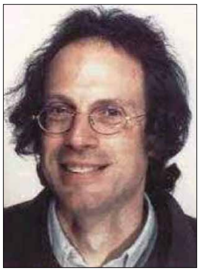
Quantum Communications and Networking: Series I

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Quantum communication researchers have achieved significant progress during the recent decades and quantum networking has shown promise in terms of improving the overall functional benefits of the Internet and enabling applications with no counterpart in the classical world. It is a breakthrough technology towards the unimaginable future. In a quantum network, the source and destination may be connected by quantum repeaters/routers for facilitating qubit transmissions. The quantum network of the future is envisaged to pervade the entire globe, relying on terrestrial components, satellites, airplanes, ships and other vehicles. It is anticipated that it will support nearly unconditional security, super-computing power, large network capacity–even at high velocity–and privacy.

In the current era, quantum networks are similar to the early stage of the classical Internet in the 1970s. However, they exhibit fundamentally different features, obeying the uncertainty principle, the non-orthogonal indistinguishable theorem, the quantum non-cloning theorem, entanglement and superposition. These constraining features make the design of quantum networks a challenging task. Circumventing this task, we successfully organized IEEE Network special issue on Quantum Communications and Networking (September Issue, 2022). Following that issue, we continue to organize series on this topic, and this is series 1 issue. For this issue, of the 48 submitted papers, 10 were selected. The selected articles cover the topics including the integration with 6G and beyond (6GB) network, architecture and application, and entanglement distribution, routing, management, and error correction.

Besides the co-existence with the classical Internet, the integration between quantum communication and networking (QCN) with the emerging 6GB network including space-air-ground network is crucial for the design at the early stage. In [A1], Chang et al. take into consideration the movement of satellites and inter-satellite links and proposes a novel concept of logical graphs for solving the entanglement distribution problem in such a dynamic physical network. In [A2], Prados-Garzon et al. highlight how 6GB can support various quantum scenarios, proposes a software-defined programmable architecture for integrating quantum networks into 6GB, and presents a proof-of-principle that underscores the importance of ultra-reliable low-latency connectivity for QApps, with a focus on a blind quantum computing application. In [A3], Wang et al. proposes a quantum-empowered federated learning framework integrating variational quantum algorithms (VQA) and quantum relays in space-air-ground integrated networks, and presents a case study to validate their proposed VQA-based local training and quantum relaying model transmission.

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For the QCN architecture and applications, the extensive research and in-depth thinking are required. In [A4], Cacciapuoti et al. argues the key drawbacks arising by adopting classical, location-aware addressing, proposes the novel quantum addressing functionality for the quantum Internet, and further employs a toy-model of a quantum addressing scheme to overcome the limitations of classical addressing schemes. In [A5], Khalid et al. identifies the key architectural and operational differences between quantum internet and functional noisy intermediate-scale quantum (NISQ) networks, proposes figures-of-merit for quantum network quality on account of their computing, communication, and sensing performance metrics, and comparatively analyzes the overtime performance improvement in noisy and perfect near-term quantum networks. In [A6], Chehimi et al. provides the comprehensive investigation of the challenges and opportunities of quantum federated learning (QFL), examines the key components of QFL, and develops novel solutions and articulate promising research directions.

The enabling technologies, entanglement distribution, routing, management, and error correction, are indispensable for the research advancement of QCN. In [A7], Xiao et al. designs a connectionless remote entanglement distribution protocol to let Source-Destination (S-D) pairs compete for entanglement resources simultaneously, where a fair request scheduling algorithm and a fast scheduling trigger mechanism are proposed to reduce the waiting time and the delay of E2E entanglement connection establishment, respectively. In [A8], Shi and Malaney designs a combined circuit for quantum routing and quantum error correction, and carries out an implementation of such a circuit on a noisy real-world quantum device. In [A9], Zeng et al. considers two entanglement-swapping methods, Bell state measurement (BSM) entanglement-swapping and Greenberger-Horne-Zeilinger (GHZ) measurement entanglement-swapping, and proposes two efficient entanglement management protocols which respectively make use of the unique properties of BSM and GHZ. In [A10], Hu et al. proposes a novel one-way communication procedure allowing for partitioning of individual surface codes and simultaneous transmission via multiple paths, and further presents a routing protocol which optimizes resource utilization of the network while maintaining a fidelity threshold for each communication.

This special issue has successfully addressed important topics in QCN from the aspects of integration with 6GB, architecture and applications, and fundamental entanglement technologies.

Besides these studies, there are still many open challenges in this area, which will be further addressed in IEEE Network Series 2 on QCN.

We would like to take this opportunity to thank all the reviewers for their great support in reviewing these manuscripts. We also thank the Editor-in-Chief, Dr. Chonggang Wang, for his supportive guidance during the entire process.

Appendix: Related Articles

[A1] A. Chang et al., “Entanglement distribution in satellite-based dynamic quantum networks,” *IEEE Netw.*, vol. 38, no. 1, pp. 79–86, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3321706.

[A2] J. Prados-Garzon et al., “Deterministic 6GB-assisted quantum networks with slicing support: A new 6GB use case,” *IEEE Netw.*, vol. 38, no. 1, pp. 87–95, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3328587.

