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Principles, Protocols and Architectures

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Guest Editorial
The Quantum Internet: Principles, Protocols and Architectures

Angela Sara Cacciapuoti, *Senior Member, IEEE*, Anne Broadbent, Eleni Diamanti, Jacquiline Romero, and Stephanie Wehner

I. Introduction

THE Quantum Internet is envisioned as a global network, interconnecting heterogeneous quantum networks, able to transmit quantum information (qubits, qudits, or continuous variables) and to distribute entangled quantum states with no classical equivalent, by exploiting quantum links in synergy with classical links. The Quantum Internet is disruptive, since it is capable of supporting functionalities with no direct counterpart in classical networks, such as advanced quantum cryptographic services, blind quantum computing, and distributed quantum computing characterized by exponential increases in computing power and new forms of communication. These functionalities have the potential to fundamentally change the world in ways we cannot imagine yet.

Technology giants such as Amazon and IBM have recently joined the race towards the deployment of a quantum communication network infrastructure. The rationale is that such an infrastructure represents the only way to scale the number of qubits in a short-term time horizon, due to the current technology readiness level. Furthermore, a set of specifications are already being drafted, with several standardization efforts (including bodies such as ITU, IETF, IEEE, GSMA, and ETSI) aiming at defining architectures, interfaces, and protocols for the Quantum Internet.

There is still a long path ahead for the deployment of the Quantum Internet, which is governed by the laws of quantum mechanics. Indeed, phenomena with no counterpart in classical networks — such as entanglement, the impossibility of safely reading and copying qubits, and decoherence — impose overwhelming constraints for the network design. As a consequence, most of the protocols designed and adopted for the classical Internet cannot be reused. As an example, the Internet operates by extensively duplicating information among the different components of a network node and among different nodes. In the Quantum Internet, the no-cloning theorem forbids copying an unknown qubit. Hence, the classical strategies, e.g., data replication, adopted for ensuring the integrity of information flowing through the network are now forbidden.

From the above, it becomes evident that the Quantum Internet design requires a major paradigm shift for harnessing the peculiarities of quantum information and entanglement.

This Special Issue is aimed at collecting and catalyzing scientific results on key aspects related to the Quantum Internet design, principles, and protocols, which advance the state-of-the-art. All the submissions received demonstrated the timeliness and the importance of the topic. After a rigorous and selective two-round peer-review process, 17 high-quality papers were accepted, which are briefly presented in the following. They provided a significant step towards the collective understanding of the Quantum Internet, which is still at its early stage of conceptualization. The papers included in this issue are grouped into the following four areas: *Entanglement Distribution and Routing*, *Quantum Error Correction Techniques*, *Quantum Communication Protocols*, *Architecture and Proof of Concept*, with each paper in the subject areas summarized hereafter.

II. Entanglement Distribution and Routing

In [A1], Chen et al. propose a decentralized reliable entanglement distribution protocol (REDP) for large-scale quantum networks. REDP employs a forward-backward propagation approach for solving the path consensus among distributing entangled pairs. The authors introduce a source window strategy and an entanglement allocation strategy to assign sending windows and allocate resources for multiple requests, with the objective of ensuring a high level of fairness and efficiency from a network perspective. In [A2], Iacovelli et al. analyze the entanglement distribution process by jointly optimizing the position of the device in charge of generating the entangled states and the entanglement distribution plan. Specifically, the authors formulate a mixed-integer non-linear programming problem, and they provide an iterative optimization algorithm based on block coordinate descendent and successive convex approximation techniques. In [A3], Promponas et al. discuss the problem of allocating quantum memories to distribute entanglement according to end-to-end requests. Specifically, the authors characterize the capacity region of

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the device — referred to as the quantum switch — in charge of generating link level entanglement (LLEs) and they study how it scales with respect to the number of quantum memories and probability of successful LLEs. The authors also propose a memory allocation policy that is throughput optimal. In [A4], Liu et al. propose a theoretical framework for establishing high-fidelity entanglement in quantum repeater chains, via entanglement generation, distillation, and swapping operations. In particular, the authors derive an upper bound on optimal entanglement rate under minimum fidelity constraints, and they design a policy that achieves such a bound asymptotically. In [A5], Chen and Jia formulate and analyze the problem of entanglement purification scheduling. In particular, they developed optimal and quasi-optimal algorithms maximizing the entanglement throughput over a single hop and between two distant nodes separated by a network of quantum routers. Finally, in [A6], Mor-Ruiz and Dur focused on the scenario where multipartite entangled states are distributed and stored among the nodes and locally manipulated upon request for establishing the desired target configuration. The authors consider diverse resource states corresponding to linear chains, trees, or multi-dimensional rectangular clusters, as well as centralized topologies using bipartite or tripartite entangled states. In addition, the impact of noise on state preparation, memories, and measurements is analyzed. As a result, the paper identifies high-dimensional cluster states as favorable in large networks since they significantly enhance target state fidelity.

