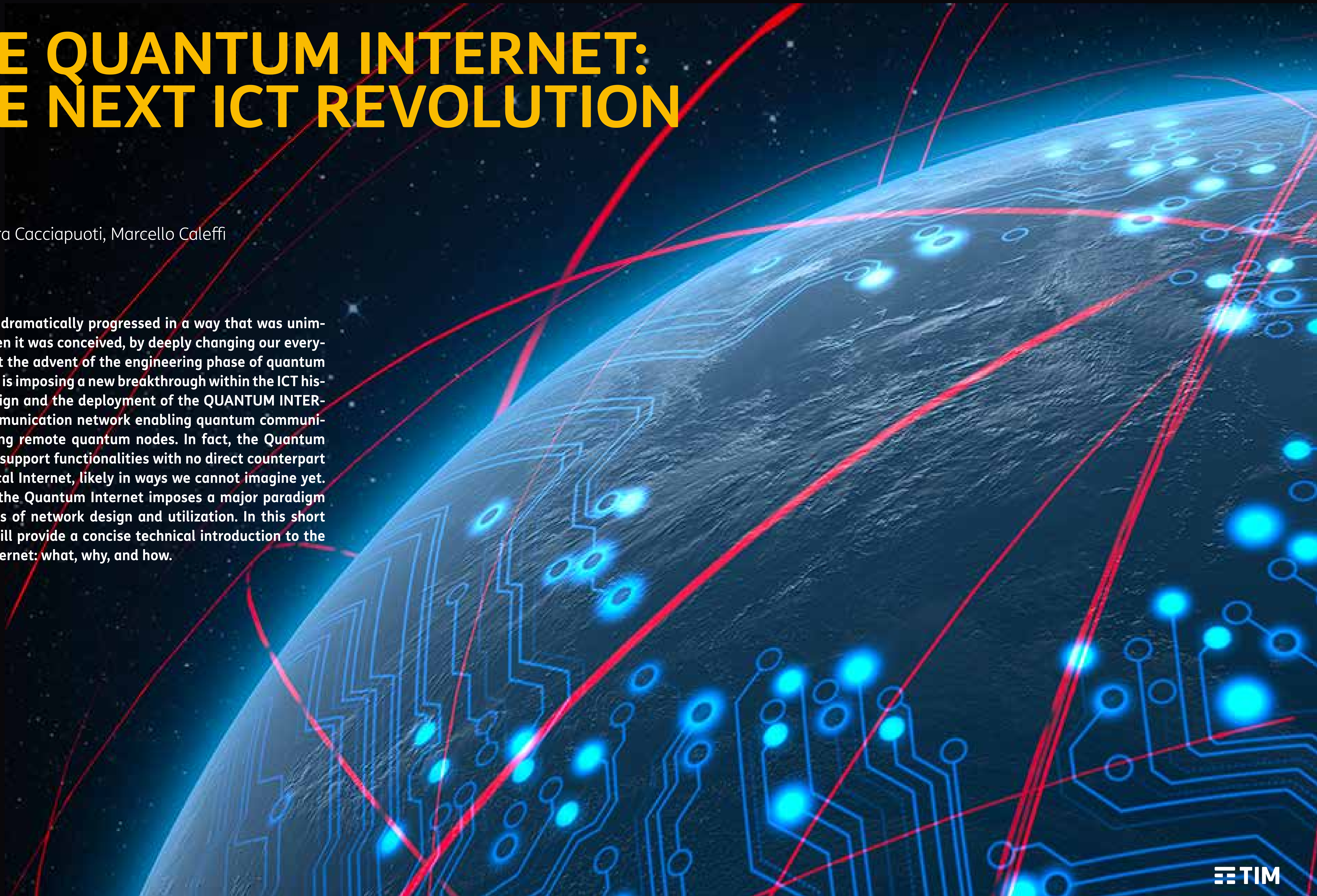


THE QUANTUM INTERNET: THE NEXT ICT REVOLUTION

Angela Sara Cacciapuoti, Marcello Caleffi

Internet has dramatically progressed in a way that was unimaginable when it was conceived, by deeply changing our everyday lives. But the advent of the engineering phase of quantum technologies is imposing a new breakthrough within the ICT history: the design and the deployment of the QUANTUM INTERNET – a communication network enabling quantum communications among remote quantum nodes. In fact, the Quantum Internet will support functionalities with no direct counterpart in the classical Internet, likely in ways we cannot imagine yet. To this aim, the Quantum Internet imposes a major paradigm shift in terms of network design and utilization. In this short article, we will provide a concise technical introduction to the Quantum Internet: what, why, and how.

