Towards a Distributed Quantum Computing Ecosystem
(Invited Paper)

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Abstract—The Quantum Internet, by enabling quantum communications among remote quantum nodes, is a network capable of supporting functionalities with no direct counterpart in the classical world. Indeed, with the network and communications functionalities provided by the Quantum Internet, remote quantum devices can communicate and cooperate for solving computational tasks by adopting a distributed computing approach. The aim of this paper is to provide the reader with an overview about the Quantum Internet as the fundamental underlying infrastructure for the design and the realization of a distributed quantum computing ecosystem. For this we first introduce the Quantum Internet. Then we present a high-level system abstraction of a distributed quantum computing ecosystem, by describing the constituting layers from a communication engineering perspective. Finally we discuss the challenges connected to the design of the aforementioned layers.

I. INTRODUCTION

Nowadays, a tremendous amount of heterogeneous players entered the quantum race, ranging from tech giants - such as IBM and Google in fierce competition to build a commercial quantum computer - to states and governments, with massive public funds to be distributed over the next years.

In 2017, the European Commission launched a €1-billion flagship program to support the quantum research for ten years starting from 2018, and a first €132-million tranche is being provided during the following three years [1]. In 2018, the United States of America launched the National Quantum Initiative funded with $1.2-billion over ten years and China entered the quantum race, ranging from tech giants - such as IBM and Google — in fierce competition to build a commercial quantum processor embedding roughly 160 noiseless qubits, thanks to the superposition principle.

To give a flavor of the above, let us consider one of the killer applications of quantum computing: chemical reaction simulation [11]. As highlighted in [12], the amount of information needed to fully describe the energy configurations of a relatively simple molecule such as caffeine is astonishingly large: $10^{48}$ bits. For comparison, the number of atoms in the Earth is estimated between $10^{49}$ and $10^{50}$ bits. Hence, describing the energy configuration of caffeine at one single instant needs roughly a number of bits comparable to 1 to 10 per cent of all the atoms on the planet. But this energy configuration description becomes suddenly feasible with a quantum processor embedding roughly 160 noiseless qubits.

Unfortunately, qubits are very fragile and easily modified by interactions with the outside world, via a noise process known as decoherence [13], [14]. Indeed, decoherence is not the only source of errors in quantum computing. Errors practically arise with any operation on a quantum state. However, isolating the qubits from the surrounding is not the solution, since the qubits must be manipulated to fulfill the communication and computing needs, such as reading/writing operations. Moreover, the challenges for controlling and preserving the quantum information embedded in a single qubit get harder as the number of qubits within a single device increases, due to coupling effects. In this regard, Quantum Error Correction...
QEC (Quantum Error Correction) represents a fundamental tool for protecting quantum information from noise and faulty operations [15]. However, QEC operates by spreading the information of one logical qubit into several physical qubits. Hence, solving problems of practical interest, such as integer factorization – which constitutes one of the most widely adopted algorithms for securing communications over the Internet – or molecule design may require millions of physical qubits [2], [3].

Hence, on one hand researchers worldwide are leveraging on the advancement of different technologies for qubit implementation: superconducting circuits, ion traps, quantum dots, and diamond vacancies among the others and innovative QEC techniques to scale the number of qubits beyond two-digits. On the other hand, the Quantum Internet, i.e., a network enabling quantum communications among remote quantum nodes, has been recently proposed as the key strategy to significantly scale up the number of qubits [16], [17], [18], [19], [20].

The aim of this paper is to provide the reader with an overview about the Quantum Internet as the fundamental underlying infrastructure for the design and the realization of a distributed quantum computing ecosystem. Specifically, in Sec. II we introduce the Quantum Internet and we highlight some key applications beyond the distributed quantum computing paradigm. In Sec. III we present a high-level system abstraction of a distributed quantum computing ecosystem, by describing the constituting layers. In Sec. IV we discuss the challenges connected to the design of the aforementioned layers. Finally in Sec. V we conclude the paper with some perspectives.

II. THE QUANTUM INTERNET

As mentioned above, one promising approach to address the challenges arising with large-scale quantum processor design is to mimic modern high-performance computing, where thousands of processors, memories and storage units are inter-connected via a communication network, and the computational problems are solved by adopting a distributed computing approach.

