Optimal working points for continuous-variable quantum channels

Imran Khan,[1,2] Christoffer Wittmann,[1,2] Nitin Jain,[1,2] Nathan Killoran,[3,4]
Norbert Lütkenhaus,[3] Christoph Marquardt,[1,2] and Gerd Leuchs[1,2]

[1] *Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, 91058 Erlangen Germany*
[2] *Institute for Optics, Information and Photonics, University of Erlangen-Nuernberg, Staudtstrae 7/B2, 91058 Erlangen, Germany*
[3] *Institute for Quantum Computing and Department of Physics & Astronomy, University of Waterloo, N2L 3G1 Waterloo, Canada*
[4] *Institut für Theoretische Physik, Albert-Einstein Allee 11, Universität Ulm, 89069 Ulm, Germany*

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How well does a quantum channel preserve the quantum properties of the transmitted quantum states? We investigate this question in the context of a continuous-variable quantum communication system using the framework of effective entanglement. This framework allows for a quantification of the transmitted entanglement using only coherent states and the well-established double homodyne detection. Experimentally, we investigated fiber channels up to a length of 40 km for a wide range of coherent state amplitudes. Additionally, we induced phase noise to study the quantum-classical transition within the framework. From the measured parameters we are able to identify the optimal point of operation for each quantum channel with respect to the rate of transmitted entanglement. We note that the benchmarking procedure is independent of the physical implementation of the quantum channel and would therefore be a promising candidate for benchmarking of future quantum technologies.

I. INTRODUCTION

A. Classical and quantum benchmarking

With new quantum technologies, such as quantum repeaters, computers, cryptographic systems and memories emerging, it is clear that these devices require some sort of benchmarking. However, already existent benchmarks from classical devices (e.g. CPUs or GPUs) may not be transferred to the quantum domain due to the fundamentally different mechanisms present in quantum devices. This motivates research towards the development of quantum benchmarks to make an accurate assessment of how well a device makes use of its quantum features.

B. What makes a good benchmark system?

A good benchmark system should be fast and use minimal experimental resources. A construction that uses standard components may ease the implementation of the system as well as provide stability. It also saves a lot of effort if the same device can be used for benchmarking different physical implementations. The measurement results should give an accurate representation of the quantum domain. Finally, it is helpful if the measurement results have an operational interpretation. Benchmarking also depends on the task that one envisions for the system. Here we concentrate on the use of quantum devices for quantum communication purposes.

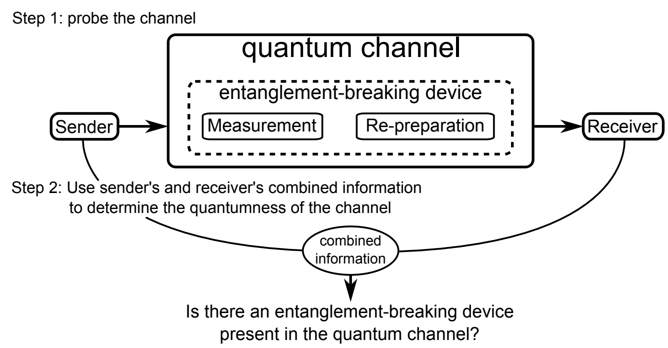

FIG. 1. Concept of the benchmarking scheme. By contrasting the channel with an entanglement-breaking device, the sender and receiver may quantify the quantumness of the channel in a two-step protocol.

II. MAIN IDEAS

A. Entanglement-breaking channels (adversary picture)

For our work, all different physical systems which could potentially be investigated with our benchmarking procedure are consolidated under the notion of a *quantum channel*. To probe a quantum channel, we utilize well-known quantum mechanical primitives/entities such as quantum states.