[A3] T. Wang et al., “Quantum-empowered federated learning in space-air-ground integrated networks,” *IEEE Netw.*, vol. 38, no. 1, pp. 96–103, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3318083.

[A4] A. S. Cacciapuoti, J. Illiano, and M. Caleffi, “Quantum Internet addressing,” *IEEE Netw.*, vol. 38, no. 1, pp. 104–111, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3328393.

[A5] U. Khalid et al., “Quantum network engineering in the NISQ age: Principles, missions, and challenges,” *IEEE Netw.*, vol. 38, no. 1, pp. 112–123, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3328892.

[A6] M. Chehimi et al., “Foundations of quantum federated learning over classical and quantum networks,” *IEEE Netw.*, vol. 38, no. 1, pp. 124–130, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3327365.

[A7] Z. Xiao et al., “A connectionless entanglement distribution protocol design in quantum networks,” *IEEE Netw.*, vol. 38, no. 1, pp. 131–139, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3321044.

[A8] W. Shi and R. Malaney, “Quantum routing for emerging quantum networks,” *IEEE Netw.*, vol. 38, no. 1, pp. 140–146, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3317821.

[A9] Y. Zeng et al., “Entanglement management through swapping over quantum internets,” *IEEE Netw.*, vol. 38, no. 1, pp. 147–154, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3327232.

[A10] T. Hu, J. Wu, and Q. Li, “SurfaceNet: fault-tolerant quantum networks with surface codes,” *IEEE Netw.*, vol. 38, no. 1, pp. 155–162, Jan./Feb. 2024, doi: 10.1109/MNET.2023.3326291.

Biographies

Ruidong Li (liruidong@ieee.org) received the Ph.D. degree in computer science from the University of Tsukuba in 2008. He is an Associate Professor with Kanazawa University, Japan. His research interests include quantum networks, metaverse, and future networks. He was a recipient of the Best Paper Awards for IEEE ICC 2022 and IWCMC 2022. He serves as the Chair for IEEE Internet Technical Committee (ITC), and served as the Chairs for several conferences, such as the General Chairs for IEEE HealthCom 2024, MSN 2021, CPSCom 2021, the Area TPC Chair for INFOCOM 2023, the TPC Chairs for ICNC 2024, IEEE MetaCom 2023, HotICN 2022, IWQoS 2021, and IEEE MSN 2020.

Prineha Narang received the M.S. and Ph.D. degrees in applied physics from Caltech. She is currently a Professor and the Howard Reiss Chair in physical sciences with UCLA. Prior to moving to UCLA, she was an Assistant Professor of computational materials science at Harvard University. Before starting on the Harvard Faculty in 2017, she was an Environmental Fellow at HUCE, and worked as a Research Scholar in condensed matter theory at the Department of Physics, MIT. Her research interests include quantum information science including quantum algorithms for quantum computation, simulation and emulation directions in quantum network science, and quantum repeaters. Her work has been recognized by many awards and special designations, including the 2023 Maria Goeppert Mayer Award from the American Physical Society, the 2022 Outstanding Early Career Investigator Award from the Materials Research Society, the Mildred Dresselhaus Prize, the Bessel Research Award from the Alexander von Humboldt Foundation, a Max Planck Award from the Max Planck Society, and the IUPAP Young Scientist Prize in Computational Physics all in 2021, an NSF CAREER Award in 2020, being named a Moore Inventor Fellow by the Gordon and Betty Moore Foundation, the CIFAR Azrieli Global Scholar by the Canadian Institute for Advanced Research, and a Top Innovator by MIT Tech Review (MIT TR35).

Melchior Aelmans is a Chief Architect with Juniper Networks, where he has been working with many operators on the design and evolution of their networks. He has 20 years of experience in various operations and engineering positions with Cloud Providers, Data Centers, and Service Providers. His research interests include routing protocols, routing security, internet routing, and Cloud and Data Center architectures. He actively participates in IETF and RIPE. He is a member of the NANOG Program Committee, the Internet Society Organization Member Advisory Council Vice Chairperson, and a Board Member at NLNOG Foundation.

Peter Mueller is a Research Staff Member with IBM Research, Rüschlikon, Switzerland. He has authored or coauthored over 100 papers, two books, has been granted ten patents and served as a Guest Editor for many special issue publications. His research interests include distributed computing systems architecture, center storage security and reliability, and quantum communications. He is a Founding Member and was the Chair of the IEEE ComSoc Communications and Information Systems Security Technical Committee. He is a Senior Member of the Industrial and Applied Mathematics Society, the Electrochemical Society, and the Swiss Physical Society.

Guilu Long received the B.S. degree in 1982 and the Ph.D. degree in 1987. He is currently a Professor with Tsinghua University, China, and the Vice-President with the Beijing Academy of Quantum Information Sciences. He has published more than 400 refereed papers and received many awards. His research interest includes quantum communications and computing, and optical microcavity. He is an IoP and APS Fellow. He served as the President for AAPPS (2017–2019) and the Vice-Chair for C13 of IUPAP (2015–2017).