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# Foregoing quantum chaos to achieve high-fidelity quantum state transfer

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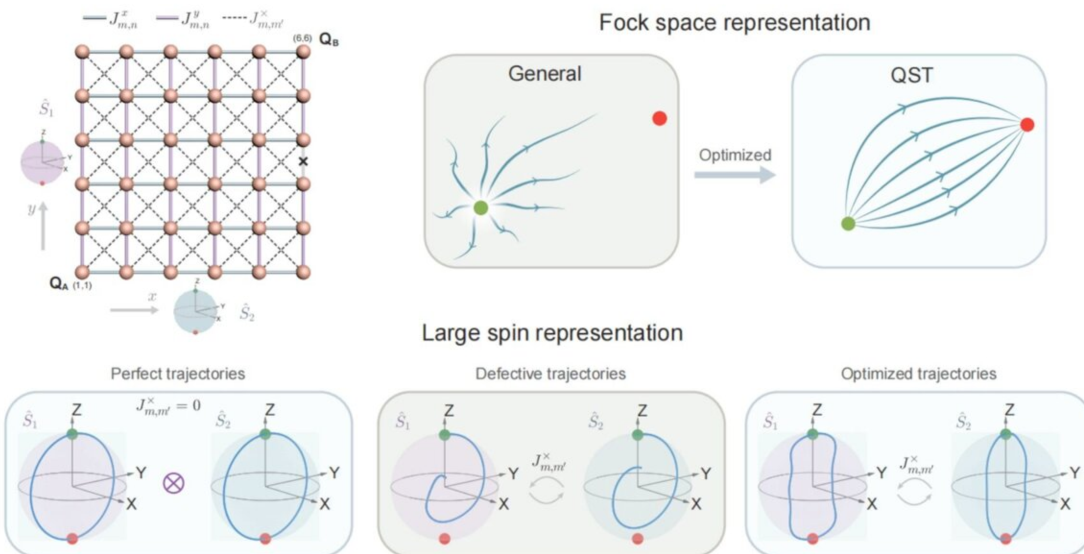


Quantum state transfer (QST) performed in a 6x6 qubit lattice. Credit: Liang Xiang et al. 10.1038/s41467-024-48791-3.

An international team of scientists from China and the U.S. has developed a scalable protocol for high-fidelity quantum state transfer (QST) in a 36-qubit superconducting quantum circuit.

The researchers focused on optimizing qubit coupling to overcome quantum chaos in 2D quantum networks.

As quantum computing systems grow and focus on using more solid-state architectures, so does the need for high-fidelity, short-range quantum communication. In particular, superconducting qubits are favored as they offer more scalability and practicality in building 2D quantum networks.

The more traditional approaches for QST in 2D networks face challenges with the accumulation of errors. Therefore, the researchers propose an alternate approach focused on optimizing qubit coupling.

Phys.org spoke to some of the researchers behind the *Nature Communications* study to understand more about their work.

Co-authors Prof. Qiujiang Guo and Postdoctoral fellow Dr. Liang Xiang from Zhejiang University, China, explained their motivation behind the research: "Technically, short-range communication between different parts of the solid-state quantum system is demanding for both scaling up quantum processors and efficient implementation of quantum algorithms.

"On the other hand, programmable superconducting processors are the natural choice to act as the medium for quantum information transfer. Yet experimental demonstration of quantum state transfer is largely confined to small chains with few qubits," they said.

## Understanding QST

"In the quest to build a full-fledged quantum computer, one aims to reproduce the capabilities of its classical counterpart, namely, processing, storage, and communication," said Prof. Richard T. Scalettar from the University of California, Davis, co-author of the study.

"Our research focused on the latter, tackling how to efficiently transport a quantum state between two ends of a quantum device," added Prof. Rubem Mondaini from the University of Houston, also a co-author of the study.

QST is the process of transferring the state of a quantum system from one qubit to another. It is the foundation of all quantum information and communication systems.

When referring to the fidelity of QST, it means how accurately the transfer of information happens without errors or decoherence. One of the main challenges is minimizing errors due to environmental interactions.

Previous research has demonstrated QST for ideal single-particle systems.

"What this original approach fails is to account for the fact that actual quantum devices are far from perfect, and ideal cases without defects or unwanted couplings are unlike what is possibly seen in a real-life quantum device," explained Prof. Mondaini.

