# The Quantum Internet: Enhancing Classical Internet Services One Qubit at A Time

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## Abstract

Nowadays, the classical Internet is mainly envisioned as the underlying communication infrastructure of the Quantum Internet, aimed at providing services such as signaling and coordination messages. However, the interplay between the classical and the quantum Internet is complex and its understanding is pivotal for an effective design of the Quantum Internet protocol stack. The aim of the article is to shed light on this interplay, by highlighting the fact that such an interplay is indeed bidirectional rather than unidirectional. The Quantum Internet exhibits the potential of supporting and even enhancing classical Internet functionalities.


## Introduction

Quantum Internet is attracting worldwide research interest, given its potential of enabling a set of applications with no counterpart in the classical Internet [1].

Yet, a misconception that may arise with the research interest is the idea of the Quantum Internet eventually replacing classical Internet. As a matter of fact, the very opposite holds. The Quantum Internet can not operate unassisted nor independently from the classical Internet [2–5], but it rather — widely and extensively — depends on classical network functionalities and services for providing quantum network functionalities.

A pivotal example of this dependence is provided by the *quantum teleportation* process [6], which represents one of the key communication protocols enabled by the Quantum Internet infrastructure. Specifically, quantum teleportation constitutes an astonishing strategy for transmitting a qubit without the physical transfer of the particle storing the qubit. But it requires two different communication resources. One is quantum: a pair of (maximally) entangled qubits shared between source and destination. And the other is classical: a pair of bits transmitted from the source to the destination. Indeed, classical signaling is not limited to teleportation, but it rather constitutes a requirement widespread within the different quantum network tasks and functionalities [5, 7], ranging from entanglement generation through distillation to swapping as discussed in the next section.

From the above, it becomes evident that the successful design of the Quantum Internet must carefully assess and account for the interdependence between classical Internet and Quantum Internet. Yet, despite its fundamental role, such an interdependence is still under-analyzed, and its deep understanding represents a crucial open problem [7].

The aim of this article is precisely to shed light on the interdependence between classical Internet and Quantum Internet, with the objective of allowing the reader to:

- Acknowledge the deep interplay between classical Internet and Quantum Internet
- Understand that this interplay is bidirectional rather than unidirectional, with the Quantum Internet exhibiting the potential of supporting and even enhancing classical Internet functionalities;
- Appreciate the profound impact of this classical-quantum interplay on the design of the Quantum Internet protocol stack.

To this aim, we first substantiate the complex, bidirectional nature of the interplay between classical Internet and Quantum Internet in the following section. Then, we analyze the potentialities of the Quantum Internet to enhance the classical Internet services. This is corroborated through different use cases involving communication functionalities, ranging from physical through data link to network layer. Finally, we conclude the article.

## Classical vs. Quantum Internet Interplay

As highlighted above, the Quantum Internet depends on the availability of classical communication and network functionalities. And, indeed, it is fairly reasonable to assume these classical services as provided by the existing classical Internet. As a consequence, the interplay between classical Internet and Quantum Internet must be properly understood and modeled as a preliminary, mandatory task for the design of the protocol stack of the Quantum Internet.

In this context, classical Internet has been implicitly considered so far as an underlying communication infrastructure, aimed at providing services to the Quantum Internet. Accordingly and by oversimplifying, the Quantum Internet can be modeled as some sort of complex system laying on top of the classical Internet protocol stack — as shown in Fig. 1a — and interacting with the former at the application layer.

Quantum teleportation constitutes a representative case justifying such a modeling. In fact, the teleportation of a qubit is implemented with

