when knowledge of -15.7, -18.7 -25.7, -29.7, -32.7 dBm co-existence power is presented in the existing model, 350 sets of experimental data (out of 3500) with -21.7 dBm co-existence power is added for transfer learning purpose,

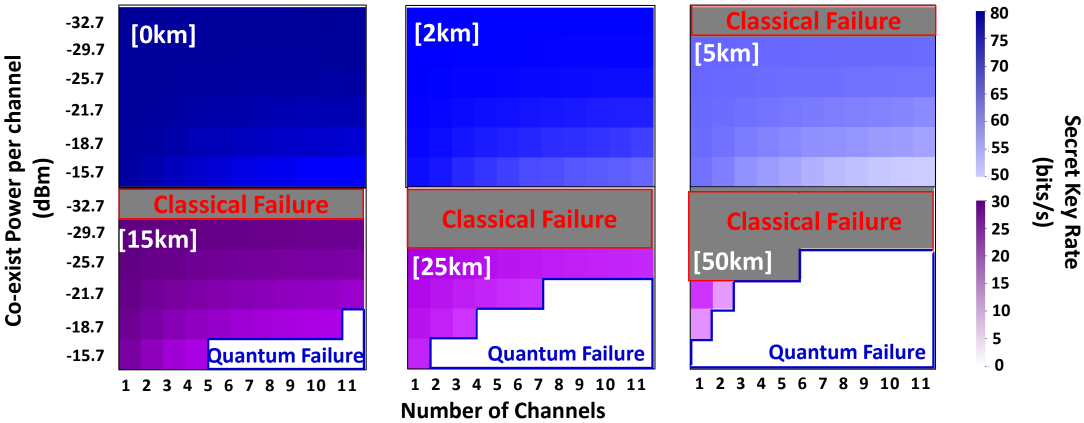

Fig. 2: SKR heatmap with various co-existence power and the number of classical channels for quantum-classical co-existence over 0, 2, 5, 15, 25, and 50km of fibre.

achieving increasing in R^2 prediction precision from 94.09% to 99.24%. A more significant improvement, from 81.57% to 98.6%, is observed when seeding 10% data in co-existed power of -18.7, -21.7, -29.7 dBm for transfer learning compared to the pre-trained model only possessing the knowledge of [-15.7 -25.7 -32.7] dBm co-existence power. It is worth noting that the direct prediction would fail in predicting Raman scattering noise for 50 km fibre, however, can achieve R^2 96.1% prediction precision for the transfer learning.

At last, we investigate the performance of both classical and quantum systems in the co-existence scheme. On the quantum side, the experimental data and predicted Raman scattering noise are both fed into an entanglement-based QKD simulator, which has been fine-tuned using the experimental data with detectors jitter of 100 ps, 20% source heralding efficiency and photon generation rate at 1E6/s per 100 GHz channels. As shown in Fig.1a, Alice directly connects to the EPR source, and the quantum/classical co-existence is at Bob's side. The quantum channel fails due to Raman scattering when the overall QBER exceeds 11%. The classical channels fail either due to low power with uncorrectable errors from FEC or below the EDFA's amplification sensitivity threshold. The heatmap of the SKR is plotted for coexistence over 6 fibre lengths with different numbers of classical channels, and different per-channel co-existed power, as depicted in Fig.2. The grey area marks the region where classical channels fail, while the white region shows quantum failure. The results clearly reveal that when the co-existence fibre length is shorter than 5 km, both classical and quantum channels can co-propagate within the investigated power and channel number. However, classical channel failure starts to occur at 5km and quantum failure starts at 15 km, and only 1 or 2 classical channels are permitted for a co-existence system over 50km of fibre.

4. Conclusion

In this work, we implemented a high-precision machine-learning framework to account for the Raman scattering noise for the quantum and classical co-existence scheme. The accuracy of the machine-learning tool has been experimentally investigated and verified, which can perform Raman scattering noise prediction over broad scenario conditions with a limited experimental data set. Combining the experimental data and the machine-learning prediction, this work also provides insight into the regions where the co-existence scheme is possible and highlights the quantum failure areas with excessive Raman scattering noise and the classical failure region.

Acknowledgements

This work was supported by the EPSRC QComm Hub (EP/T001011/1), European Allegro (101092766), and a collaborative project with CSA Catapult, UK.

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