Quantum Internet: Networking Challenges in Distributed Quantum Computing

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Abstract

The Quantum Internet, a network interconnecting remote quantum devices through quantum links in synergy with classical ones, is envisioned as the final stage of the quantum revolution, opening fundamentally new communications and computing capabilities. But the Quantum Internet is governed by the laws of quantum mechanics. Phenomena with no counterpart in classical networks, such as no-cloning, quantum measurement, entanglement and quantum teleportation, impose new challenging constraints for network design. Specifically, classical network functionalities are based on the assumption that classical information can be safely read and copied. However, this assumption does not hold in the Quantum Internet. As a consequence, its design requires a major network-paradigm shift to harness the quantum mechanics specificities. The goal of this work is to shed light on the challenges and open problems of Quantum Internet design. We first introduce some basic knowledge of quantum mechanics, needed to understand the differences between a classical and a quantum network. Then, we introduce quantum teleportation as the key strategy for transmitting quantum information without physically transferring the particle that stores the quantum information or violating the principles of quantum mechanics. Finally, the key research challenges to design quantum communication networks are discussed.

Introduction

Nowadays, the development of quantum computers is experiencing a major boost, since tech giants entered the quantum race. In November 2017 IBM built and tested a 50-qubits processor; in March 2018 Google announced a 72-qubits processor; and other big players, like Intel and Alibaba, are actively working on double-digit-qubits proof-of-concepts. Meanwhile, in April 2017 the European Commission launched a ten-year 1 €-billion flagship project to boost European quantum technologies research. And in June 2017 Prof. Jian-wei Pan's team successfully tested a 1200 km quantum link between satellite Micius and ground stations in China [1].

Such a race in building quantum computers is not surprising, given their potential to completely change markets and industries, such as commerce, intelligence, and military affairs [2–5]. In fact, a quantum computer can tackle classes of problems that choke conventional machines, such as chemical simulations, optimization in manufacturing and supply chains, financial modelling, machine learning and enhanced security.

The building block of a quantum computer is the quantum bit (qubit), describing a discrete two-level quantum state as detailed in the next section. By oversimplifying, the computing power of a quantum computer scales exponentially with the number of qubits that can be embedded and interconnected within [2, 4, 6]. The greater is the number of qubits, the harder is the problem that can be solved by a quantum computer. For instance, solving some fundamental chemistry problems is expected to require[1] "hundreds of thousands or millions of interconnected qubits, in order to correct errors that arise from noise" [6].

Quantum technologies are still far away from this ambitious goal. In fact, so far, although the quantum chips storing the qubits are quite small, with dimensions comparable to classical chips, they usually require to be confined into specialized laboratories hosting the bulked equipment, such as large near absolute-zero cooling systems, necessary to preserve the coherence of the quantum states. And the challenges for controlling, interconnecting, and preserving the qubits get harder as the number of qubits increases. Currently, the state-of-the-art of the quantum technologies limits this number to double digits.

Hence, very recently, the *Quantum Internet* has been proposed as a possible strategy to significantly scale up the number of qubits [2, 4, 5]. More in detail, the Quantum Internet is a *quantum network*, that is, a network able to connect remote quantum devices through quantum links in synergy with classical links, as described below. Such a quantum network constitutes a breakthrough, since it will provide unparalleled capabilities [5], by exploiting its exponentially larger state space [2, 4]. Among them, there is certainly *distributed quantum computing*. Specifically, by adopting the distributed paradigm, the Quantum Internet can be regarded as a virtual quantum machine constituted by a high number of qubits, scaling with the number of interconnected devices. This, in turn, implies the possibility of an exponential speed-up of quantum computing power [4, 7], with just a linear amount of the physical resources, that is, the connected quantum devices.

However, from a communication engineering perspective, the design of the Quantum Internet is not an easy task at all. In fact, it is governed by

[1] Qubit redundancy is mandatory due to the unavoidable presence of an external noisy environment.

