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Quantum Teleportation: Current Trends, Technological Innovations, and Prospects Towards the Quantum Internet

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ABSTRACT

Study This aim study development latest in teleportation quantum based on review of 10 articles scientific international 2024–2025, with focus on approach theory, experiment, and potential application. Methods used is studies literature qualitative. Article chosen in a way purposive from journal reputable and analyzed use technique analysis content as well as comparative thematic based on system quantum, entanglement, and fidelity Teleportation succeed implemented on various platforms such as photons, ion-traps, silicon spins, and quantum dots, with fidelity reach more from 94%. Hybrid systems and approaches correct error show performance high. Simulation also strengthens direction integration with device physical. Study This give synthesis latest teleportation quantum cross -platform and highlights trend new such as logical qubit teleportation, chip-to-chip transfer, and integration nanophotonics as enhancer fidelity and efficiency.

INTRODUCTION

The recent development of quantum technology has created various breakthroughs in communication and information delivery, one of which is the phenomenon of quantum teleportation. Quantum teleportation allows the transfer of the quantum state of one system to another without physically moving particles, but rather by utilizing the phenomena of quantum entanglement, superposition, and Bell measurements. This technology is a key pillar in the development of the quantum internet and distributed computing (Marques et al., 2024; Negnevitsky et al., 2025).

The phenomenon of entanglement, as described in the EPR experiment and formalized through Bell theory, is a state where two particles cannot be described independently of each other. When one particle is measured, its partner particle immediately enters an exactly matching state, regardless of the distance separating them (Ruo-Berchera et al., 2024; Wang et al., 2024). In entanglement, the entangled particle is combined with its entangled partner, and then a Bell measurement is performed on the first two particles. The measurement results are then transmitted classically to a receiver to apply the appropriate unitary transformation to the third particle, which reconstructs the initial state (Bennett et al., 1993; Lingaraju et al., 2024).

This concept has been successfully tested in various platforms: using a 30-km public optical fiber (Lingaraju et al., 2024), on logic qubits with real-time error correction (Marques et al., 2024), and on multi-qubit gates such as Toffoli (Wang et al., 2024). Research by Ryu & Ryu (2024) even demonstrated the transmission of quantum transmission protocols on silicon-based spin qubits, marking advances in hardware integration. On the other hand, a hybrid entanglement approach (polarization and

frequency) has demonstrated the ability to overcome environmental disturbances and improve transmission fidelity (Ruo-Berchera et al., 2024).
Furthermore, recent studies have explored transmission between ion-trap modules via photonic connections (Negnevitsky et al., 2025), chip-to-chip teleportation in silicon platforms (Kim et al., 2024), and state transfer to erbium ion-based memories (Zopf et al., 2025), as the basis for quantum repeaters. Experiments with non-uniform emitters, such as different quantum dots, have also been successfully conducted in hybrid networks (Chen et al., 2024). In fact, an approach using nonlinear nanophotonics has successfully increased transmission efficiency by up to 94% (Gong et al., 2025).
These studies demonstrate that theoretical approaches to transmission not only provide fundamental proof of the principles of transmission mechanics but also provide practical guidance for the realization of global transmission networks, with key challenges being decoherence, channel efficiency, and the uniformity of the physical systems used.