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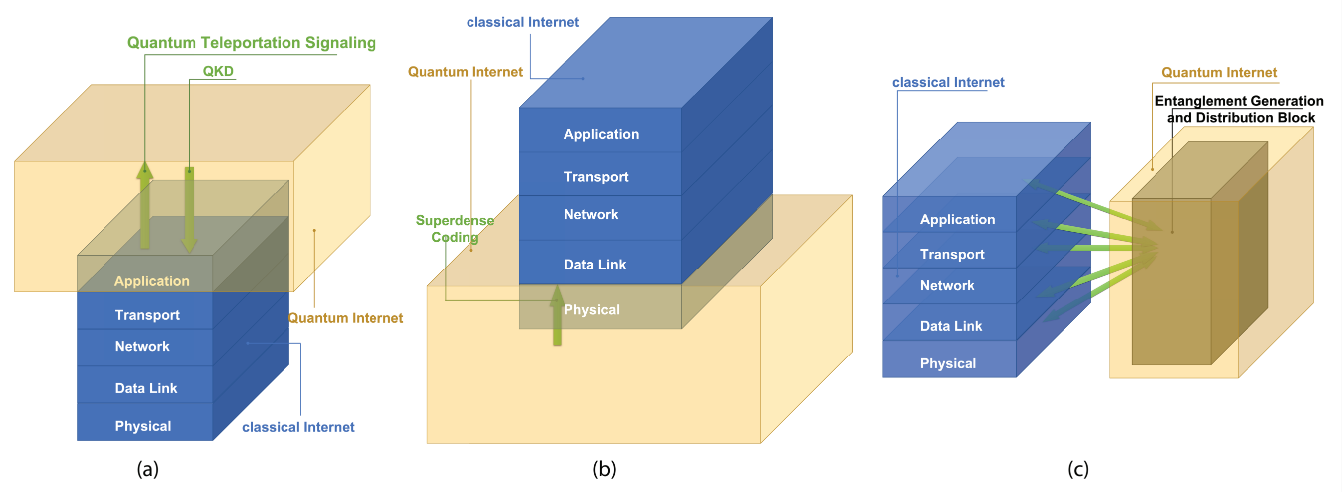


FIGURE 1. Interplay between classical Internet (blue boxes) and Quantum Internet (yellow box) protocol stack. The arrows represent an interaction between the two protocol stacks, with arrow direction flowing from the stack offering a service to the stack demanding such a service. The different layers constituting Quantum Internet protocol stack have been omitted given the lack of a univocal standard [7]. a) From the classical Internet perspective, quantum teleportation can be regarded as some sort of complex application laying on top of the classical Internet protocol stack and down-calling classical end-to-end communication services; b) From the classical Internet perspective, superdense coding can be regarded as some sort of complex functionality of the classical physical layer providing a classical communication service, namely, bit transmission; c) From the classical Internet perspective, the core functionality of the Quantum Internet — that is, entanglement generation and distribution (grey box) as well as its manipulation — requires the availability of multiple services from all the classical Internet protocol stack.

a sequence of quantum functionalities — namely, entanglement generation and distribution, as well as local quantum operations at source and at destination — interleaved by the transmission of a classical message. Accordingly, it seems reasonable from the classical Internet perspective — and in agreement with the separation of concern approach, the key principle behind OSI and TCP/IP design — to consider quantum teleportation as some sort of complex application down-calling classical end-to-end communication services provided by the classical Internet stack.

Similar reasoning holds by considering another fundamental quantum communication protocol, namely, Quantum Key Distribution (QKD) [1]. Essentially, QKD protocols fit with the former modeling [8]. However, differently from quantum teleportation, QKD provides — rather than requests — a service to classical Internet, by generating keys for encrypting a classical message, as we analyze in more details later.

On the other hand, a different modeling arises by considering another popular quantum communication protocol — namely, *quantum superdense coding* [1] — that enables the transmission of two bits by "coding" them into a qubit, under the assumption of sender and receiver pre-sharing an entangled resource. By accounting for the specificity of superdense coding, it sounds more reasonable to envision it — from the classical Internet perspective — as a sort of complex functionality of the physical layer of the classical Internet protocol stack, as shown in Fig. 1b. According to this model, packets received from the data link layer can be either encoded and then transmitted classically through the classical physical layer, or directed to some sort of quantum super-physical layer to be encoded according to the superdense protocol.

Indeed, while classical Internet provides quantum teleportation with classical communication functionalities, when it comes to superdense coding the opposite holds: a classical Internet functionality as bit transmission is implemented through a quantum protocol. This difference is clearly represented within Fig. 1 in terms of "relative placement" of the Quantum Internet stack with respect to Internet stack.