The Quantum Internet

In the realm of computing, probably the most commonly referred quantum algorithm is the pioneering Shor's factoring algorithm, which proved the disruptive potential of quantum computation for integer factorization [1].

The hardness of the integer factorization problem constitutes the essence of the most widely adopted method for securing our communications over the modern Internet. Cracking a 2048-bit RSA encryption key with a classical supercomputer takes billions of years – more than the age of the universe – but it would take only a few minutes (or hours) by using a quantum computer [2]. This implies that our online banking system, encrypted so far with 1024-bit keys, can be almost instantaneously decrypted when a fully functioning quantum computer is available.
A quantum computer inherits its computing power owing to the unique features of its building blocks – aka the quantum bits (qubits), describing a discrete two-level quantum state – to be in unconventional states such as superposition and entanglement. To elaborate a little further, in classical domain, the unit of information is conveyed by the binary digit (bit), which can only hold the value "0" or "1" at a certain time. By contrast, the unit of quantum information – the so-called qubit – can be used to convey "0", "1", or the superposition of both of them at the same time. Meanwhile, entanglement – the most distinguishing quantum phenomenon with no counterpart in the classical world – is a special case of superposition of multiple qubits in which the quantum states of the particles become inextricably linked.

And any action experienced by one particle will immediately influence the others even if they are separated at a great distance [3]–[5].

Thanks to these marvels – and by grossly oversimplifying – the computing power of a quantum computer scales exponentially with the number of qubits that can be embedded and interconnected within [4]–[6].
The greater is the number of qubits, the harder is the problem that can be solved by a quantum computer.

Unfortunately, qubits are very fragile and easily corrupted by interactions with the outside world, via a noise process known as decoherence [3], [7]. And the challenges for controlling, interconnecting, and preserving the qubits get harder as the number of qubits within the quantum processor increases.

A very promising approach to address the challenges arising in the realization of large-scale quantum processors is to realize a quantum communication network – aka the Quantum Internet – to mimic modern high-performance computing infrastructures –where thousands of processors, memories and storage units are inter-connected, and the computational tasks are solved by adopting a distributed computing approach [5].

In fact, with the availability of this communication infrastructure and 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 the quantum computing power, with just a linear amount of the physical resources [6], i.e., the quantum processors.

More in detail, the Quantum Internet is a global quantum network, able to transmit qubits and to distribute entangled quantum states among remote quantum devices through quantum links, in synergy with classical links.

Such a quantum network constitutes a breakthrough, since it will provide unparalleled capabilities [8]–[10] – by exploiting its exponentially larger state space – ranging from blind computing through secure communications to noiseless communications, which have already been theorized or even experimentally verified [3], [5], [6], as recently overviewed by an IETF Quantum Internet Draft [11].