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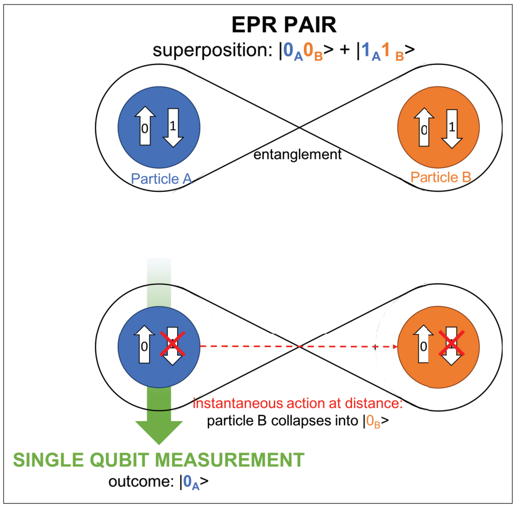


FIGURE 1. Quantum entanglement: measuring one qubit of an EPR pair instantaneously changes the status of the second qubit, regardless of the distance dividing the two qubits. Specifically, the two particles forming the EPR pair are in superposed state, with an even *amount* of zero and one. Hence, by measuring one of the two qubits, we obtain either zero or one with even probability. But once the qubit is measured, say particle A with outcome corresponding to state zero, the second qubit instantaneously collapses into state zero as well.

the laws of quantum mechanics, thus phenomena with no counterpart in classical networks, such as no-cloning, quantum measurement, entanglement and teleporting, impose terrific constraints on the network design. As an example, classical network functionalities are based on the assumption that classical information can be safely read and copied. But this assumption does not hold in a quantum network. As a consequence, the design of a quantum network requires a major paradigm shift to harness the peculiarities of quantum mechanics, as discussed later.

The goal of this article is to shed light on the challenges in designing a quantum network. Specifically, we first introduce some basic knowledge of quantum mechanics — superposition principle, no-cloning theorem, quantum measurement postulate and entanglement — needed to understand the differences between a classical and a quantum network. Then, we focus on quantum teleportation as *the key strategy* for transmitting quantum information without either the physical transfer of the particle storing the quantum information or the violation of the quantum mechanics principles. Finally, we draw the key research challenges related to the design of a quantum network.

Quantum Mechanics Background

In this section, we briefly review some quantum mechanics postulates and principles needed to understand the challenges behind the design of a quantum network.

A quantum bit, or *qubit*, describes a discrete two-level quantum state, which can assume two (orthogonal) basis states: the zero (or ground state) and the one (or excited state), usually denoted[2] as $|0\rangle$ and $|1\rangle$. As an example, if we represent the state of a photon with a qubit, the two basis states represent the horizontal and the vertical polarization of the photon, respectively.

Superposition Principle: As is widely known, a classical bit encodes one of two mutually exclusive states, being in only one state at any time. Conversely, a qubit can be in a superposition of the two basis states. As an example, a photon with 45 degrees of polarization is described by a superposed qubit, with an even amount of zero and one, being simultaneously horizontally and vertically polarized. Hence, while n classical bits can encode only one of 2^n possible states at a certain time, n qubits can simultaneously encode all the 2^n possible states at once, thanks to the superposition principle.

Quantum Measurement: According to one of the quantum mechanics postulates, whenever a measurement can have more than one outcome, as is the case for the two possible states of a qubit, after the measurement the original quantum state collapses in the measured state. Hence, the measurement alters irreversibly the original qubit state [8]. The result of such a measurement is probabilistic, since one obtains either the state zero or the state one, with a probability depending on the *amount* of zero and one in the original superposed quantum state. For instance, if the outcome of measuring a superposed qubit corresponds to the state zero, the qubit collapses into such a state and any further measurement will give zero as the outcome, independently of the original amount of one in the superposed state. As a consequence, by measuring a qubit only one bit of information can be obtained.

No-Cloning Theorem: The no-cloning theorem states that an unknown qubit cannot be cloned, and it is a direct consequence of the quantum mechanics laws. Specifically, Nature does not allow arbitrary transformations of a quantum system. Nature forces these transformations to be unitary. The linearity of unitary transformations alone implies the *no-cloning theorem* [8], which has critical consequences from a communication engineering perspective. In fact, classical communication functionalities are based on the assumption to be able to safely copy the information. This in turn deeply affects the quantum network design, as pointed out below.

Entanglement: The deepest difference between classical and quantum mechanics lays in the concept of *quantum entanglement*, a sort of correlation with no counterpart in the classical world. In a nutshell, the entanglement is a special case of superposition of multiple qubits where the overall quantum state cannot be described in terms (or as a tensor product) of the quantum states of the single qubits.