RESEARCH METHOD

This research method consists of three main components: participants (reviewed articles), instruments and procedures, and data analysis techniques. This research method is qualitative with a literature study approach. This research method is designed to review articles published in reputable journals between 2024 and 2025. This research method focuses on searching, selecting, reviewing, and comparing relevant articles. This research method is used to uncover variations in theoretical approaches, experimental models, and application results of quantum teleportation. This research method involves searching data through international journal databases such as Nature, Science, Optica, Physical Review Letters, and arXiv.
The research sample consists of 10 international scientific articles purposively selected based on the following criteria: (1) published in Q1-indexed journals or arXiv preprints on highly relevant topics; (2) focused on quantum teleportation, whether theoretical, experimental, or simulated; (3) published between 2024 and 2025; and (4) written in English and available for full online access. This research sample represents a variety of approaches: teleportation in optical fiber, chip-to-chip photonic teleportation, ion trap systems, heterogeneous quantum dots, and teleportation to solid-state quantum memory.
The research instrument consisted of a journal review guide developed based on the structure of a scientific literature review: identifying the research background, theoretical approach, experimental or simulation methodology, main results, and research challenges and prospects. The procedure began with a literature search through official journal pages, followed by selection based on abstracts and thematic focus, followed by in-depth reading and systematic recording of article content. The review procedure was conducted manually, using comparison tables and content annotations to synthesize the results.
The data were analyzed using content analysis and thematic comparative analysis techniques, identifying similarities and differences between articles in terms of experimental approach, type of quantum system used (photon, ion, spin), performance parameters (e.g., fidelity, teleportation distance), and direction of technology development. The analysis was conducted descriptively and qualitatively to assess the

scientific and applied contributions of each article. This analysis was also used to synthesize the results in a narrative form that links the phenomenon of quantum teleportation to the fundamental theory of quantum mechanics and future applications.

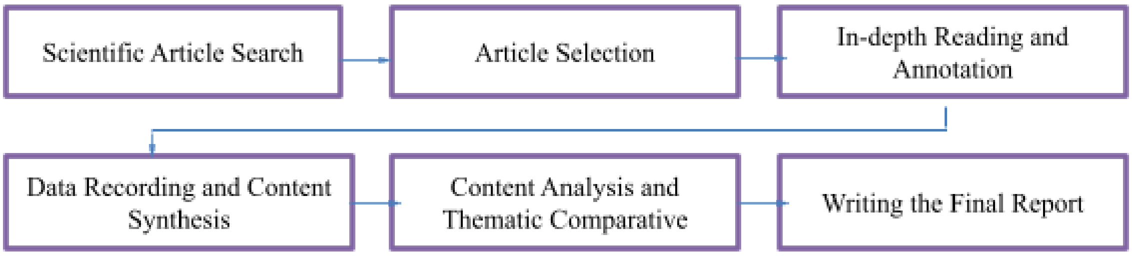

Figure 1. Research flow diagram

RESULTS AND DISCUSSION

Teleportation systems and infrastructure

Studies have shown that quantum teleportation has been successfully implemented across various types of physical infrastructure, representing significant progress toward realizing global quantum networks. One key achievement was demonstrated by Lingaraju et al. (2024), who successfully performed quantum teleportation over a 30-km stretch of public fiber optic network. This achievement was remarkable because the system was able to perform the teleportation without disrupting high-speed classical data communications running concurrently over the same channel.

Furthermore, Kim et al. (2024) demonstrated that teleportation between photonic chips over a distance of 12.3 km over optical fiber, marking progress in the integration of miniaturized quantum systems compatible with existing optical communication infrastructure. Meanwhile, a modular approach connecting two ion-trap quantum processors via a photonic link was also successfully implemented by Negnevitsky et al. (2025). This configuration demonstrates the potential of a teleportation-based distributed quantum computing architecture.

In a more diverse experimental environment, Chen et al. (2024) demonstrated that teleportation can be achieved in a hybrid network combining optical fiber and free-space paths, even when using two different quantum dot emitters. The achieved teleportation distance was about 270 meters, and their success demonstrated that emitter systems do not have to be identical to be used in a practical teleportation network.

Media and qubit types

Various physical media have been used in quantum teleportation implementations, reflecting the approach's flexibility and potential for cross-platform applications. Photonic systems are one of the most commonly used media due to their advantages in speed and compatibility with optical networks. Lingaraju et al. (2024) and Gong et al. (2025) each successfully teleported qubits using photons as quantum information carriers. These systems enabled fast, long-distance transmission and could be integrated with classical communication channels.

Furthermore, trapped ions were used by Negnevitsky et al. (2025) in a modular, intermodular quantum teleportation system. Ions offer advantages in stability and control precision, making them strong candidates for large-scale quantum computing architectures. In a different category, Ryu & Ryu (2024) simulated teleportation using electron spins in silicon-based quantum dots, demonstrating the potential for integrating teleportation into a more stable solid-state platform compatible with CMOS technology.

