Centre for Theoretical Atomic, Molecular, and Optical Physics

Ph.D. Project 2022-2025

Machine learning for quantum networking

Project supervisors: **Mauro Paternostro**
Contacts: **m.paternostro@qub.ac.uk**

State of the art and motivations

Communication underpins all the activities of our connected society. The necessity to exchange information reliably and safely has become a prerequisite and an enabler for economic and social growth. Faster, more secure global-scale communication requires the development of new platforms and architectures for exchanging information. In this scenario, the paradigm-shift embodied by the development of quantum communication holds the potential to deliver a framework for robust, long-haul, ultra-secure information transfer across networks consisting of multiple (sending and receiving) nodes. The price to pay is the use and consumption of a sufficient quantity of suitable quantum resources, i.e. features that are specific of quantum operations, boost their performance, and that do not occur in any classical systems. The most relevant among such resources is embodied by quantum entanglement, which describes how two or more quantum systems get correlated in ways that cannot be accounted for by classical Newtonian mechanics. Entanglement is so strong a resource that seemingly impossible tasks are enabled by its use, such as quantum teleportation.

Architectures based on the quantum counterpart of the well-known primitive of classical communication networks represented by a repeater have been proposed and developed in the form of table-top prototypes for proof-of-principle demonstrations. A significant step forward is needed to translate the potential of quantum repeater-based networks to exploitable technologies for large-scale quantum communication architectures that can compete with current classical infrastructures.

This is precisely the goal of this project. We will work on a framework for the advance of quantum communication infrastructures underpinning the development of a world-scale quantum internet.

Objectives & Methodology

We will specifically focus on classical networking machine-learning techniques for the optimisation of quantum networks and the use of quantum resources to enhance classical machine learning approaches such as reservoir computing. Classical communication technology currently being employed was made robust by means of a thorough characterisation of individual components and networking systems. Achieving the same level of confidence with quantum devices will be key to introducing them as widely used technologies. However, the same physics that unleashes their capabilities also seems to set tight requirements on their optimisation and characterisation. We will address such needs by following main goals:

(i) Explore the solutions that novel, unconventional computing models based on Artificial Intelligence can offer to optimise the structure and working principles of communication and general information-processing networks. We will investigate new applications of neural networks, and

introduce new solutions from reservoir computing, extreme learning machines and deep neural networks;
(ii) Understand how to certify specific quantum properties, pertaining to the characterisation of a quantum state of networks based on a reduced set of data being available. This will permit us to draw conclusions on the functioning of the network itself, particularly when exposed to the effects of environmental noise;
(iii) Leverage on these techniques to extend the reach of the network architecture towards the achievement of fully controlled quantum states of large size.

We will address the AI based joint optimization of quantum repeater networks and classical networks as control infrastructure. As the operation of quantum networks is fundamentally different compared to classical networks, new concepts are needed to enable the development of the future quantum internet. An important goal in this context is the establishment of reliable quantum entanglement between arbitrary nodes of the network. A classical network can be used to exchange state information between different nodes in the networks at a given capacity. However, in presence of loss and noise, designing the optimal quantum encoding/decoding steps is challenging, as it would require the control of the connections between quantum links (routing, scheduling) and the sharing of classical information to maximize/optimize the rate of communication between multiple users.

Explicit questions that will be address include
(i) the identification of the best strategy for sharing state information across a repeater-based network using classical communication, given that this transmission takes time and increasing time leads to link decoherence. In this respect, we will explore whether distributed or centralized control strategies are more advantageous;
(ii) the determination of the best routing strategy for a network with multiple users. These investigations will be extended to the study of noisy communication channels. The research for the optimal network protocol utilizing multi-path routing will be extended to the design of encoding/decoding steps aimed to achieve the best end-to-end quantum capacity for channels affected by thermal loss. We will consider multiple access and broadcast channels, and study encoding/decoding for classical and quantum rates.

Collaborations
The work entailed by this project will be performed within the context of a collaborative network involving the Irish CONNECT research centre (Prof. Dan Kilper) and the US Centre for Quantum Networks led by Prof. Saikat Guha (University of Arizona).
The project will benefit from in-house interactions with members of the Quantum Technology Group, specifically P. Sgroi, I. Palmisano, Dr. Alessandro Ferraro and Dr. Gabriele De Chiara.

Required skills
The candidate student will have excellent mathematical and physical background. A good knowledge of Quantum Theory and Mathematical Methods of Quantum Information Processing are required. A natural inquisitive and curious mind associated with originality and creativity in the approach to problems will be appreciated. Advanced computing skills are not required, although the student will become familiar with instruments such as Python and Mathematica.

Further information
For further information contact Prof. Paternostro: **m.paternostro@qub.ac.uk**