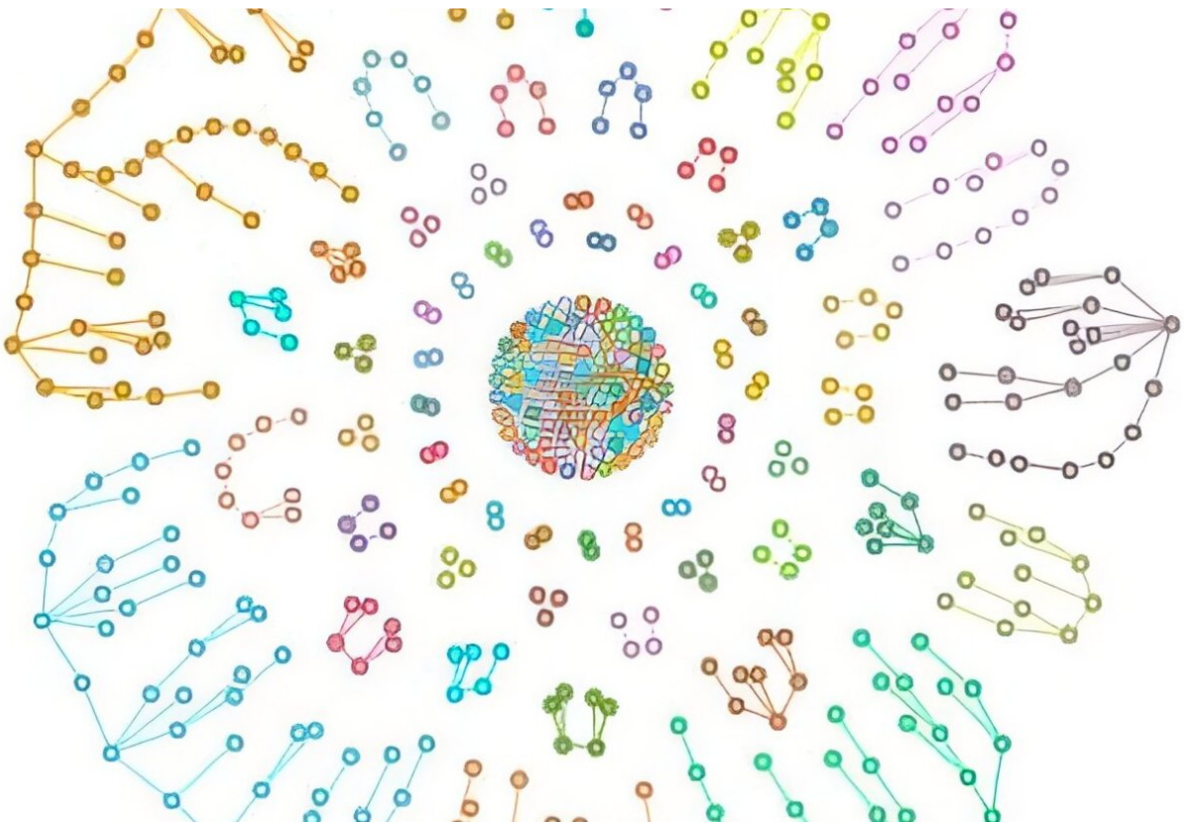
Physicists propose 'bridge' strategy to stabilize quantum networks

January 23 2025



Tree-like components in the steady state, starting with an ER initial topology of $\alpha = 10.0$. (a) Snapshot of the steady state. (b) In the steady state ($N = 10^3$), all components exhibit tree-like behavior, i.e., the average characteristic path length ℓ scales as $\ell \sim \sqrt{s}$. This plot shows a collection of 10 samples for each α. Error bars represent one standard error. (c) Length distribution of the paths removed in the steady state ($N = 10^3$). The solid line indicates theoretical prediction from the generalized Smoluchowski equation. Credit: *arXiv*: (2024). DOI: 10.48550/arxiv.2406.12228

While entangled photons hold incredible promise for quantum computing and communications, they have a major inherent disadvantage. After one use, they simply disappear.

In a new study, Northwestern University physicists propose a new strategy to maintain communications in a constantly changing, unpredictable quantum network. By rebuilding these disappearing connections, the researchers found the network eventually settles into a stable—albeit different—state.

The key resides in adding a sufficient number of connections to ensure the network continues to function, the researchers found. Adding too many connections comes with a high cost, overburdening the resources. But adding too few connections results in a fragmented network that cannot satisfy the user demand.

The findings potentially could lead to optimally designed quantum networks for lightning-fast computing and ultra-secure communications.

The study appears in the journal *Physical Review Letters*.

"Many researchers are putting significant efforts into building larger and better quantum communication networks around the globe," said Northwestern's István Kovács, the study's senior author. "But, as soon as a quantum network is opened up to users, it burns down. It's like crossing a bridge and then burning it down behind you. Without intervention, the network quickly dismantles.

"To tackle this problem, we developed a simple model of users. After each communication event, we added a fixed number of bridges, or links, between disconnected nodes. By adding a large enough number of links after each communication event, we maintained network connectivity."

An expert in complex systems, Kovács is an assistant professor of physics and astronomy at Northwestern's Weinberg College of Arts and Sciences.

Network of disappearing links

Quantum networks work by harnessing quantum entanglement, a phenomenon in which two particles are linked, regardless of the distance between them. Xiangi Meng, an expert in quantum communication and one of the study's first authors, describes entanglement as a "spooky" but effective resource. At the time of the research, Meng was a research associate in the Kovács group but now is an assistant professor of physics at Rensselaer Polytechnic Institute in New York.

"Quantum entanglement is the spooky, space-time-defying correlation between quantum particles," Meng said. "It's a resource that allows quantum particles to talk to each other, so they can perform complex tasks together while ensuring no eavesdropper can intercept their messages."

When two computers communicate using entangled links, however, the links involved in that communication disappear. The act of communication itself alters the quantum state of the link, making it unusable for further communications.

"In classical communications, the infrastructure has enough capacity to handle many, many messages," Kovács said. "In a quantum network, each link can only send a single piece of information. Then it falls apart."

Pinpointing the magic number

To better understand how networks behave under constant change, Kovács and his team built a simplified model of users within a quantum network. First, the researchers enabled users to randomly select other users with whom to communicate. Then, they found the shortest, most efficient communication path between those users and removed all the links along that path. This created a "path percolation," where the network gradually breaks down with each communication event.

After exploring this problem, Kovács and his team sought to offer a solution. Through modeling, they found the exact number of links to add after each communication event. That number resides at the critical boundary between maintaining the network and fracturing the network. Surprisingly, the team found the critical number is just the square root of the number of users. If there are 1 million users, for example, then 1,000 links need to be re-added for every 1 qubit of information sent through the network.

"It would be natural to expect that this number increases linearly with the number of users, or maybe even quadratically, as the number of user pairs that could communicate," Kovács said. "We found the critical number actually is a very small fraction compared to the number of users. But, if you add fewer than that, the network will fall apart, and people cannot communicate."

Kovács envisions this information potentially could help others design an optimized, robust quantum network that can tolerate failures. New links could be automatically added when other links disappear—creating a more resilient network.

"The classical internet was not built to be fully robust," Kovács said. "It naturally emerged due to technological constraints and user behavior. It was not designed, it just happened. But now we can do better with the quantum internet. We can design it to ensure it reaches its full potential."

More information: Xiangyi Meng et al, Path Percolation in Quantum Communication Networks, *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.134.030803. On *arXiv*: DOI: 10.48550/arxiv.2406.12228

Provided by Northwestern University

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