To better understand the entanglement concept, let us consider Fig. 1, showing a couple of maximally entangled qubits, known as an *EPR pair*. The couple of qubits forming the EPR pair are in a superposed state, with an even amount of zero and one. By measuring each of the two qubits independently, one obtains a random distribution of zero and one outcomes with equal probability. However, if the results of the two independent measurements are compared, one observes that every time the measurement of qubit A yielded zero so did the measurement of qubit B, and the same happened with the outcome one. Indeed,

[2] The bra-ket notation $|\cdot\rangle$, introduced by Dirac, is a standard notion for describing quantum states. In a nutshell, a ket $|\cdot\rangle$ represents a column vector, hence the standard basis $|0\rangle$, $|1\rangle$ is equivalent to a couple of 2-dimensional orthonormal vectors.

according to quantum mechanics, as soon as one of the two qubits is measured the state of the other is *instantaneously* fixed.

This quantum entanglement behavior induced Einstein and his colleagues to the so-called EPR paradox: the measurement of one qubit instantaneously changes the state of the second qubit, regardless of the distance dividing the two qubits. This seems to involve information being transmitted faster than light, violating the Relativity Theory. But the paradox is illusory, as discussed below.

	Classical communications	Quantum communications
Classical message (bits)	Internet	QKD/SuperDense Coding
Quantum message (qubits)		Quantum Internet

TABLE 1. Classical vs. Quantum. Both classical Internet and QKD/SuperDense Coding are utilized to convey classical messages. However, QKD/SuperDense Coding exploit quantum communications to either encrypt the classical message or double the bit rate. Instead, the Quantum Internet enriches and expands the quantum communications paradigm to convey quantum messages.

The Quantum Internet

As summarized in Table 1, classical communications utilize bits to convey classical messages within the current Internet, obeying the laws of classical physics. Differently, quantum communications exploit quantum mechanics to fulfill the communications needs. However, so far, quantum communications have been widely restricted to a synonymous of specific applications, such as Quantum Key Distribution (QKD) and *superdense coding*. Such applications exploit quantum mechanics only to convey classical messages (bits) as depicted in Table 1. Differently, the Quantum Internet expands and enriches the concept of quantum communications by conveying quantum messages (qubits).

More in detail, QKD is a cryptographic protocol enabling two parties to produce a shared random secret key by relying on the principles of quantum mechanics, either quantum measurement or entanglement. However, in a QKD system, quantum mechanics plays a role only during the creation of the encryption key: the encrypted information subsequently transmitted is entirely classical. Similarly, superdense coding is a communication protocol enabling two parties to enhance the transmission of classical information through a quantum channel, that is, to exchange two bits of classical information by exchanging a single qubit.

Differently, the Quantum Internet relies on the ability to share quantum states among remote nodes, by relying on the physical network entities described below. However, quantum mechanics restricts a qubit from being copied or safely measured. Hence, although a photon can encode a qubit and it can be directly transmitted to a remote node, for example, via a fiber link, if the traveling photon is lost due to attenuation or corrupted by noise, the quantum information is definitely destroyed. This quantum information cannot be recovered via a measuring process and/or a copy of the original information, due to the postulate of quantum measurement and the no-cloning theorem. As a consequence, the direct transmissions of qubits via photons is not feasible and quantum teleportation, described in the following, must be employed.

Quantum Teleportation

Quantum Teleportation [8] provides an invaluable strategy for transmitting qubits without either the physical transfer of the particle storing the qubit or the violation of the quantum mechanics principles. Indeed, with just local operations, referred to as Bell-State Measurement (BSM), and an EPR pair shared between source and destination, quantum teleportation allows one to "transmit" an unknown quantum state between two remote quantum devices.

Quantum teleportation implies the destruction of both the original qubit (encoding the quantum information to be transmitted) and the entanglement-pair member at the source, as a consequence of a measurement operation. Then, the original qubit is reconstructed at the destination once the output of the BSM at the source, two classical bits, has been received at the destination through a classical channel.

The teleportation process of a single qubit is summarized in Fig. 2. In a nutshell, it requires: the generation and the distribution of an EPR pair between the source and destination, and a classical communication channel to send[3] the two classical bits resulting from the BSM measurement. Hence, it is worth noting that the integration of classical and quantum resources is a crucial issue for quantum networks.

Regarding the EPR pair, the measurement at the source destroys the entanglement. Hence, if another qubit needs to be teleported, a new EPR pair must be created and distributed between the source and the destination.

Before discussing the key research challenges arising with the design of a quantum network harnessing entanglement and teleportation, it is preliminary to describe the principal physical entities constituting such a network.