As a matter of fact, the above discussion has been conducted by neglecting the fundamental communication resource of the Quantum Internet, namely, entanglement. In fact, most of the quantum protocols require, as a prerequisite, the distribution of entangled quantum states shared between source and destination [2]. However, entanglement generation and distribution depend on a tight synchronization as well as on proper classical signaling exchanged between the entangled nodes [7]. Indeed, classical communication services are not required only for entanglement generation: they rather constitute an essential requirement for different functionalities — spread along the whole quantum protocol stack — of the Quantum Internet. In this regard, it is worthwhile to point out that (together with the pivotal example of teleportation) classical signaling is mandatory for entanglement swapping [9]. Indeed, when it comes to swapping or teleporting, signaling is not limited to neighbor nodes — namely, single-hop signaling — but they rather require end-to-end classical signaling. As a consequence, network-layer signaling among nodes belonging to different networks is required, as graphically represented in Fig. 1c.

From the above, it becomes clear that the interplay between classical Internet and Quantum Internet can not be limited to a single classical-quantum interface between a classical layer offering (or requiring) some specific services to a quantum counterpart layer. But it rather requires several interactions — likely, differing in which part (quantum or classical) behaves as communication service provider — potentially involving different layers of the classical Internet protocol stack, as

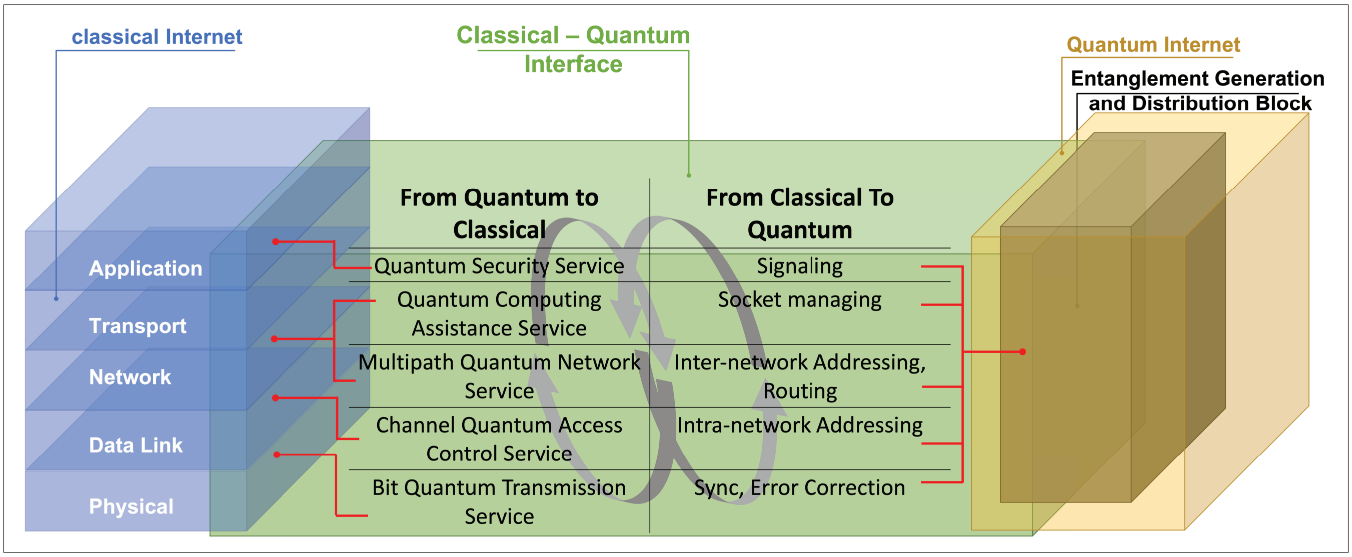


FIGURE 2. Examples of classical Internet functionalities that may benefit from, or may be enhanced by, some quantumness provided by the Quantum Internet. The classical Internet (blue stack on the left) and the Quantum Internet (yellow box on the right) interact through the classical-quantum interface (green box). The deep interplay between quantum Internet and classical Internet is not bounded to some specific layers. Conversely, it is made by a tangle of cross-layer inter-dependencies. The right part of the table represents a partial list of the main classical functionalities exploited by the Quantum Internet. The grey arrows represent the tangle of interdependencies of the services.

graphically represented in Fig. 2. In the next section, we further elaborate on this complex interaction between classical Internet and Quantum Internet, by enlarging the perspective from design challenges to opportunities.