III. Quantum Error Correction Techniques

In [A7], Forlivesi et al. analyze topological-planar quantum codes, by focusing on the XZZX and rotated-surface codes. Specifically, the authors derive closed-form performance equations for these codes when decoded using complete decoders, such as the low-complexity MWPM-based decoder. The proposed approach provides accurate code logical error rates across a wide range of quantum channels, including depolarizing, phase-flip, and asymmetric channels. In [A8], Senthoor and Sarvepalli propose a framework based on extended Calderbank–Shor–Steane codes for designing communication efficient quantum secret sharing schemes (CE-QSS). Specifically, the authors derive a bound on communication cost for CE-QSS, and they provide a construction of CE-QSS schemes meeting this bound using the proposed framework. In [A9], Goodenough et al. consider a class of distillation protocols, that uses bilocal Clifford operations, a single round of communication, and a possible final local operation depending on the observed measurement outcomes. They find a correspondence between these distillation protocols and graph codes. By leveraging this correspondence, the authors find provably optimal distillation protocols in this class for different tasks. Entanglement distillation is further analyzed in [A10] which aims at estimating the amount of distillable entanglement. Specifically, the authors consider a resource measure, known as the reverse divergence of resources, which quantifies the minimum divergence between a target state and the set of free states. Leveraging this measure, bounds on the one-way distillable entanglement are derived.

IV. Quantum Communication Protocols

A crucial aspect of the design of entanglement-based networks is discussed in [A11], namely, the tight integration with classical networks. Specifically, in [A11], Bush et al. emphasize that such integration requires strict synchronization between the classical and quantum networks towards sub-nanosecond time-sensitive networking (TSN). The analysis reveals the limitations of traditional TSN, which is characterized by accuracy on the order of microseconds. A high-precision TSN is proposed for enhancing accuracy and resolution toward sub-nanosecond TSN gate control. In [A12], Zhao et al. propose a quaternary modulated continuous-variable quantum key distribution (CV-QKD) protocol, by using displacement receivers and adopting the post-selection scheme. The study optimizes the transmitted signal photons for different channel transmission efficiencies under system limitations, such as noises and device imperfections. The authors analyze the security of the proposed CV-QKD protocol under collective beam-splitting attacks. The secret key rate is derived for different types of displacement receivers. In [A13], Zhao et al. propose an asynchronous quantum transport protocol (AQTP) for quantum data networks to support high-speed and reliable end-to-end quantum data transmission. To enhance the protocol scalability, each quantum node in AQTP locally determines the quantum resource assignment. In addition, to increase the quantum resource utilization, AQTP processes the requests asynchronously. Finally, in [A14], Jiang et al. characterize the bipartite quantum communication capacity by leveraging von Neumann entropy. They discuss various quantum network topologies, such as chain topology and star topology. The result yields preliminary outcomes concerning quantum communication capacity across general quantum networks, shedding light on the potential of quantum networks for advanced communication protocols.

V. Architectures and Proof of Concept

In [A15], He et al. propose a hierarchical architecture for the Quantum Internet. Specifically, the study first identifies potential drawbacks of distributed architectures, such as high maintenance overhead, suboptimal entanglement distribution, and challenges in supporting optimal entanglement routing. Then, the hierarchical architecture is designed by selecting a multipartite state — namely, a W state — as main resource for such a design. Furthermore, both a W-state-based centralized entanglement preparation and distribution scheme and a centralized entanglement routing algorithm are proposed within the hierarchical architecture. In [A16], Kozlowski et al. highlighted that the lack of shared tooling and community-agreed quantum node architectures has resulted in quantum protocol implementations that are tightly coupled to their simulators. For this, they proposed a prototyping framework for designing and implementing quantum network protocols in a platform-agnostic fashion. Specifically, the authors develop QuIP, namely, a P4-based Quantum Internet Protocol prototyping framework, which decouples quantum network protocol implementation from simulation, by using

P416. The code is also publicly available. Finally, in [A17], Anis et al. propose an experimental scheme for quantum superdense coding using Bragg diffracted hyperentangled atoms. This work achieves classical information transmission through a single hyperentangled atom. This is achieved by introducing multiple quantum gates using resonant and off-resonant Bragg diffraction in cavity cavity quantum electrodynamic setup.

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Appendix: Related Articles

[A1] L. Chen et al., “REDP: Reliable entanglement distribution protocol design for large-scale quantum networks,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1723–1737, Jul. 2024.

[A2] G. Iacovelli, F. Vista, N. Cordeschi, and L. A. Grieco, “A probability-based optimization approach for entanglement distribution and source position in quantum networks,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1738–1748, Jul. 2024.

[A3] P. Promponas, V. Valls, S. Guha, and L. Tassiulas, “Maximizing entanglement rates via efficient memory management in flexible quantum switches,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1749–1762, Jul. 2024.

[A4] Z. Liu, S. Marano, and M. Z. Win, “Establishing high-fidelity entanglement in quantum repeater chains,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1763–1778, Jul. 2024.