Hence, to this aim, it is mandatory to design and deploy the quantum internet, which formally defines a quantum network able to transmit qubits or to create distributed entangled quantum states with no classical equivalent among remote quantum devices [13].

In fact, the availability of the corresponding network infrastructure and the adoption of a distributed computing approach [21] allows to regard the Quantum Internet as a virtual quantum computer with a number of qubits that scales linearly with the number of interconnected devices. Hence, such a quantum network may allow an exponential speed-up [21], [22], [18] of the quantum computing power with just a linear amount of physical resources, represented by the wired quantum processors. Indeed, by comparing the computing power achievable with quantum devices working independently vs. working as a unique quantum cluster, the gap comes out - as depicted in Figure 1 - as

![Fig. 1. Distributed quantum computing speed-up. The volume of cubes represents the ideal computational power, i.e., in absence of noise and errors. Interconnecting quantum processors via the Quantum Internet provides an exponential speed-up with respect to isolated devices.](image)

Specifically, increasing the number of isolated devices lays to a linear speed-up, with a double growth in computational power by doubling the number of devices. Conversely, increasing the number of interconnected devices provides an exponential growth, with a significant advantage clearly visible with just two inter-connected devices. As instance, a single 10-qubit processor can represent $2^{10}$ states thanks to the superposition principle. But if we wire two processors, the resulting virtual device can represent up to $2^{18}$ states [13], depending on the number of qubits devoted to quantum information sharing via the teleporting process, described in Sec. IV-B.

Before analyzing with further details in Sec. III the distributed quantum computing from a communication engineering perspective, it is worthwhile to note that the availability of the Quantum Internet infrastructure scalable in the number of interconnected devices enables unparalleled capabilities not restricted to the distributed computing [10]. Specifically, applications such as blind computing, secure communications and noiseless communications have already been theorized or even experimentally verified.

Blind quantum computing [23], [24] refers to a server-client architecture where clients can send sensitive data to server, which elaborates inputs without knowing their values. This functionality allows to achieve a twofold goal: preserving data confidentiality as well as solving tasks that are intractable for the client – that can be a classical computer – but tractable for the server, which implements the quantum paradigm.

Secure communications in quantum field refers to the class of communication protocols that exploit quantum mechanics.
in order to get benefits unattainable using classical Internet. For instance, quantum key distribution enables two parties to produce a shared key, in total secrecy [15]. Whilst quantum byzantine agreement, a protocol used by several processors to agree on a common bit, allows to achieve the goal in a constant number of rounds, whereas classical version scales polynomially with the number of processors [25].

Finally, noiseless communications can be achieved by exploiting the Quantum Internet infrastructure given though the information exchanges are performed through noisy communication channels [26], [27]. Specifically by exploiting the capability of quantum particles to propagate simultaneously among multiple space-time trajectories, superpositions of noisy channels can behave as perfect quantum communication channels, even if no quantum information can be sent throughout either of the component channels individually.

III. DISTRIBUTED QUANTUM COMPUTING

The overall aim of classical distributed computing is to deal with hard computational problems by splitting out the computational tasks among several classical devices in order to lighten the loads on single devices.

As mentioned in Sec. II with the network infrastructure provided by the Quantum Internet, this paradigm can be extended to quantum computing as well: remote quantum devices can communicate and cooperate for solving computational tasks by adopting a distributed computing approach. Since an entirely new paradigm – characterized by unconventional phenomena ruled out by the quantum mechanics such as no-cloning and entanglement as discussed in [18] – is involved, a new infrastructure needs to be engineered.

The infographic in Figure 2 is a stack depicting dependencies among a possible set of layers that together provide a distributed quantum computing ecosystem. For the sake of clarity, we restrict our attention to an infrastructure composed by two quantum devices, directly inter-connected. Nevertheless, the discussion in the following can be easily extended to more complex network architectures, provided that end-to-end routing and network functionalities are available [28], [29], [30], [31], [32], [33].

Starting from bottom, in Fig. 2 we have the communication infrastructure underlying the Quantum Internet: spatially remote quantum devices able to communicate quantum information by means of a synergy of both classical and quantum communication technologies. Indeed, as we will overview in Sec. IV-B the transmission of quantum information generally requires the transmission of classical information as well, hence the availability of a classical network infrastructure – such as the classical Internet – is required [10], [14], [19]. This constraint has been highlighted by interconnecting two quantum devices with both a classical and a quantum link.