Physical Network Entities

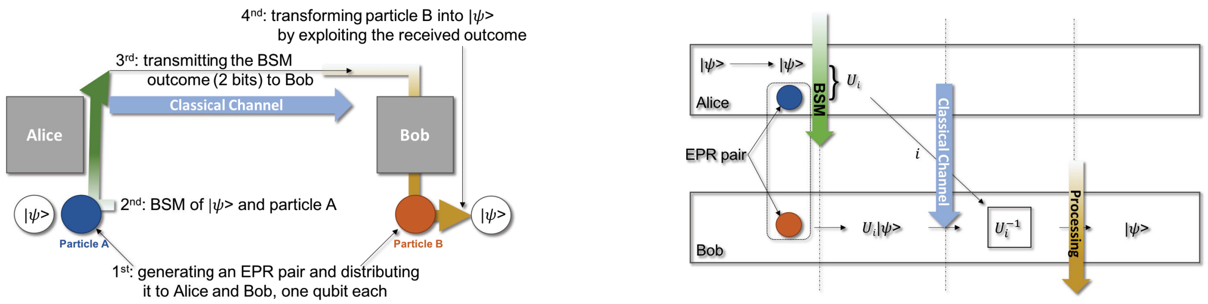
The principal network entities constituting the Quantum Internet are depicted in Fig. 3.

The quantum nodes, that is, the quantum devices to be interconnected with each other, represent the key building block of the Quantum Internet. Clearly, the nodes could have a different set of functionalities and capabilities, ranging from computation to sensing. Additionally, the Quantum Internet is constituted by both classical and quantum links interconnecting the quantum nodes.

Another key physical entity is represented by the Entanglement Generator, responsible for the generation of the EPR pairs to be distributed among the quantum nodes by exploiting the quantum links. Indeed, the Entanglement Generator could be either located within a node or it could be an independent self-contained physical entity. The choice is rather technological, depending on the particulars of the hardware underlying the Entanglement Generator, as shown in [8].

Finally, two more physical entities are needed: memories and measurement devices. On one hand, quantum memories are responsible for

3 We note that, once Alice performed the measurement at her side, the qubit at Bob's side is instantaneously fixed. As a consequence, in principle, Bob can utilize his qubit (e.g., for a computational task) before receiving the two classical bits. And Bob can "correct" the result of its task a-posteriori, whenever the two bits will be available at his side. This weak synchronization constraint — which allows Bob to manipulate the qubit as long as he corrects the result (according to the two classical bits) before the end of the computational task — can be leveraged in the communication protocols handling the integration between classical and quantum resources. As an example, Alice can exploit classical error-correction techniques (such as ARQ and FEC) to face with the errors introduced by the classical communication channel on the two classical bits, given that the additional delays introduced by these classical techniques do not pose severe issues according to the weak synchronization constraint.



(a) High-Level Schematic. Two entangled qubits, forming an EPR pair, are generated and distributed so that one qubit (particle A) is stored by Alice and another qubit (particle B) is stored by Bob. Alice performs a BSM upon the two qubits at her side, i.e., the qubit $|\psi\rangle$ to be transmitted and particle A. Then, Alice sends the measurement outcome, i.e., 2 classical bits, to Bob with a classical channel. By processing particle B according to the measurement outcome, Bob finally obtains the qubit $|\psi\rangle$.

(b) Low-Level Schematic. An EPR pair is distributed among Alice and Bob so that particle A goes to Alice and particle B to Bob. Via a BSM upon particle A and the qubit $|\psi\rangle$ to be transmitted, the particle B at Bob's side collapses into a state resembling the qubit to be teleported, i.e. $U_i\,|\psi\rangle$. The result of Alice's measurement, sent through a classical channel, allows Bob to properly process particle B, i.e., to choose, among 4 possible operations, the unique operation U_i^{-1} able to transform particle B into $|\psi\rangle$.

FIGURE 2. Quantum Teleportation: unknown qubit $|\psi\rangle$ is "transmitted" from Alice to Bob by consuming an EPR pair, shared between Alice and Bob. Relativity is not violated since $|\psi\rangle$ is obtained by Bob only after a classical communication between Alice and Bob occurred.

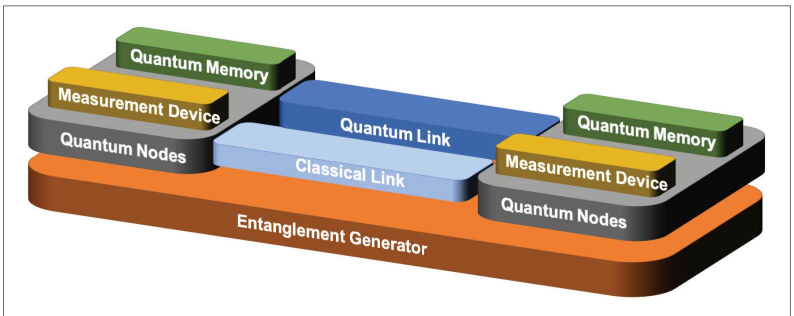


FIGURE 3. Principal physical network entities constituting the Quantum Internet.

storing the quantum states to fulfill the communication needs, at hand exemplified by waiting for reply messages from across the network. The quantum memories should be considered as separated physical entities due to their crucial role in the network. On the other hand, quantum measurement devices are needed for both assessing the generation of entangled states through heralding techniques and, within the quantum nodes, complying communication tasks, for example, in quantum teleportation.