## Augmenting Classical Internet with Quantumness

From the above discussion, it follows straightforward that a successful design of the Quantum Internet requires an accurate understanding of the interplay between classical and Quantum Internet. So far, we mainly highlighted the dependence of the Quantum Internet on classical network functionalities spread among multiple classical layers.

Differently, in the following, we discuss many examples of classical Internet functionalities that may benefit from or may be enhanced by some quantumness. To this aim, we provide the reader with different use cases for each layer of the classical protocol stack, showing how adding quantum resources to classical layers can lead to an enhancement of the classical Internet, in its crucial functionalities. Starting from the lowest layer of the classical protocol stack — namely, the physical layer — later we discuss how a paradigm shift from classical to quantum can enable a *bit quantum transmission service*, resulting in a gain of the point-to-point data rate with no counterpart in classical networks. Following that, we face with the core service of the data link layer, by showing that — by enriching the classical Internet with quantumness represented by entanglement — it is possible to solve the contention of a shared channel. Then we spread the quantum benefits to the network layer by extending the bit quantum transmission service to end-to-end communications for boosting the end-to-end throughput. Furthermore, we hit the network layer with a resource with no counterpart in classical Internet, namely, the computational power of quantum distributed computing. Finally we discuss the quantum benefits to the classical transport and application layers for boosting the performance of classical security service.

The aim of the following is to acknowledge that, by filling the classical protocol stack with quantum resources through quantum services enabled by the Quantum Internet, the classical Internet can be fundamentally enriched in its performance.

### Physical Layer

An example of classical Internet functionalities that may benefit from quantumness is bit transmission at physical layer. Specifically, in the classical Internet, the achievable data rates are upper-bounded by the physical channel capacities, with no information transmitted reliably whenever the channel exhibits zero capacity. Additionally, if the information is transmitted through a concatenation of two different channels with different capacities, the data rate is upper-bounded by the minimum of the considered capacities. Similarly, if the information is transmitted through parallel channels, the data rate is upper-bounded by the sum of the individual capacities, according to the *additivity* property of the capacities.

Surprisingly, the paradigm shift from classical to quantum — imposed by Moore's law and stimulated by Landauer: "Information is physical" — comes with a whole new dazzling phenomena that overcome the aforementioned information bottlenecks. Specifically, information can be encoded in quantum carriers that propagate through quantum communication channels. Interestingly, quantum channel capacities are not necessarily limited by the additivity: when quantum channels are used together for transmitting classical information, the overall capacity can be higher than the sum of the individual capacities characterizing the channels. This is known as the *superadditivity phenomenon* of capacities of quantum channels [10], and it has no counterpart in the classical Internet.

There is more to it. The shift of paradigm from classical to quantum does not mean only that the information carriers and their transmission links follow the rules of quantum mechanics. Recently, it has been shown that also the placement of quantum channels can be *quantized* in order to beat some transmission limitations, which constitute major fundamental obstacles to the classical physical layer [10]. Such limitations can be overcome by exploiting the *quantum switch*, a device that places quantum channels in a genuinely quantum superposition of causal orders [11]. In particular, feeding the quantum switch with two channels characterized by zero-capacities activates a non-vanishing capacity, by beating the classical bottleneck inequality [10]. Stemming from the above, enriching the classical physical layer with some sort of quantumness allows the classical Internet to overcome existing data rate bounds and bottlenecks. Specifically, by exploiting the quantum switch and quantum phenomena such as superadditivity, the classical Internet can be boosted through a service provided by the Quantum Internet. This service, referred to as *bit quantum transmission service* in Fig. 2, offers the capability of transmitting classical bits over noisy channel in a newly quantum way, which changes the core functionality of communication channels (namely, how the transmitted signal is affected by noise) and, correspondingly, the error correction technique at bit level. Hence, the bit quantum transmission service deeply affects the physical layer functionalities, and the ultimate result is the possibility of a remarkable enhancement of the transmission rates in the classical Internet.

## Data Link Layer

The benefits arising from the interplay between the classical Internet and the Quantum Internet are not limited to the classical physical layer functionalities. Quantumness — specifically, entanglement — may offer further benefits when exploited at the data link layer of the classical Internet.