To understand how well a quantum channel transmits quantum states, one may turn the question around and ask what it means to have a quantum channel that does not preserve the essential properties of the quantum states. Such a channel is called an entanglement-breaking channel. One can imagine such a channel as follows: The

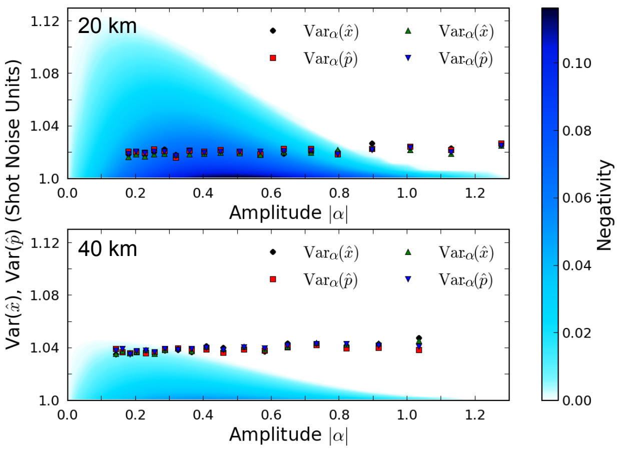

FIG. 2. Measured negativity for a 20 km and a 40 km fiber channel. We probed the two channels over a range of different coherent state amplitudes $|\alpha|$. The experimentally recorded quadrature variances allow us to compute the corresponding negativity. Non-zero negativity indicates that the channel preserves entanglement for the specific parameters. By comparing the computed values for the negativity we find an optimal point of operation for each quantum channel.

channel performs at the input side a measurement and then prepares at the output side a quantum state determined only by the measurement result obtained at the input (Fig. 1). Two things are important to note:

1. Such a channel cannot mimic a general quantum channel, as the input measurement is limited by quantum mechanics, and cannot determine an arbitrary input state completely. For example, it is impossible to mimic the identity channel in this way, which leaves any input quantum states unchanged.
2. Such a channel cannot be useful to realize a quantum advantage in a quantum communication context, as it can be shown to correspond to a completely classical communication channel.

One can show that one can (under certain conditions) construct a set of test input states so that the characterization of the corresponding mixed output states is sufficient

- to prove that the given device/channel is not an entanglement breaking channel, and
- to provide a lower bound on the entanglement transmission rate of the probed quantum channel [1].

B. Experimental setup

The experimental setup is based on a previous quantum key distribution experiment employing a 2 km fiber channel [2]. In our experiment, the sender randomly prepares one of two coherent states $|\alpha\rangle$ and $|-\alpha\rangle$ and sends them to the quantum channel. Our receiver is set up in the well-established double homodyne configuration to allow the characterization of the state amplitude and the quadrature variance of the incoming quantum states. Throughout the whole setup, we use standard telecom components and operate at a wavelength of 1550 nm. Our system runs at a repetition rate of 1 MHz, which allows for fast data acquisition.

C. Measurement results

We have characterized a 20 km and 40 km fiber channel for a wide range of coherent state amplitudes(Fig. 2). Additionally, we made measurements with induced phase noise to show the transition between the classical and the quantum regime. In the framework of effective entanglement [1, 3, 4], we characterize our measurement results using an entanglement measure known as the negativity. The calculation requires the amplitude (overlap) of the coherent states, the quadrature variance and the transmission of the quantum channel. We use the computed negativity to compare different sets of parameters to find the optimal set for a given quantum channel with respect to the transmitted entanglement. We do this using the logarithm of the negativity which has the useful property of being additive. To get the rate of transmitted entanglement we simply multiply the log-negativity with the repetition rate of our system. Our calculation results in maximum rates of 166,000 log-neg units/s for a 20 km and 15,000 log-neg units/s for a 40 km channel.

III. IMPACT AND IMPORTANCE TO QUANTUM CRYPTOGRAPHY

With our results we are able to determine the optimal working point with respect to the effective entanglement for a real physical system. Additionally, we were also able to show quantum correlations over a very long link of 40 km for a continuous-variable quantum communication system, currently only surpassed by the commercial SeQureNet system [5].

These quantitative results further motivate research on how to distill the "‘less entangled bits"’ into a string of "‘maximally entangled bits"’. Once the distillation aspect is better understood, future works may bridge the gap to a prediction of the secret key rates for a quantum cryptographic system from the measured entanglement transmission rates.

Distributed entanglement is a precondition for quantum key distribution [6]. Our system not only shows the distribution of entanglement, but also the associated rates that provide a hint on the final secret key rate. The adversarial scenario used in our benchmarking procedure also fits well into a quantum cryptographic context.

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