Quantum Internet Design: Challenges and Open Problems

In this section, we discuss the key research challenges and open problems related to the design of the Quantum Internet.

Network Functionalities

The impossibility of safely reading and copying quantum information, as a consequence of the combined effect of the no-cloning theorem and the quantum measurement postulate, greatly complicates the design of the network functionalities within the Quantum Internet. Indeed, a major paradigm shift is required to harness the quantum mechanics peculiarities, so that a one-to-one mapping between classical network layers and quantum network layers may be unfeasible.

For example, with reference to error correction in classical packet-switching networks, ARQ assumes that whether a packet is lost or irremediably corrupted, a copy of the original packet is available at the source so that it can be subsequently re-transmitted to the next hop. But this strategy cannot be employed within the Quantum Internet, and novel error correction strategies explicitly tailored for the quantum mechanics peculiarities have to be designed.

But the challenges arising with the Quantum Internet design are not limited to layer-1/layer-2 error correction strategies. The no-broadcasting theorem, a corollary of the no-cloning theorem, prevents quantum information from being transmitted to more than a single destination. This is a fundamental difference with respect to classical networks, where broadcasting is widely exploited for implementing several layer-2 and layer-3 functionalities, such as medium access control and route discovery. As a consequence, the link layer must be carefully re-thought and re-designed.

Furthermore, it has already been shown that classical routing protocols based on the Dijkstra or Bellman-Ford algorithms fail in selecting the optimal route at layer-3 [9] due to the complex and stochastic nature of the physical mechanisms underlying quantum entanglement.

Finally yet importantly, connection-mode layer-4 protocols such as TCP employ packet retransmissions to face with datagram losses. But, as said, this strategy cannot be employed within the Quantum Internet and the same concept of connection-oriented service must be re-engineered.

Decoherence and Fidelity

Qubits are very fragile: any interaction of a qubit with the environment causes decoherence, that is, a loss of information from the qubit to the environment as time passes.

Clearly, a perfectly-isolated qubit preserves its quantum state indefinitely. However, isolation is hard to achieve in practice given the current state-of-the-art of quantum technologies. Furthermore, perfect isolation is not desirable, since computation and communication require to interact with the qubits, for example, for reading/writing operations.

Decoherence is generally quantified through *decoherence times*, whose values largely depend on the adopted technology for implementing qubits. For qubits realized with superconducting circuits [10], the decoherence times exhibit an order of magnitude within 10–100 μs. Although a gradual decrease of the decoherence times is expected with the progress of the quantum technologies, the design of a quantum network must carefully account for the constraints imposed by quantum decoherence.

Decoherence is not the only source of errors. Errors practically arise with any operation on a quantum state due to imperfections and random fluctuations. Here, a fundamental figure of merit is the *quantum fidelity*. The fidelity is a measure of the distinguishability of two quantum states, taking values between 0 and 1. The larger is the imperfection of the physical implementation of an arbitrary quantum operation, the lower is the fidelity. Since teleportation consists of a sequence of operations on quantum states, the imperfection of such operations affects the fidelity of the teleported qubit.

The effects of these imperfections have been recently analyzed in [8], through an extensive experimental campaign conducted on the IBM Q quantum processor. However, from a communication engineering perspective, the joint modeling of the errors induced by the quantum operations, together with those induced by entanglement generation/distribution (as described in the next subsection), is still an open problem.

Furthermore as said, the no-cloning theorem prevents the adoption in quantum networks of classical error correction techniques, depending on information cloning, to preserve quantum information against decoherence and imperfect operations. Recently, many quantum error correction techniques have been proposed as in [11]. However, further research is needed. In fact, quantum error correction techniques must handle not only bit-flip errors, but also phase-flip errors, as well as simultaneous bit-flip and phase-flip errors. Differently, in the classical domain, a single type of error, that is, the bit-flip error, has to be considered.

From the above, in a quantum network the counteraction of the errors induced by decoherence and imperfect quantum operations is a functionality embracing aspects that traditionally belong to the physical layer of the classical network stack.