The Road Towards the Quantum Internet

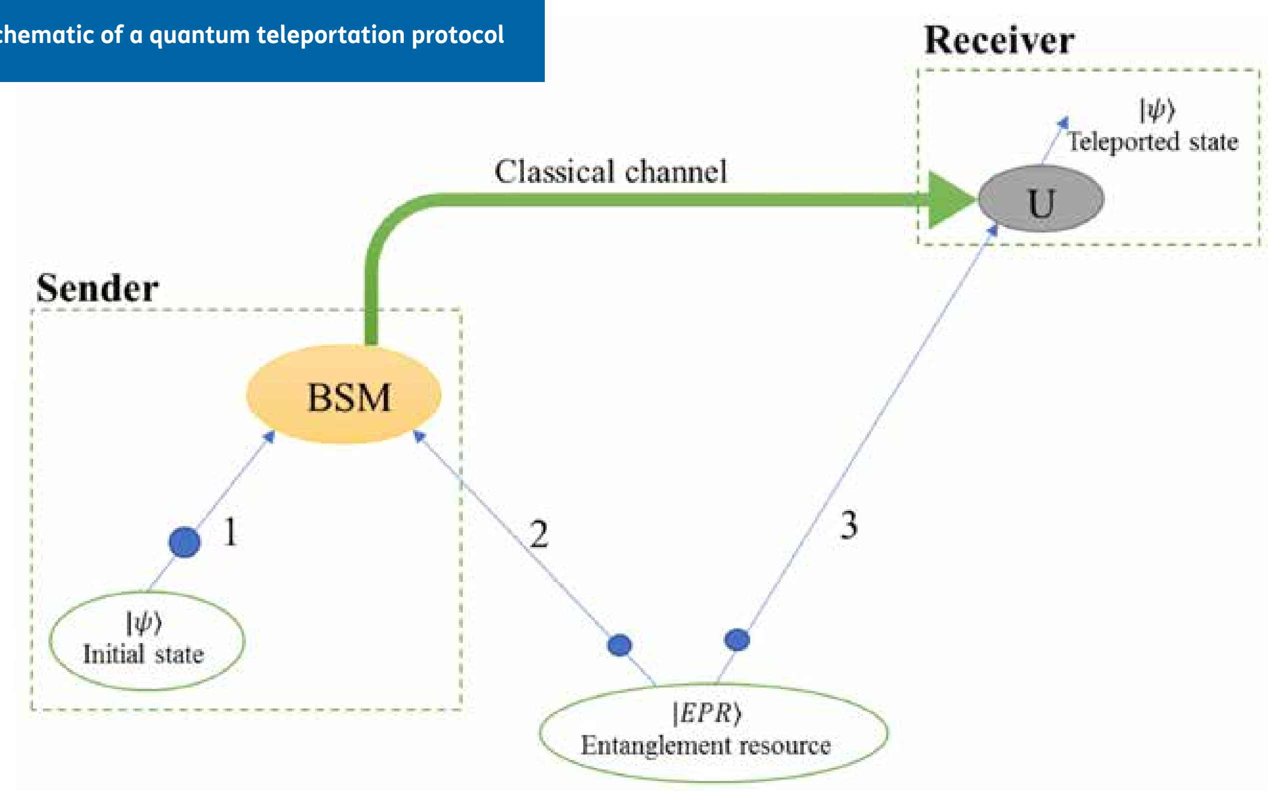
As mentioned before, the gravest challenge of quantum information technologies is mitigating the deleterious effects of quantum decoherence, a type of noise with no counterpart in classical networks.
An immeasurable amount of efforts has been invested for perfecting the physical implementation of quantum processors and quantum links as well as for composing various error control protocols on the upper layers for circumventing the unavoidable imperfection.

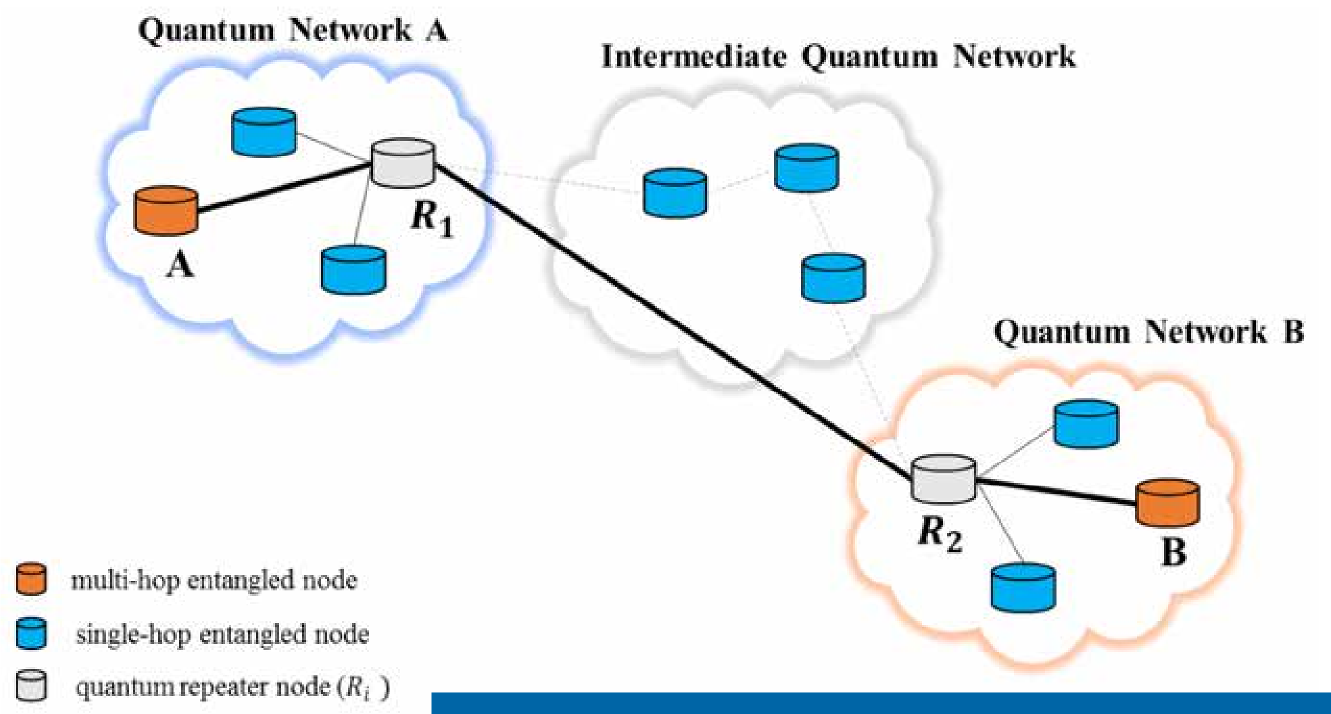
In the classical domain, several methods of error-control or congestion are invoked to guarantee the successful transmission of information, such as forward error-correction in the physical layer as well as automatic request protocol (ARQ) in the data-link and network layer within the classical TPC/IP network stack.