By exploiting the communication functionalities provided by the lowest level, both local and remote qubit operations can be executed. Specifically, the local operations – i.e., operations between qubits hosted on the same quantum devices – can be executed by exploiting the physical (or logical, whether the quantum device should natively implement QEC functionalities [34]) controls and readouts functionalities provided by the device. Conversely, the remote operations – i.e., the operations between qubits hosted on different quantum devices – pose further constraints, as discussed in Sec. IV.

Thanks to the abstraction provided by the two layers residing at the very bottom, a virtual quantum processor is obtained, where remote qubits are interconnected through virtual connections made possible by the remote operations. Clearly, remote operations are likely to be characterized by delays and error rates larger than local operations. Hence, local operations should be preferred over remote ones as much as possible, even though remote operations are unavoidable whenever the number of qubits required to perform the computational task exceeds the number of qubits available on a single device. Hence, an optimization must be performed by the compiler so that the different operations required by the quantum algorithm as well as the input to the algorithm itself are allocated among the qubits of the different devices.

Finally, at the very top we have the quantum algorithm, which is completely independent and unaware of the physical/logical constraints imposed by both the hardware and network configuration and particulars, thanks to the abstraction provided by the underlying levels.

Nevertheless, several complications have been omitted so far. Indeed, communication protocols intrinsically imply over-
IV. OPEN CHALLENGES AHEAD

The aim of this section is elaborating on the ecosystem for distributed quantum computing. Therefore, some layers are discussed individually. In Section IV-A, quantum processors are considered, paying particular attention to drawbacks induced by local operations involving multiple qubits. Section IV-B introduces the interconnection between remote quantum processors, discussing the quantum teleportation as the mean for transfer basic information between interconnected devices. After that, in Section IV-C we discuss the gate teleportation as a strategy to perform remote operations. Section IV-D presents the layer in charge of processing quantum algorithms with high level of abstraction, by optimizing the algorithm execution based on the characteristics of the underlying system.

A. Quantum Device

The most basic element of a distributed quantum computing ecosystem is identifiable with a quantum device. Here the qubits are connected following some directed and connected graph that accounts for the hardware limitations resulting from controlling and preserving the quantum information from decoherence and noise. As an example, Figure 5 depicts the architecture of the IBM QX3 quantum processor \cite{35}, with nodes representing qubits while edges represent the possibility to have interactions between two qubits, i.e., to implement one CNOT operation. As instance, a CNOT operation can be directly executed between qubits $q_1$ and $q_2$ but not between qubits $q_1$ and $q_3$.

Therefore it’s worth going further towards this discussion, expanding components of the proposed infrastructure and considering open challenges related with.

B. Quantum Link

As mentioned in Sec. III, the quantum internet architecture requires both classical and quantum links.

The overhead induced by the swapping operations explains how important is the topological organization of device and the circuit design as well.

Fig. 3. Coupling map of the IBM QX3 architecture: the nodes represent the qubits while the edges represent the possibility to have interactions between two qubits, i.e., to implement the CNOT operation. As instance, a CNOT operation can be directly executed between qubits $q_1$ and $q_2$ but not between qubits $q_1$ and $q_3$.

Fig. 4. A CNOT operation between non-adjacent qubits can be implemented through a sequence of swapping operations, with each swap consisting of three CNOT (with the in-between CNOT being reverse, i.e., with target and control qubits swapped) between adjacent qubits \cite{35}. Note that the quantum state stored within qubit $q_i$ is denoted, by adopting the standard bra-ket notation for describing quantum states, as $|\psi_i\rangle$. Thus, the circuit performs a CNOT between $q_1$ and $q_3$, leaving $q_2$ unaltered.
In this perspective, a distinction between matter and flying qubits – i.e., between qubits for information processing/storing and qubits for information transmission – must be made. As regards to the matter qubits, several candidate technologies are available, each one with its pros and cons [21]. Conversely, as regards to the flying qubits, there exists a general consensus about the adoption of photons as qubit substrate [10]. However, heterogeneity arises by considering the different physical channels the photons propagate through, ranging from free-space optical channels (either ground or satellite free-space) to optical fibers. Thus a transducer for matter-flying conversion is needed as depicted in Figure 5 and discussed with further details in [10]. And communication models need to take into account such technological heterogeneity with the aim of providing a black box for upper protocol layers with one common logic.