Entanglement Distribution

As in classical communication networks, the teleportation of quantum information is limited by the classical bit throughput, necessary to transmit the output of the BSM outcome. But, differently from classical networks, the teleportation of quantum information is achievable only if an EPR pair, generated by the physical network entity described above, can be distributed between remote nodes. In this regard, there is a global consensus toward the use of photons as entanglement carriers, that is, as candidates to generate entangled pairs among remote devices.

However, long-distance entanglement distribution, although deeply investigated by the physics community in the last 20 years, still constitutes a key issue due to the decay of the entanglement distribution rate as a function of the distance. Figure 4 reports a possible strategy for long-distance entanglement distribution. Specifically, long-distance distribution is achieved through Quantum Repeaters [12], which are devices implementing a physical process known as *entanglement swapping* [12]. In practice, two EPR pairs are generated, with source Alice and destination Bob receiving one element of each pair while the other two are sent to an intermediate node (the Quantum Repeater in Fig. 4). By performing a BSM on the two entangled particles at the intermediate node, entanglement is created between the elements at the remote nodes. Hence, instead of distributing the entanglement over a long link, the entanglement is distributed iteratively through smaller links. In this regard, decoherence effects on the entanglement generation/distribution process can be mitigated via entanglement distillation (equivalently known as entanglement purification), which can be regarded as a type of error-correction for quantum communication between two parties [8]. The distillation procedure, however, requires additional levels of qubit processing.

Despite these efforts, further research is needed from a network engineering perspective. In fact, the entanglement distribution is a key functionality of a quantum network embracing aspects belonging to different layers of the classical network stack. More in detail below.

Physical Layer: The entanglement is a perishable resource due to the decoherence. The consequent degradation of the entanglement among the entangled parties over time maps into a corre-

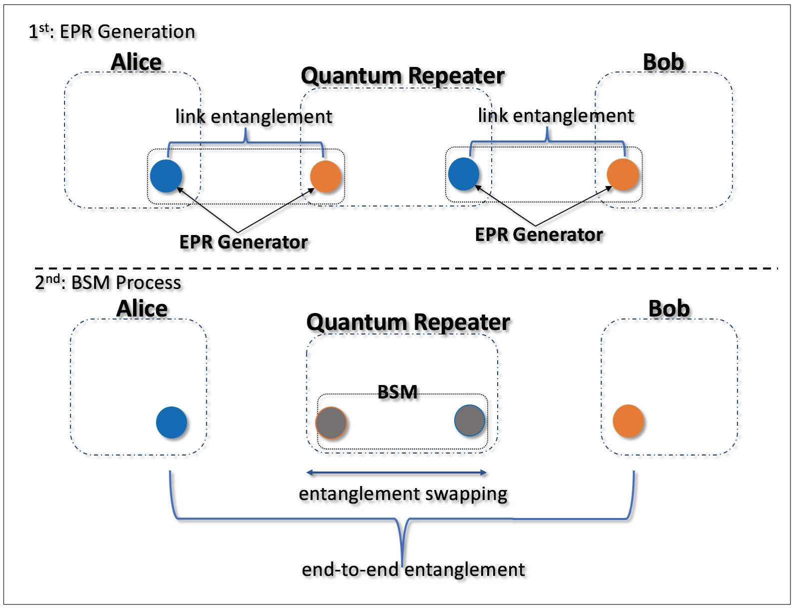


FIGURE 4. Entanglement Swapping. Two EPR pairs are generated and distributed: between a source (Alice) and an intermediate node (Quantum Repeater), and between the intermediate node and a destination (Bob). By performing a BSM on the entangled particles at the Quantum Repeater, entanglement is eventually generated between Alice and Bob.