[A5] L. Chen and Z. Jia, “On optimum entanglement purification scheduling in quantum networks,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1779–1792, Jul. 2024.

[A6] M. F. Mor-Ruiz and W. Dur, “Influence of noise in entanglement-based quantum networks,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1793–1807, Jul. 2024.

[A7] D. Forlivesi, L. Valentini, and M. Chiani, “Logical error rates of XZZX and rotated quantum surface codes,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1808–1817, Jul. 2024.

[A8] K. Senthoor and P. K. Sarvepalli, “Communication efficient quantum secret sharing via extended CSS codes,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1818–1829, Jul. 2024.

[A9] K. D. Goodenough et al., “Near-term N to K distillation protocols using graph codes,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1830–1849, Jul. 2024.

[A10] C. Zhu, C. Zhu, and X. Wang, “Estimate distillable entanglement and quantum capacity by squeezing useless entanglement,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1850–1860, Jul. 2024.

[A11] S. F. Bush, C. G. Iversen, and W. A. Challener, “Design for high-precision time-sensitive networking: Synchronization for the quantum network control plane,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1861–1870, Jul. 2024.

[A12] M. Zhao, R. Yuan, C. Feng, S. Han, and J. Cheng, “Security of coherent-state quantum key distribution using displacement receiver,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1871–1884, Jul. 2024.

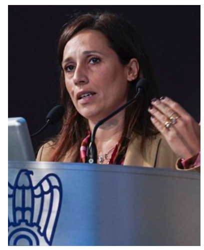
[A13] Y. Zhao, Y. Wang, E. Wang, H. Xu, L. Huang, and C. Qiao, “An asynchronous transport protocol for quantum data networks,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1885–1899, Jul. 2024.

[A14] J. Jiang, M. Luo, and S. Ma, “Quantum network capacity of entangled quantum internet,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1900–1918, Jul. 2024.

[A15] B. He, D. Zhang, S. W. Loke, S. Lin, and L. Lu, “Building a hierarchical architecture and communication model for the quantum internet,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1919–1935, Jul. 2024.

[A16] W. Kozlowski, F. A. Kuipers, R. Smets, and B. Turkovic, “QUIP: A P4 quantum internet protocol prototyping framework,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1936–1949, Jul. 2024.

[A17] S. M. A. Anis, S. Al-Kuwari, and T. A. Malik, “Superdense coding using Bragg diffracted hyperentangled atoms,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 7, pp. 1950–1959, Jul. 2024.



Angela Sara Cacciapuoti (Senior Member, IEEE) is currently a Professor with the University of Naples Federico II, Italy. Since July 2018, she has been holding the National Habilitation as a Full Professor in telecommunications engineering. Her current research interests include quantum communications, quantum networks, and quantum information processing. Her work has appeared in first-tier IEEE journals and she has received different awards and recognition, including the 2022 IEEE ComSoc Best Tutorial Paper Award, the 2022 IEEE WICE Outstanding Achievement Award, the 2021 N2Women: Stars in Networking and Communications, and the 2017 Exemplary Editor Award of IEEE Communications Letters. In 2023, she also received the IEEE ComSoc Distinguished Service Award for EMEA. From 2020 to 2021, she was the Vice-Chair of the IEEE ComSoc Women in Communications Engineering (WICE). Previously, she has been appointed as the Publicity Chair of WICE. From 2016 to 2019, she was an appointed member of the IEEE ComSoc Young Professionals Standing Committee. From 2017 to 2020, she was the Treasurer of the IEEE Women in Engineering (WIE) Affinity Group of the IEEE Italy Section. For the Quantum Internet topics, she is an IEEE ComSoc Distinguished Lecturer. She serves as the Editor at Large for IEEE Transactions on Communications and an Editor/Associate Editor for IEEE Communications Surveys and Tutorials, IEEE Transactions on Quantum Engineering, and *IEEE Network*.

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Stephanie Wehner is currently an Antoni van Leeuwenhoek Professor in quantum information with Delft University of Technology and the Director of European Quantum Internet Alliance. Her goal is to understand the world of small particles and the laws of quantum mechanics in order to construct better networks and computers. Quantum bits behave quite differently than classical bits and allow us to solve tasks that are provably impossible for any classical device. She has worked extensively in quantum cryptography and communication, and together with the Quantum Internet Alliance she is working on realizing a large-scale quantum network. She has written numerous scientific articles in both physics and computer science. From 2010 to 2014, her research group was located with the Centre for Quantum Technologies, National University of Singapore, where she was an Assistant Professor and later an Associate Professor. Previously, she was a Post-Doctoral Researcher with the Group of John Preskill, California Institute of Technology. In a former life, she was a professional hacker in the industry. She is a member of the Royal Dutch Academy of Arts and Sciences, has won the KNAW Ammodo Award, and is one of the founders of QCRYPT, which has become the largest conference in quantum cryptography.