Furthermore quantum mechanics does not allow an unknown qubit to be copied or observed/measured. As a consequence the communication techniques utilized to interconnect spatially remote quantum devices cannot be directly borrowed from classical communications. In this context, quantum teleportation is widely accepted as one of the most promising quantum communication technique between quantum nodes [40], [41], [14]. Quantum teleportation has been experimentally verified [32] and it requires, as depicted in Fig. 6, a pair of parallel resources. One of these resources is classical: two bits must be transmitted from the source to the destination. The other resource is quantum: an entangled pair of qubits must be generated and shared between the source and the destination [14].

In the context of the distributed quantum computing ecosystem, quantum teleportation constitutes the foundation of a communication paradigm known as teledata [43], which generalizes the concept of moving state among qubits to remote devices.

To provide a concrete example of the teledata concept, a further distinction must be made between communication qubits and data qubits. Specifically, within each quantum device, a subset of qubits is reserved for transmitting/receiving quantum information through the quantum teleportation process. This type of qubits are referred to as communication qubits, to distinguish them from processing/memory qubits, referred to as data qubits.

As example, consider two IBM QX2 architectures interconnected via quantum teleportation as depicted in Figure 7. The \( c_0, c_1 \) pair is in the entangled state \( |\Phi^+\rangle \). Note that the chosen embedding involves the loss of that pair as possible resource exploitable for computation. On the other hand though, any kind of interaction between remote devices involves communication qubits, but not all the data qubits are connected with them. As already explained in Section IV-A, interactions between non-adjacent qubits are feasible but they imply an overhead. A solution would be adding more qubits to the communication set, but it means sacrifice further valuable resources. For this reason, choosing the connectivity organization is a fundamental task and it is necessary to evaluate the trade-off between the number of data and communication qubits.

Next section shows how to exploit teleportation in order to not only send information but also perform joint operations between remote qubits.

C. Teleporting Gates

Distributed quantum computation requires the capability to perform quantum operations on qubits belonging to remote quantum devices.

As mentioned in the previous section, one possible solution is to resort to the teledata concept, by moving the quantum information from a quantum device to another via the teleportation process, through an entangled pair.

However, an entangled pair allows one to implement also a so-called teleporting gate, or telegate [44]. From a theoretical perspective, we have already observed that providing the CNOT operation - together with other single qubit gates - is enough to perform any kind of quantum algorithm. Therefore, returning to stack dependencies of Figure 2 we can conceptualize a service that provides a set of remote CNOT operations based on teleported gates. Such service will directly interact with the physical system, exploiting the entanglement generation and distribution functionality [14].
entanglement state for communication qubits pair \( c_0 \) and \( c_1 \). Indeed, the availability of two communication qubits – \( c_0 \) and \( c_1 \) – shared between the two remote devices and storing an EPR pair, it is possible to perform a remote CNOT operation with, for example, \( q_0 \) as control qubit and \( q_4 \) as target qubit. Figure 8 shows the corresponding circuit, consisting of local CNOT operations and single-qubit operations and measurements.

D. Distributed Quantum Compiler

Layers discussed so far belong to the Quantum Internet infrastructure and all provide some fundamental communication functionality. Thus, they provide the underlying foundation to be exploited for distributed quantum computation.

Indeed, the definition of a quantum algorithm can be very abstract. In general, it goes through the definition of a quantum circuit – where a computation is a sequence of quantum gates on a n-qubit register – as those depicted in Figs. 6 and 8. Indeed, an algorithm designer may benefit from an abstraction which hides the complications due to physical features.

However, as mentioned in Sec. III within the virtual quantum processor remote qubits belonging to remote quantum devices are interconnected through virtual connections made possible by the remote operations as described in Secs. IV-B and IV-C. Unfortunately, remote operations are likely to be characterized by delays and error rates larger than local operations. Hence, given a particular quantum circuit describing a quantum algorithm, the distributed quantum compiler is responsible for optimizing the circuit so that the number of remote operations is minimized as much as possible.