More into details, within the classical Internet framework, communication resources such as channels are not reserved to a specific node. Conversely, they are likely shared among a set of nodes. For solving the access to such a shared resource with a distributed approach, internet devices mainly adopt carrier-sense multiple access (CSMA) protocols, and/or its variations. However, such protocols are highly affected by interference and collisions. Hence, the main data link layer functionality has never been efficiently solved.

Surprisingly, entanglement natively provides a distributed, collision-free strategy for the access to a shared classical communication resource. More into details, among the entangled states there exists a specific class of multipartite entangled states, referred to as W states, exhibiting the ability of fairly and randomly electing a leader among a set of nodes.

Specifically, the aforementioned unique ability of W states — coupled with the maximally-connected feature [7] of GHZ states — has been exploited for jointly solving the access and the subsequent distillation of an EPR pair from a multiparty entangled state shared among the network nodes. This protocol, referred to as *entanglement access control* protocol [12], can be easily adapted — by down-scaling its complexity — for the contention resolution of a classical communication channel. More into details, let us consider a set of *n* nodes, each sharing a qubit being entangled in an *n*-qubit W state, that must coordinate each other to access a classical communication channel. Each of the involved nodes simply performs a local measurement of its W-state qubit. Accordingly [12], only one node of the set observes the outcome 1, whereas the remaining nodes observe the outcome 0. Crucially, each node can observe the outcome 1 with the same probability.

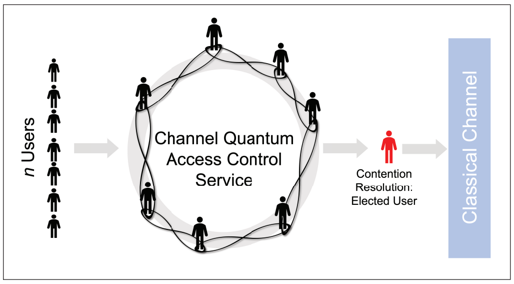


FIGURE 3. Pictorial representation of the contention resolution functionality enabled by the *channel quantum access control service*. The black men-alike icons represent the users aiming at accessing a shared classical channel, that is, the contender nodes. Through the classical-quantum interface, the *channel quantum access control service* exploits entanglement (black circular lines) for deterministically granting to only one user the access to the classical channel.

The aforementioned procedure, pictorially represented in Fig. 3, solves the contention problem within the classical Internet without the need of classical signaling or any form of subsequent coordination among the involved nodes. Indeed, the measurement outcome 1 corresponds to the node allowed to use the communication resource, namely, only the elected leader can transmit on the shared channel. Differently, by observing the outcome 0, the remaining nodes become aware of the unavailability of the channel and are not allowed to transmit. Hence, by enriching the classical nodes with quantum resources, namely, entangled qubits, with a single operation, that is, a local measurement, the resource contention is solved.

Correspondingly, the interplay between classical Internet and the Quantum Internet enriches the former. Remarkably, this strategy is not affected by interference and it is robust with the respect to the hidden node problem. A side result worthwhile to mention is the privacy of the leader identity; indeed, among the set of nodes, only the elected leader is aware of having won the resource access.

The *channel quantum access control* described above and depicted in Fig. 2, entails several interaction between the classical network protocol stack and the Quantum Internet protocol stack. Clearly, it interacts with the classical data link layer. Furthermore, it relies on some sort of quantum physical connectivity for entanglement generation and distribution. Finally, it also exploits the classical physical layer, at the very least for the actual access to the channel.