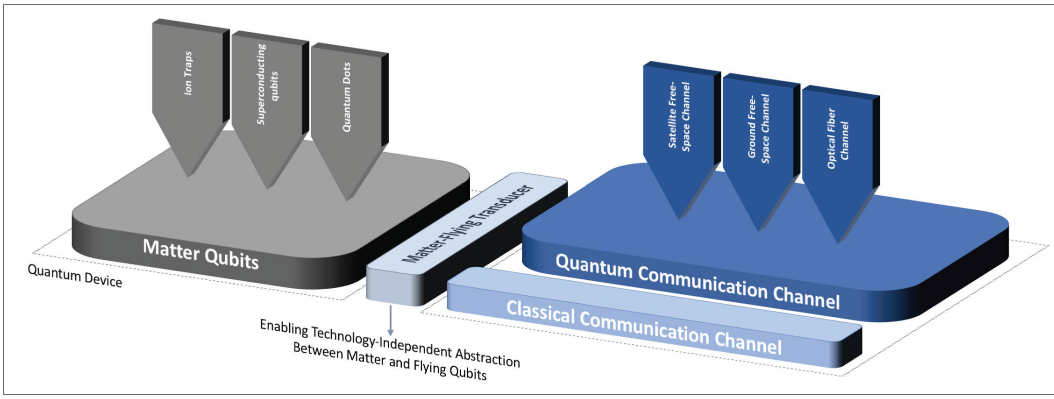


FIGURE 5. Matter-Flying Interface for entanglement distribution within the quantum nodes of the network.

sponding degradation of teleportation quality. For the reasons highlighted in the previous subsection, classical error correction techniques cannot be used to counteract this degradation. Hence, robust entanglement distribution techniques based on quantum error correction are mandatory for the deployment of a quantum network. This still represents a very hard challenge in this field.

Link Layer: The link layer must be carefully re-thought and re-designed to account for the constraints imposed by the no-broadcasting theorem as discussed previously. Specifically, with reference to entanglement distribution, effective multiplexing techniques should be designed to allow multiple quantum devices to be connected to a single quantum channel.

Network Layer: The entanglement distribution determines the connectivity of a quantum network in term of capability to perform teleporting among the quantum devices. Hence, novel quantum routing metrics are needed to ensure effective entanglement-aware path selection [9]. Furthermore, the teleportation process destroys the entanglement as a consequence of the BSM at the source. Hence, if another qubit needs to be teleported, a new entangled pair needs to be created and distributed between the source and the destination. This constraint has no-counterpart in classical networks and it must be carefully accounted for in an effective design of the network layer.

Interface between Matter Qubits and Flying Qubits

As mentioned before, photons are the ideal substrate for the so-called flying qubits, that is, as entanglement carriers. The rationale for this choice lays in the advantages provided by photons for entanglement distribution: weak interaction with the environment (thus, reduced decoherence), easy control with standard optical components as well as high-speed low-loss transmissions. The aim of the flying qubits is to "transport" qubits out of the physical quantum devices through the network for conveying quantum information from the sender to the receiver. Hence, as shown in Fig. 5, a transducer [13] is needed to convert a *matter* qubit, that is, a qubit for information processing/storing within a computing device, in a flying qubit, which creates entanglement among remote nodes of the network [8].

Nowadays, there exist multiple technologies for realizing a matter qubit (quantum dots, transmons, ion traps, etc.) and each technology is characterized by different pros and cons [10]. As a consequence, a matter-flying interface is required also to face with this technology diversity.

Moreover, from a communication engineering perspective, the interface should be compatible also with the peculiarities of the physical channels the flying qubits propagate through. In fact, there exist different physical channels for transmitting flying qubits, ranging from free-space optical channels (either ground or satellite free-space) to optical fibers.

In the last ten years, the physics community has been quite active investigating schemes and technologies enabling such an interface, with a heterogeneity of solutions [13, 14]. As a consequence, the communication engineering community should join these efforts by designing communication models that account for both the technology diversity in fabricating qubits and the propagation diversity in characterizing the different physical channels.

Deployment Challenges

Quantum Internet is probably still a concept far from a real world implementation, but it is possible to outline a few deployment challenges for the near future:

- The current technological limits to qubits and quantum processors physical realizations: At first, quantum computers will be available in a few highly specialized data centers capable of providing the challenging equipment needed for quantum computers (ultra-high vacuum systems or ultra low temperature cryostats). Companies and users will be able to access quantum computing power as a service via cloud. In this regard, the quantum cloud market is estimated to be nearly half of the whole 10 billion quantum computing market by 2024 [15]. IBM already allows researchers to practice quantum algorithm design through a classical cloud access to isolated 5-, 16- and 20-qubits quantum devices.
- Existing technological limits to quantum communication and quantum interfaces: The first realizations of a Quantum Internet will be small clusters of quantum processors within a data center. Architectures will have to take into account the high cost of data buses (economically and in terms of quantum fidelity) limiting both the size of the clusters and the use of connections for processing.
- Hybrid architectures will probably be used for connections faring both the use of cryo-cables (expensive and necessarily limited in length) and of optical fibers or free space photonic links.

•Given the fragile nature of quantum entanglement and the challenges posed by the sharing of quantum resources, a substantial amount of conceptual work will be needed in the development both of novel networking protocols and of quantum and classical algorithms.

