A Practical Introduction to Quantum Computing and Networking

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ABSTRACT

Quantum computing addresses the construction and operation of quantum computers to solve more efficiently instances of specific problems that are difficult to tackle with classical computers. Even if we are currently in the so-called Noisy Intermediate Scale Quantum (NISQ), steady signs of progress are being made towards the realization of a fast and reliable quantum computer, materializing the basic building blocks of quantum circuits, i.e., quantum bits and gates. On the other hand, quantum communications cover the transmission of quantum states across distances. Recent advances in this context have led to the novel research area of quantum networking, which is set to define the programming interfaces and protocols for the practical operation of quantum communication and computing infrastructures. The tutorial has the objective of raising awareness about these emerging topics, i.e., quantum computing and quantum networking, in the research community by i) introducing briefly the latest technologies developed in each, then ii) providing hands-on examples of how to use them for simple use cases, and iii) finally sketching the more promising open research challenges.

KEYWORDS

quantum computing, quantum communications, quantum networking, quantum internet

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1 INTRODUCTION

Thanks to recent advances in technologies for manipulating matter at a microscopic scale, quantum technologies are experiencing a significant boost of public and private investments, as well as raising interest in the scientific community[7] and leading to the creation of many successful start-ups[9]. Traditionally, quantum technologies are clustered into three areas:

(1) **quantum sensing**[11]is the exploitation of quantum mechanics to measure phenomena with unprecedented levels of scale or accuracy, and it is not tackled in the tutorial because, at the moment, it is of interest only for scientific or very specialized applications (such as prolonged navigation in the absence of satellite positioning systems);
(2) **quantum computing**[8], which addresses the construction and operation of quantum computers to solve more efficiently instances of specific problems that are difficult to tackle with *classical* computers; and
(3) **quantum communications**[6], which cover the transmission of quantum states across distances.

The tutorial has the objective of raising awareness about the emerging topics of quantum computing and quantum networking in the research community, briefly introduced below.

1.1 Quantum computing

As far as quantum computers are concerned, we are in the so-called Noisy Intermediate Scale Quantum (NISQ) era: despite sensational claims made by the most active actors (Google, IBM, Microsoft, etc.) today's quantum computers are not powerful enough to outperform High Performance Computing (HPC) clusters of classical computers. However, steady signs of progress are being made towards the realization of a fast and reliable quantum computer, for which many business applications have been already identified in different domains: health, engineering, construction, materials, pharmaceutical, optimization. Internally, quantum computers use *qubits* (or quantum bits) as their elementary components, much like classical computers use bits; the qubits are then manipulated through quantum gates to compose a circuit, which provides the solution for a given problem through the measurement of the qubits's states.

1.2 Quantum communications

Quantum communications, on the other hand, enable the transmission of qubits from one host to another. In its most basic application, this allows two parties interconnected by an optical fiber or a free-space satellite link to run a Quantum Key Distribution (QKD) protocol, which results in the exchange of secret material to enable unconditional security in a future message exchange. In more sophisticated configurations, which are still under study, a Quantum Internet is envisioned, which will interconnect quantum computers all over the globe. At that point, new applications will be possible, including the pooling of resources of quantum computers far away (called distributed quantum computing) and the execution of private code in a remote quantum computer (called blind quantum computing). For all these applications, it is foreseen that the classical and quantum Internet will have to be integrated and cooperate. This leads to the developing research area of **quantum networking**, which is set to define the programming interfaces and protocols for the practical operation of quantum communication and computing infrastructures[3].

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$$\min xy - xz + yz - k - x - 2y + z$$

s.t.

$$x, y, z, k \in \{0, 1\}$$

Figure 1: Example of a (toy) optimization problem in a QUBO formulation.

2 OUTLINE

The tutorial will cover the basics of quantum computing, quantum communications and quantum networking. In each area, we introduce the latest technologies, provide practical examples, and sketch some promising open research challenges. The scripts used in the tutorial are publicly available on GitHub[1].

The tutorial has the following outline:

Part#1 – Quantum computing

(1) Matter qubits: definition, properties, and how to realize them
(2) Quantum gates and circuits
(3) Quantum teleportation
(4) From quantum circuits to algorithms
(5) A practical example: Quadratic unconstrained binary optimization (QUBO) with Variational quantum algorithms (VQA)[5], e.g. see Fig. 1.

Part#2 – Quantum communications

(1) From matter to flying qubits: terrestrial vs. satellite
(2) Prepare&Measure QKD protocols[4]
(3) From single- to multi-hop: trusted relay nodes
(4) Beyond P&M schemes[2]

Part#3 – Quantum networking

(1) The quantum repeater[1]
(2) Heralded generation, purification, and error correction
(3) 1G, 2G, and 3G quantum repeaters
(4) The Quantum Internet (Fig. 2) and its applications
(5) The quantum routing problem[13]

The interested reader/participant may refer to [10] for a gentle introduction to the key quantum information theory and quantum computing concepts and to [12] for a recent literature survey, with a focus on communications and networking topics.

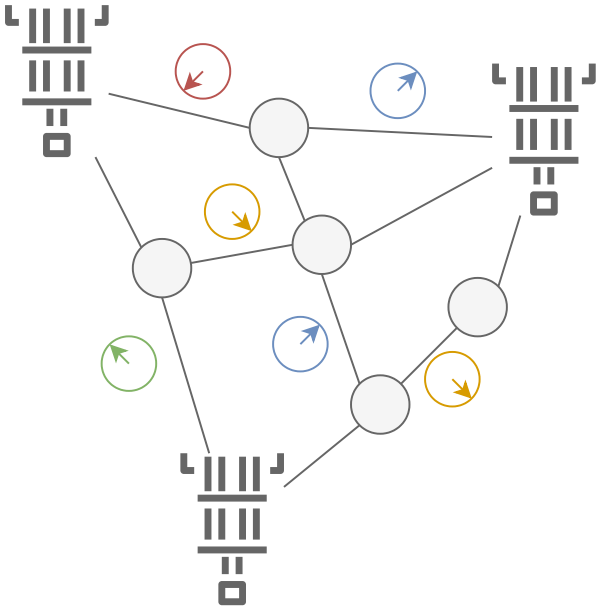

Figure 2: The Quantum Internet interconnects quantum computers through end-to-end entanglement of qubits.

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[1] https://github.com/ccicconetti/tutorial-quantum