The use of quantum dots as emitters in a teleportation network was also successfully demonstrated by Chen et al. (2024), even though the two emitters have non-identical properties. This demonstrates that systems with different characteristics can still be used in flexible teleportation schemes. Meanwhile, Zopf et al. (2025) successfully transferred the quantum state of a telecommunications wavelength photon to a solid-state quantum memory based on erbium ions, opening up significant opportunities for the realization of quantum repeaters in long-range quantum networks.

Specifically, Marques et al. (2024) demonstrated the teleportation of logical qubits, which are quantum information encoded in multiple physical qubits and equipped with error correction. Using an ion-trap platform and a real-time correction protocol, this experiment achieved high teleportation fidelity while demonstrating the technology's readiness for fault-tolerant quantum computing.

Experimental technology and entanglement

Progress in quantum teleportation is greatly influenced by the development of experimental technology that supports the generation, manipulation, and measurement of entangled states. One innovative approach was demonstrated by Ruo-Berchera et al. (2024), who used hybrid entanglement between polarization and frequency degrees of freedom. This approach not only allows the system to operate in two quantum domains simultaneously, but has also been shown to improve teleportation fidelity even in noisy environments. This indicates that hybrid entanglement could be a practical solution for teleportation systems outside of the ideal laboratory.

Furthermore, teleportation approaches are not limited to the transfer of single quantum states, but have expanded to the transmission of quantum logic operations. Wang et al. (2024) successfully demonstrated the teleportation of multiqubit Toffoli gates using a linear optical system. Although complexity increases with the number of qubits, the achieved fidelity approached the theoretical minimum required for successful logic gate teleportation, demonstrating the feasibility of implementing teleportation not only for quantum data but also for logic instructions.

Another important breakthrough came from the integration of nonlinear optics in nanophotonic systems, as demonstrated by Gong et al. (2025). By utilizing a sum-frequency generation process in an indium-gallium-phosphide platform, they successfully increased teleportation efficiency and fidelity to 94%, significantly higher than conventional approaches. This technology enables the integration of Bell-state analysis functions directly on-chip, opening the possibility of designing compact and efficient teleportation devices ready for implementation on a real-world quantum system scale.

These findings demonstrate that the success of quantum teleportation depends not only on theoretical concepts but also heavily on the ability to engineer stable, controllable entanglement systems compatible with current optoelectronic technologies.

Fidelity and performance

Fidelity is a key indicator in assessing the success of a quantum teleportation process, as it reflects how accurately the transferred quantum state can be reconstructed in the receiving system. Studies have shown that teleportation fidelity varies significantly, depending on the experimental approach, the type of quantum system, and the test environment. Multiqubit logic gate teleportation, such as that conducted by Wang et al. (2024), achieved a fidelity of approximately 70%, slightly above the minimum threshold required to distinguish quantum teleportation from classical processes. This achievement demonstrates that despite the increased complexity of multiqubit systems, fidelity can still be maintained at a functional level.

Conversely, the highest fidelity was achieved by Gong et al. (2025) using a nonlinear nanophotonic approach, reaching over 94%. This value marks a significant improvement over previous teleportation systems, particularly in terms of the efficiency and accuracy of quantum information transfer. Furthermore, the hybrid entanglement approach implemented by Ruo-Berchera et al. (2024) and teleportation to solid-state ion quantum memory by Zopf et al. (2025) also demonstrated fidelity exceeding the classical fidelity limit (~66.7%), statistically distinguishing quantum teleportation from mere estimation and copying.

In general, these results indicate that increased fidelity can be achieved through two main pathways: optimizing entanglement technology and applying correction or stabilization techniques to interference sources. Therefore, fidelity is an indicator that not only measures experimental success but also illustrates the readiness of teleportation systems for application in real-world scenarios such as quantum communication and the quantum internet.

System simulation and evaluation

In addition to experimental approaches, this study also identified important contributions from quantum teleportation system simulations, particularly in the context of protocol development and validation on physical platforms still in the design or early integration stages. One notable study in this context is the work by Ryu & Ryu (2024), who conducted teleportation simulations using silicon quantum dot-based spin-qubits.