## Qubit coupling and quantum chaos

For quantum communication, one of the key elements is qubit coupling. This is an interaction between qubits where the state of one qubit influences the state of another. It is typically mediated by electromagnetic fields for superconducting qubits. The extent of this interaction is measured by coupling strength, which can often be tuned or controlled.

While qubit coupling is needed for information transfer between qubits in a system, it also brings up challenges like chaos.

Quantum chaos refers to a state where a quantum system's behavior is unpredictable due to complex interactions within the system. This unpredictability is highly sensitive to the initial state of the system, leading to significant changes in behavior with slight variations in initial conditions.

Chaos is exaggerated in systems with high coupling strength between qubits, causing errors in QST by disrupting coherence. Defects (like irregularities or imperfections), as Prof. Mondaini mentioned, can also exacerbate chaotic behavior.

Therefore, managing chaos in quantum systems is essential for quantum communication.

"Our method works for non-ideal quantum networks, i.e., even if the coupling between the qubits cannot be set at pre-established values needed for a perfect state transfer," said Prof. Scalettar.

## Monte Carlo annealing

The team approached the problem using a hybrid method, wherein a classical computer performed the optimization task, and a superconducting quantum circuit used the optimization to carry out QST.

For optimization, the researchers used a method called Monte Carlo (MC) annealing. Annealing is a process used in metallurgy, where a material is heated to a very high temperature and then slowly cooled down to modify the material's properties.

In this case, the researchers want to maximize fidelity (or efficient QST) and optimize the coupling strength parameter. Simply put, they want to find the optimum value of the coupling strength for which we can get efficient QST.

Exploring every possible configuration to optimize coupling strength is not practical. The MC method randomly samples and optimizes the coupling in superconducting quantum circuits.

This stochastic or probabilistic approach efficiently navigates the parameter values to maximize the fidelity of QST. The process is iterative, and the coupling strength is adjusted on probabilistic sampling and classical computing power.

## Implementing a 36-qubit superconducting quantum circuit

The researchers used their optimization technique to employ a 2D 6x6 superconducting qubit network, i.e., a network containing 36 qubits.

They tested this network for three types of quantum states, which they transferred.

The first was a single-excitation transfer, which means only one qubit is excited in the system. The aim is to see how this excitation is transferred across multiple qubits within the quantum system.

For single-excitation transfers, the fidelity was found to be 0.902. A fidelity of 0.902 means that the actual transferred state closely matches the desired state, with an accuracy of 90.2%.

For two-excitation transfer (two excited qubits), the fidelity rate was 0.737, which is to say that the information was transferred with an accuracy of 73.7%.

The researchers also tested their network for transferring a Bell state. A Bell state is a state of two maximally entangled qubits. When qubits are in a Bell state, their quantum properties are correlated such that if you measure the state of one qubit, you instantly know the state of the other, no matter how far apart they are.

For this case, the fidelity was found to be 0.84 between two qubit pairs. Demonstrating QST for a Bell state is crucial, as it verifies foundational quantum principles.

"We not only technically demonstrate a Monte Carlo annealing process to improve the transfer fidelity, but also reveal the underlying physical pictures from the perspectives of quantum chaotic behavior and large-spin representation," said Prof. Guo.

"Our findings are far beyond the scope of previous experiments, not only establishing a practical way to realize few-particle QST in imperfect 2D networks but also revealing the underlying physical understanding of QST from angular momentum theory and quantum ergodicity," added Dr. Xiang.

## Looking ahead

The team's optimization approach works in such a way that the couplings between the qubits in a quantum network evade the manifestation of quantum chaos, which was confirmed by their experimental results.

Speaking of potential direct applications of their protocol, Prof. Mondaini and Prof. Scalettar said, "It is likely that fabrication of a future quantum device can be facilitated by connecting a collection of smaller quantum processors. Transmission of a state within each of them and then passing the state to the next one would form a distributed quantum processor, which could use the approach we have pioneered."

In essence, this highlights the scalability and practicality of their system for large interconnected systems.

Prof. Guo and Dr. Xiang added that their system could also provide a constructive technique for designing quantum channels and routers as building blocks for connecting processor nodes.

They said, "Building upon the high-fidelity quantum state transfer, one can implement efficient remote quantum gates across the quantum processor, thus speeding up the quantum algorithm."

Therefore, their protocol could open up possibilities for developing foundational components of quantum communication and information networks.

**More information:** Liang Xiang et al, Enhanced quantum state transfer by circumventing quantum chaotic behavior, *Nature Communications* (2024). DOI: 10.1038/s41467-024-48791-3

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