Furthermore, the compiler should be able to optimize the circuit so that it can be executed regardless of the underlying network topology. Indeed, it may be the case that two remote quantum devices are not directly connected – i.e., no entangled qubits are shared between the two devices – even though some remote operations between qubits stored at these devices are required. Hence, the compiler should optimize the corresponding quantum circuit so that the entanglement swapping operations among remote devices are minimized. Finally, as discussed in Sec. IV-B, there exists a trade-off between data and communication qubits. The larger is the number of communication qubits in a device, the higher is the rate of remote operations achievable at the price of reducing the number of qubits devoted to computation.

V. Conclusions

With this paper, we have presented a layered structure that outlines a possible key strategy towards large-scale quantum processor design based on the distributed quantum computing paradigm, where multiple quantum devices communicate and cooperate for solving computational tasks beyond the computing capabilities of a single quantum processor. To sum up, the lowest layers integrate the Quantum Internet as the fundamental underlying infrastructure providing networking and communication functionalities among remote quantum devices. Conversely, the upper layers are responsible for mapping the quantum algorithm onto the underlying physical infrastructure by optimizing the available computational resources as well as by accounting for the constrains induced by the hardware/network configuration.

References

[1] E. Cartlidge, “Europe’s €1-billion quantum flagship announces grants.” Science, vol. 362, no. 6414, p. 512, 2018.
[2] E. Gibney, “The quantum gold rush.” Nature, vol. 574, no. 7776, pp. 22–24, 2019.
[3] K. Bourzac, “4 tough chemistry problems that quantum computers will solve.” IEEE Spectrum, vol. 54, no. 11, pp. 7–9, 2017.
[4] M. Schuld, I. Sinayskiy, and F. Petruccione, “An introduction to quantum machine learning.” Contemporary Physics, vol. 56, no. 2, pp. 172–185, 2015.
[5] D. Gottesman, H.-K. Lo, N. Lutkenhaus, and J. Preskill, “Security of quantum key distribution with imperfect devices.” in International Symposium on Information Theory, 2004, p. 136.
[6] J. Preskill, “Quantum computing and the entanglement frontier.” arXiv preprint, p. arXiv:1203.5813, 2012.
[7] F. Arute, K. Arya, R. Babbush, D. Bacon, J. C. Bardin, R. Barends, R. Biswas, S. Boixo, F. G. Brandao, D. A. Buell et al., “Quantum supremacy using a programmable superconducting processor.” Nature, vol. 574, no. 7779, pp. 505–510, 2019.
[8] E. Pednault, J. Gunnels, D. Maslov, and J. Gambetta, “On quantum supremacy.” IBM Research Blog, vol. 21, 2019.
[9] E. Pednault, J. A. Gunnels, G. Namnitchi, L. Horesh, and R. Wisnieff, “Leveraging secondary storage to simulate deep 54-qubit sycamore circuits.” arXiv preprint, p. arXiv:1910.09534, 2019.
[10] A. S. Cacciapuoti, M. Caleffi, F. Tafuri, F. S. Cataliotti, S. Gherardini, and G. Bianchi, “Quantum internet: Networking challenges in distributed quantum computing.” IEEE Network, pp. 1–7, 2019.
[11] Y. Cao, J. Romero, J. P. Olson, M. Degroote, P. D. Johnson, M. Kieferová, I. D. Kivilcim, T. Menke, B. Peropadre, N. P. Sawaya et al., “Quantum chemistry in the age of quantum computing.” Chemical reviews, vol. 119, no. 19, pp. 10856–10915, 2019.
[12] G. Drouin, “IBM Qs Dr. Robert Sutor explains the state of the quantum computing industry.” May 2018.
[13] A. S. Cacciapuoti and M. Caleffi, “Toward the quantum internet: A directional-dependent noise model for quantum signal processing.” in IEEE International Conference on Acoustics, Speech and Signal Processing, May 2019, pp. 7978–7982.

Fig. 8. CNOT operation between remote qubits \( q_0 \) and \( q_4 \) of architecture in figure 7. Initial state is \( |\psi\rangle \) for \( q_0 \), \( |\phi\rangle \) for \( q_4 \) and \( |\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}} \) is the entanglement state for communication qubits pair \( c_0 \) and \( c_1 \).