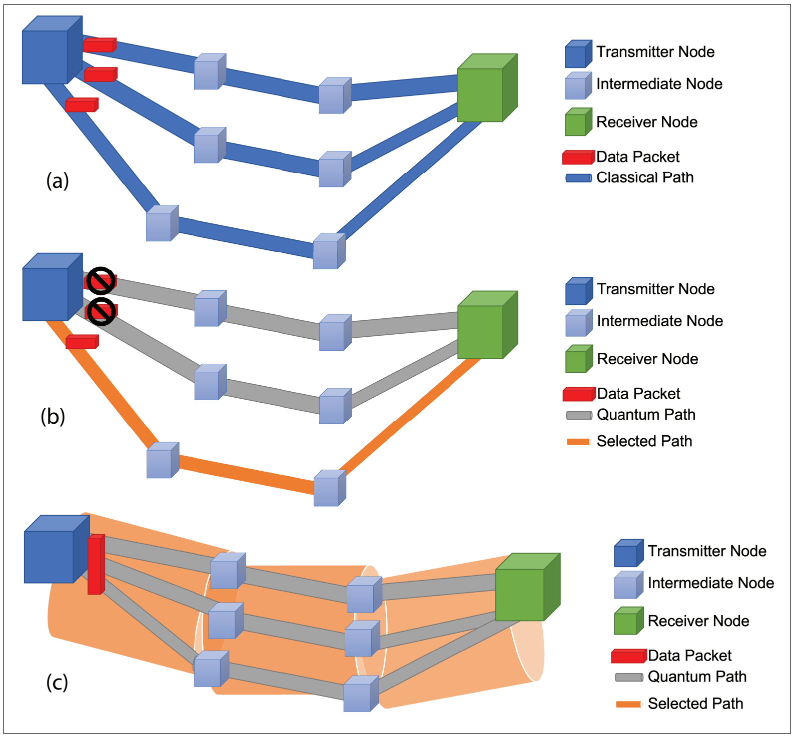


FIGURE 4. A pictorial representation of the concept of coherent multipath in quantum routing: a) Classical multipath routing. Multiple copies of the same data packet (red blocks) are forwarded through different classical paths (blue) and transmitted to the receiver; b) Quantum singlepath routing. Due to the no-cloning theorem, quantum information cannot be copied and sent through all the possible paths. Hence, a single path (orange) must be selected; c) Quantum coherent multipath routing. A quantum superposition (orange tube) among multiple paths allows the transmission of a single packet simultaneously through them.

## Network Layer

To continue the analysis of the possibilities arising from the interplay between the classical Internet and the Quantum Internet, we now extend the discussion about quantum benefits from point-to-point to end-to-end communications.

Main functionalities of the classical network layer provide the necessary tools to transfer data packets from a source to destination belonging to different networks. Interestingly, a classical network architecture harnessing quantum effects allows one to route classical information encoded in quantum carriers through multiple quantum trajectories simultaneously, while preserving the quantum coherence of the quantum packet. Specifically, a point-to-point link that could not be used to transmit the information because of severe noise can turn into an effective communication link with this genuinely quantum tool described earlier. This in turn affects the communications among nodes belonging to different networks, which — by exploiting network layer functionalities (such as routing and forwarding) — rely on point-to-point links to deliver the packet to the destination node.

While this quantum multipath routing shares similarities with the known classical multipath routing technique, namely, fault tolerance and increased network bandwidth, it still possesses certain genuinely quantum characteristics. Indeed, *the quantum path*, or *quantum trajectory*, does not rely on the ability of duplicating the data packets and sending each redundant copy through different paths: this is an imposed limitation of no-cloning theorem of quantum information [6]. Instead, the quantum path is manifested by a quantum superposition between multiple paths that allows transmission of a single classical packet simultaneously through them. In other words, when quantum trajectories are allowed, the same packet is delivered via different sets of intermediate nodes and point-to-point links that exhibit different qualities of service. The aforementioned concept is illustrated in Fig. 4.

As a result, properly assessing the quantumness with the design of a *multipath quantum network service* would significantly assist the classical Internet to enhance the performance of the network layer through end-to-end paths with no classical counterpart. As a result, the interplay between the classical Internet and the Quantum Internet enriches the classical network layer.

Similarly to the *channel quantum access protocol*, the *multipath quantum network service* interacts with the classical network layer. From the Quantum Internet perspective, this service relies on coherent control functionalities that, in turn, depend on entanglement generation and distribution. Additionally, multipath quantum network service exploits the bit quantum transmission service in order to obtain information on quantum trajectories over point-to-point links. Accordingly and as represented in Fig. 2, the interface between the classical Internet and the Quantum Internet should act as a global interface that goes beyond the separation of concerns.