And they have been proven to be effective solutions for the classical Internet during the last decades. However, these techniques rely on the capability of extensively reading and copying information.

Bits are duplicated among the different components of a network and among different nodes.

1
The schematic of a quantum teleportation protocol





2
The stylized topology of entanglement distribution in the Quantum Internet. The initial network consists of a transmitter node (A), a distant target node (B) and intermediate repeater nodes (Ri)

Unfortunately, this does not hold in the Quantum Internet as a consequence of the no-cloning theorem – which forbids any possibility of duplicating an unknow qubit.

Furthermore, the simple act of measuring – i.e., reading – a qubit irremediably alters the encoded quantum information due to the quantum measurement postulate.

Due to the aforementioned quantum principles, it results that – although one can transmit directly a qubit to a remote node via a fiber link by encoding the quantum information within an inner state of a photon – if the traveling photon is lost due to attenuation or it is corrupted by noise, the associated quantum information cannot be recovered via a measuring process or a copy of the original information.

As a consequence, the direct transmission of qubits via photons is not readily feasible, unless the network applications can tolerate the loss of information and/or low transmission success rates, as in Quantum Key Distribution (QKD) networks [3].

If the quantum links are inevitably noisy and direct transmission of qubits is not feasible, how can we possibly conceive a reliable connection between two remote quantum processors? Luckily, the wonderful properties of quantum mechanics equip the Quantum Internet for transferring quantum information without actually sen-

ding any qubit through the quantum channel by the virtue of quantum teleportation [3], [12].
The quantum teleportation process of a single qubit is illustrated in Fig. 1.

Specifically, to realize the marvel of quantum teleportation, two resources are needed.

One resource is classic: two classical bits must be transmitted from the source to the destination.

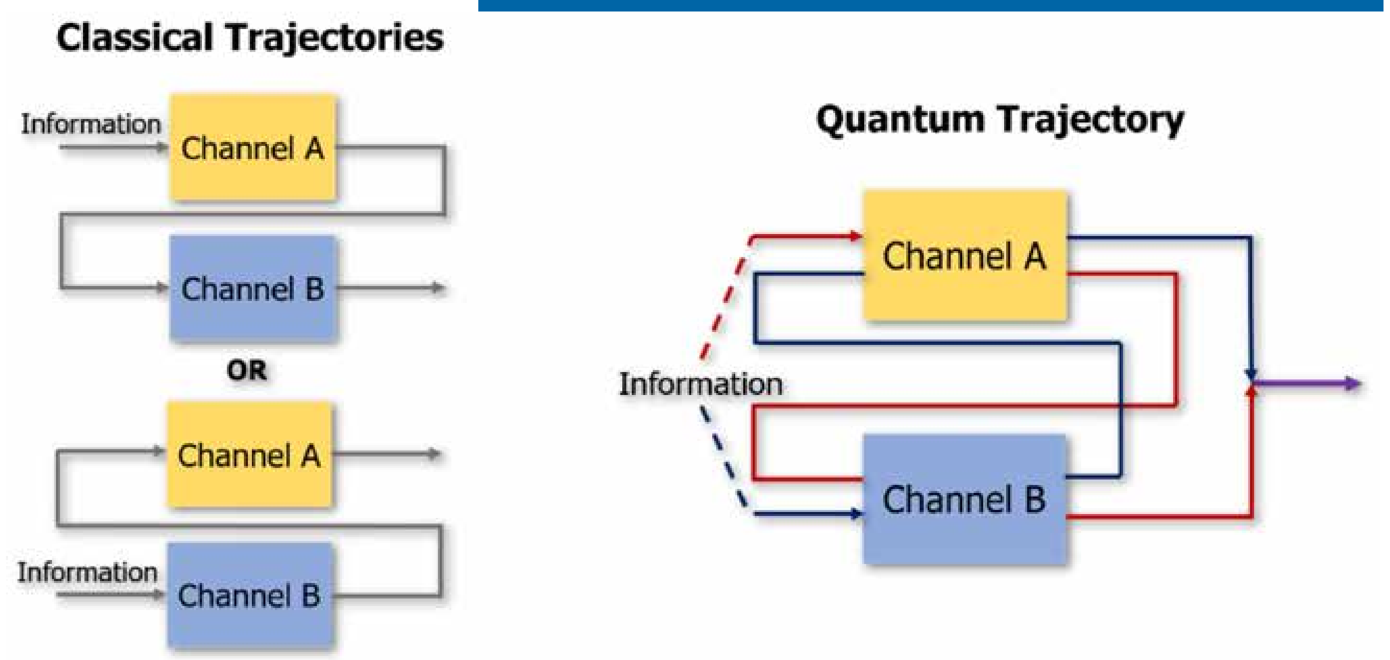
The other resource is quantum: a maximally entangled pair of qubits, also known as EPR pair, must be generated and shared between the source and the destination.
As a consequence, quantum teleportation requires two communication links, a classical link for transmitting the pair of classical bits and a quantum link for entanglement generation and distribution.