•The integration of classical and quantum communication resources: Regarding the classical communications resources, they will likely be provided by integrating classical networks such as the current Internet with the Quantum Internet. Regarding the quantum communication resources, it seems attractive to utilize existing optical fiber networks. However, it is still an open problem to determine whether it is feasible to utilize a single link, for example, a single optical fiber, for both quantum and classical communications, so that existing network infrastructures can be exploited without the need for additional new infrastructure. Furthermore, in light of a flexible integration among classical and quantum resources, the software-defined network paradigm could be envisioned to play a crucial role.

In summary, the integration among classical and quantum resources represents an exiting open problem, and its solution requires a multidisciplinary effort, spanning from communications theory to the networking engineering communities.

In conclusion, the Quantum Internet, though still in its infancy, is a very interesting new concept where a whole new set of novel ideas and tools at the border between quantum physics, computer and telecommunications engineering will be needed for the successful development of the field.

Acknowledgment

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Biographies

Angela Sara Cacciapuoti [M'10, SM'16] is a Tenure-Track Assistant Professor at the University of Naples Federico II, Italy. Since July 2018, she held the national habilitation as "Full Professor" in Telecommunications Engineering. Currently, she serves as an area editor for *IEEE Communications Letters* and an editor/associate editor for *IEEE Transactions on Communications*, *IEEE Trans. on Wireless Communications* and IEEE OJ-COM. In 2016 she was elevated to IEEE Senior Member and she was appointed to the board of the IEEE ComSoc YP Standing Committee. Since 2018, she is the Publicity Chair of the IEEE ComSoc WICE Standing Committee.

Marcello Caleffi [M'12, SM'16] is a Tenure-Track Assistant Professor at the University of Naples Federico II. His work has appeared in several premier IEEE transactions and journals, and he has received multiple awards, including best strategy, most downloaded article, and most cited article awards. Currently, he serves as an editor for *IEEE Communications Magazine* and *IEEE Communications Letters*. He serves as Distinguished Lecturer for the IEEE Computer Society. Since 2017, he serves as elected treasurer of the IEEE ComSoc/VT Italy Chapter and, since 2019, he serves as a member of the IEEE New Initiatives Committee.

Francesco Tafuri is a Full Professor at the University of Naples Federico II. His scientific interests fall in the field of superconductivity. He is leading an experimental research group investigating macroscopic quantum phenomena and the Josephson effect in hybrid devices, new routes for the realization of superconducting qubits for hybrid architectures, mesoscopic and nanoscale systems, vortex physics. He is currently Coordinator of the inter-university Ph.D. program in "Quantum technologies." He is author of about 170 publications in international journals and books, including 14 papers in Science/Nature/Nat.Mat./Nat.Comm./PRL. He has given more than 90 invited talks at international conferences and research institutes.

Francesco Saverio Cataliotti is active mainly in experimental work centered on atomic physics and atom-laser interactions. It includes nonlinear atom-laser interaction, manipulation of atomic momentum states, laser-cooling and the realization of Bose-Einstein condensates. The optical manipulation of condensates has allowed him to investigate superfluidity and macroscopic quantum states. More recently he has been concerned with coherent micromanipulation techniques with atoms, molecules and micro-mechanical systems with perspectives ranging from quantum computation to single molecule manipulation. He is the author of more than 70 scientific papers in international peer reviewed journals which have received more than 3000 citations to date.

Stefano Gherardini received his B.Sc. degree in electronic and telecommunications engineering and his M.Sc. degree in electrical and automation engineering from the University of Florence, Italy, in 2011 and 2014, respectively. He received his Ph.D. degree in information engineering, curriculum non-linear dynamics and complex systems, in 2018 with the Automatic Control and QDAB group at the University of Florence. His main research interests include binary measurements, networked moving-horizon estimation, Kuramoto models, disordered systems, stochastic quantum Zeno effect, open quantum systems theory, and quantum estimation and control.

Giuseppe Bianchi has been a full professor of networking in the School of Engineering at the University of Roma Tor Vergata since 2007. His research activity, documented in more than 200 peer-reviewed international journal/conference papers having received to date more than 17,000 citations, focuses on wireless networks (his WLAN modeling work received the ACM SIGMOBILE Test of Time award in 2017), network security, privacy, and programmable network systems in both the wireless and wired domains. He has chaired several international networking conferences, including IEEE Infocom, ACM CoNext, ITC, WoWMoM, and LANMAN, among others, and has coordinated several large-scale European Projects.