Clearly, each classical Internet node only holds a partial knowledge of the network. Hence, the input data required to process the multipath quantum network service should be gathered and distributed so to converge at a given node. Then, the node must exploit computational resources for processing such a (network) topological knowledge. However, this processing can be performed by exploiting again the Quantum Internet infrastructure through the distributed quantum computing paradigm. Indeed, the computational power of quantum computing can be used to speed-up the processing of a large amount of data, for instance routing algorithms. As a matter of fact, it is widely known that — among the network functionalities — classical routing algorithms are currently difficult to solve with classical algorithms. But quantum computing can support network layer functionalities by exploiting quantum algorithms for classical routing problems [13]. In particular, different quantum algorithms can be used to find sub-optimal solutions to routing optimization problems. Interestingly, this is achieved with reasonable computational effort at overhead threshold where classical computing fails to find good-quality solutions to the optimization problem. An example is given in [13], where quantum algorithms for several formulation of the vehicle routing problem with time windows are discussed. Such problems exhibit classical solution times that scale up exponentially with the number of decision variables. But in [13] such formulations are proposed in a form suitable for quantum algorithms, that is, the so-called quantum approximate optimization algorithms. Within these formulations, the quantum approach resulted capable of obtaining convergence and/or even optimality. In particular, such results hold for conditions — such as the number of variables or specific metric thresholds — where it can be difficult to obtain good-quality solutions with reasonable computational effort on modern classical hardware.

This framework gives birth to an additional service that the Quantum Internet can offer to the classical Internet, namely the *quantum computing assistance*. Indeed, as it happens for the multipath quantum network service, the local information available at each node and needed for processing path and routing tables could be jointly exploited for the quantum computing service by following a similar approach adopted in the distributed quantum computing paradigm.

### Upper Layers

We conclude the analysis, by considering the benefits to the upper layers of the classical internet resulting in exploiting quantumness. Specifically, within the classical Internet framework, communications are secured by adopting standard de-facto cryptography algorithms, which exploit mathematical problems intractable by classical machines. Specifically, they rely on the computational complexity of integer factorization and discrete logarithmic problems, which are vulnerable to attacks by a quantum computer. These include public-key algorithms such as RSA, ECC, Diffie-Hellman and DSA. Hence, the advent of quantum computing is jeopardizing the current classical cryptosystems.

In this scenario, embracing natively the quantumness provides a strategy to secure communications in the classical Internet, even against attacks by a quantum computer. More into details and as briefly mentioned in above, by exploiting the unconventional laws of quantum mechanics — for example, quantum measurement, quantum entanglement — QKD and QSDC protocols [14, 15] are able to generate keys for encrypting (and decrypting) a classical message.

As a result, the design of a *quantum security service* as depicted in Fig. 2 would significantly assist the classical Internet to enhance the confidentiality of its transport and application layers. Correspondingly, the interplay interplay between the classical Internet and the Quantum Internet enriches the former.

It is worthwhile to observe that, from the classical protocol stack perspective, the *quantum security service* lies between the application layer and the transport layer, since it provides keys for encrypting a classical message. From the Quantum Internet protocol stack perspective, the aforementioned service relies on different quantum functionalities. More into details, although there exist several versions of QKD protocols, the most performing ones are the ones exploiting quantum entanglement. As a consequence, the *quantum security service* requires at very least the quantum functionalities needed for the entanglement generation and distributions. These in turn require classical communications of data. Thus, also in this use case, it is evident that the interface between classical Internet and Quantum Internet should act as a global interface that goes beyond the separation of concerns.

Similarly to the *channel quantum access protocol*, the *multipath quantum network service* interacts with the classical network layer. From the Quantum Internet perspective, this service relies on coherent control functionalities that, in turn, depend on entanglement generation and distribution.

## Discussion and Conclusions

The race toward the design of the Quantum Internet is very vivid within the research community, and different abstract models have been proposed up to now, as recently surveyed in [7].

In this exciting and fast-evolving context, so far, classical Internet has been mainly envisioned as an underlying communication infrastructure, aimed at providing services to the Quantum Internet. Within this article, we substantiated a shift from this modeling, by discussing the bidirectional nature of the interplay between classical Internet and Quantum Internet. Indeed, the Quantum Internet is capable of boosting classical Internet functionalities laying at different layers of the classical protocol stack.

To this aim, we discussed different services the Quantum Internet can offer to each layer of the classical Internet protocol stack. Specifically, through several use cases, we highlighted that the interplay between classical Internet and Quantum Internet can not be limited to a single-layer classical-quantum interface between a classical layer offering (or requiring) some specific service to a quantum counterpart layer. Conversely, it rather requires several cross-layer interactions.