From this, it results that the integration of classical and quantum resources is a crucial aspect for the Quantum Internet. In particular, the classical communication resources – i.e., the classical links for transmitting classical bits – will be likely provided by integrating classical networks such as the current Internet with the Quantum Internet [7].

Regarding the quantum communication resources, it seems attractive to utilize existing optical fiber networks. However, efficient ways to interface photons with the hardware implementing the qubits within a quantum processor are yet to be found.

Furthermore, the heterogeneity of the hardware underlying computa-

3
Classical trajectories versus Quantum Trajectories [16]: (left plot) a message traversing two channels in a well-defined causal order; (right plot) a message traversing two channels in a superposition of different orders



tional/memory qubits – atoms, ion traps, superconducting circuits, etc. – within and among the quantum network nodes must be seamlessly handled by the network functionalities [4].
This constitutes a distinctive challenge for the Quantum Internet design with respect to classical networks.

Furthermore, the notion of connectivity in the Quantum Internet will be highly determined by the availability of EPR pairs amongst the quantum nodes across the network.

Consequently, one of the fundamental requirements of the Quantum Internet is the reliable distribution of EPR pairs amongst quantum nodes as depicted in Fig 2. Similar to the classical network, entanglement distribution is accomplished via a quantum repeater [13].

In contrast to a classical repeater, where it relies on the decode-and-forward mechanism, a quantum repeater hinges on the capability of performing entanglement swapping [11] for extending the connectivity within the quantum networks.

On the Noise Mitigation: Some more Perspectives

Obviously, we are facing similar challenges in both classical and quantum communications, namely mitigating the effects of noise introduced by the communication channels.

Borrowing the idea of classical error control, we can have the quantum version of classical error correction.

However, the major drawback of this direct approach is that error correction in the quantum domain requires a massive overhead in terms of physical qubits needed to implement a fault-tolerant logical qubit [14].

In our research group, we approach this problem in a different light. As previously mentioned, quantum information can be in the superposition of multiple states. Interestingly, the concept of superposition state can be extended to the superposition of quantum channels.

Specifically, quantum particles can propagate simultaneously among multiple space-time trajectories – aka quantum trajectories – as illustrated in Fig. 3.

By exploiting this unconventional capability, quantum superpositions of noisy channels can behave as perfect noiseless quantum communication channels, even if no quantum information can be successfully transmitted throughout either of the noisy component channels individually [15], [16].

This phenomenon has no classical counterparts and potentially opens new unexplored possibilities to achieve transmission rates exceeding the fundamental limits of conventional (quantum) Shannon theory [15], [16], with the Quantum Internet providing the underlying infrastructure.

Conclusions

The marvel of quantum technology soon will embrace the world of Internet. The Quantum Internet will enable various alluring applications without classical counterparts. Ultimately, the journey towards the Quantum Internet is a multi-disciplinary and collaborative endeavor.

The communications engineer community with both its academic and industrial components can and should play a fundamental role in this journey. Indeed, with this intent, the “Emerging Technical Committee on Quantum Communications and Information Technology (QCIT- ETC)”, where our Quantum Internet group actively participates, has been established within the IEEE Communications Society.
There are also already significant on-going efforts toward quantum network design and standardization. In this regard, we would like to mention the working group within the Internet Engineering Task Force (IETF), where researchers, including our groups, are trying to conceptualize the architectural principles of the Quantum Internet [11].

Acknowledgement

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