Using a simulation approach, this study evaluated the effects of environmental noise on teleportation success and assessed the efficiency of various control and error correction strategies. The simulation results showed that teleportation fidelity can be maintained within a specific operational range, depending on control parameters such as pulse duration, thermal noise, and magnetic field uniformity. These findings provide important insights into designing silicon-based teleportation devices integrated with conventional electronic systems.

Simulation also plays a crucial role in mapping the performance limits of teleportation systems without the need for expensive and complex live experiments. Numerical evaluation of the fidelity, efficiency, and robustness of teleportation protocols allows researchers to identify optimal parameters before physical implementation.

Thus, quantum simulations serve as a bridge between theory and practice in the development of quantum teleportation. Studies such as those conducted by Ryu & Ryu

(2024) emphasize that validation through simulation is crucial to support the development of teleportation systems that are efficient, scalable, and compatible with future quantum technology infrastructure.

RESULTS AND DISCUSSION

The study's findings demonstrate that quantum teleportation has advanced significantly, both in theory and in its technological implementation. A comparison of the ten articles reviewed reveals a variety of approaches based on physical platforms, entanglement methods, and achieved fidelity. This analysis also highlights how each approach addresses the practical challenges of realizing quantum teleportation for future information networks. In terms of physical platforms, quantum teleportation has been successfully implemented in a wide variety of systems: from photonics (Lingaraju et al., 2024; Gong et al., 2025), ion traps (Marques et al., 2024; Negnevitsky et al., 2025), to silicon-based spin qubits (Ryu & Ryu, 2024). Photonic platforms demonstrate advantages in distance and speed, while ionic systems are more stable for precision computing and logic teleportation. Quantum dots and solid-state ion memories expand the application range to quantum repeaters and hybrid quantum networks (Chen et al., 2024; Zopf et al., 2025).

Differences are also evident in the entanglement technology used. Ruo-Berchera et al. (2024) successfully used hybrid entanglement (frequency and polarization) to improve fidelity under noisy conditions. Meanwhile, Gong et al. (2025) integrated nonlinear nanophotonics to efficiently analyze Bell states, increasing fidelity to 94%. This approach underscores the importance of innovation in entanglement system engineering to achieve reliable teleportation under non-ideal conditions. In terms of fidelity and performance, studies show a wide range of values. The highest fidelity was achieved by Gong et al. (2025), while logic gate teleportation, such as that of Toffoli by Wang et al. (2024), yielded lower fidelity (~70%), although still above the classical limit. These differences demonstrate that the quantum complexity of operations also directly impacts teleportation performance and indicate the need for error correction and engineering optimization in multi-qubit systems.

In the context of system simulation and validation, Ryu & Ryu (2024) demonstrated that quantum teleportation can be effectively analyzed using numerical simulations, specifically to assess the impact of noise and protocol efficiency under specific experimental conditions. These simulation results provide an important roadmap for the development of solid-state material-based teleportation systems ready for integration with conventional electronic devices. Overall, this discussion demonstrates that while various approaches have their own strengths and limitations, they are all moving toward a convergence of more practical, scalable, and interference-resistant quantum teleportation systems. Quantum teleportation is no longer just a laboratory experiment, but is approaching realization as part of the quantum internet architecture, with a wide choice of platforms and protocols to suit application needs.

CONCLUSION

Quantum teleportation has been successfully implemented in various physical systems using various entanglement approaches, including photons, ions, spins, and quantum memory. Teleportation fidelity reached up to 94%, demonstrating readiness for practical applications in the quantum internet. This finding confirms that quantum teleportation is no longer merely a theoretical concept, but rather a crucial foundation for the development of ultra-secure quantum communication and distributed computing. Some experiments are still limited to the laboratory scale and rely on entanglement stability and system fidelity under non-ideal conditions. Future research should focus on cross-platform integration, enhanced error correction, and the development of high-efficiency long-distance teleportation in real-world environments.

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