It must be noted, though, that several technical challenges are yet to be solved for the exploitation of the classical vs. quantum interplay. To mention some of them, we may recall that currently we are in the noisy intermediate-scale quantum devices (NISQ) era. As a consequence, fault-tolerant quantum processors are yet to be available. Furthermore, reliable and deterministic entanglement generation — as well as its distribution to remote nodes — represent still an open problem, although entanglement is the key resource to enabled the aforementioned services. Even more, entanglement generation requires tight synchronization and signaling, unlikely satisfied by the best-effort nature of current classical Internet [7].

Despite that the actual design and deployment of the aforementioned services are still facing open problems and challenges, the Quantum Internet design should account for such cross-layer bidirectional interactions. An interesting research direction toward this complex tangle of interactions could be the design of a unified classical-quantum interface [7].

In conclusion, with this work, we aimed at highlighting a different angle on the promises of the Quantum Internet to be, by fueling the debate on the effective design of the Quantum Internet. Although preliminary, this contribution is necessary, since the awareness of the complex interplay between classical Internet and Quantum Internet is pivotal in the quantum-network design choices.

The aforementioned interplay represents an undiscovered field requiring a multidisciplinary collaborative effort from different communities, ranging from communications engineering to network engineering.

## References

[1] C. Wang *et al.*, "Application Scenarios for the Quantum Internet," Internet Engineering Task Force, Internet-Draft draft-irtf-qirg-quantum-internet-use-cases-11, Apr. 2022, work in Progress.

[2] W. Kozlowski *et al.*, "Architectural Principles for a Quantum Internet," Internet Engineering Task Force, Internet-Draft draft-irtf-qirg-principles-10, 2022, work in Progress.

[3] A. S. Cacciapuoti *et al.*, "Quantum Internet: Networking Challenges in Distributed Quantum Computing," *IEEE Network*, vol. 34, no. 1, 2020, pp. 137–43.

[4] S. Pirandola and S. L. Braunstein, "Physics: Unite to Build a Quantum Internet," *Nature*, vol. 532, 2016, pp. 169–71.

[5] M. Pompili *et al.*, "Experimental Demonstration of Entanglement Delivery Using a Quantum Network Stack," arXiv preprint arXiv:2111.11332, 2021.

[6] A. S. Cacciapuoti *et al.*, "When Entanglement Meets Classical Communications: Quantum Teleportation for the Quantum Internet," *IEEE Trans. Commun.*, vol. 68, no. 6, 2020, invited paper, pp. 3808–33.

[7] J. Illiano *et al.*, "Quantum Internet Protocol Stack: A Comprehensive Survey," *Computer Networks*, 2022, p. 109,092.

[8] M. Mehic *et al.*, "Implementation of Quantum Key Distribution Network Simulation Module in the Network Simulator NS-3," *Quantum Information Processing*, vol. 16, 2017, p. 253.

[9] R. Van Meter, *Quantum Networking*, John Wiley & Sons, Ltd, 2014.

[10] S. Koudia *et al.*, "How Deep the Theory of Quantum Communications Goes: Superadditivity, Superactivation and Causal Activation," *IEEE Commun. Surveys & Tutorials*, 2022.

[11] G. Chiribella and H. Kristjánsson, "Quantum Shannon Theory With Superpositions of Trajectories," *Proc. Royal Society A*, vol. 475, no. 2225, 2019, p. 20,180,903.

[12] J. Illiano *et al.*, "Quantum Internet: From Medium Access Control to Entanglement Access Control," arXiv:2205.11923, 2022.

[13] S. Harwood et al., "Formulating and Solving Routing Problems on Quantum Computers," *IEEE Trans. Quantum Engineering*, vol. 2, 2021, pp. 1–17.

[14] Y. Cao *et al.*, "The Evolution of Quantum Key Distribution Networks: On the Road to the Qinternet," *IEEE Commun. Surveys & Tutorials*, vol. 24, no. 2, 2022, pp. 839–94.

[15] G.-L. Long *et al.*, "An Evolutionary Pathway for the Quantum Internet Relying on Secure Classical Repeaters," *IEEE Network*, vol. 36, no. 3, 2022, pp. 82–88.


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