Exploring the full-stack design space of quantum computing

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In-depth analysis shows that co-designing hardware and software is essential for optimising quantum performance.

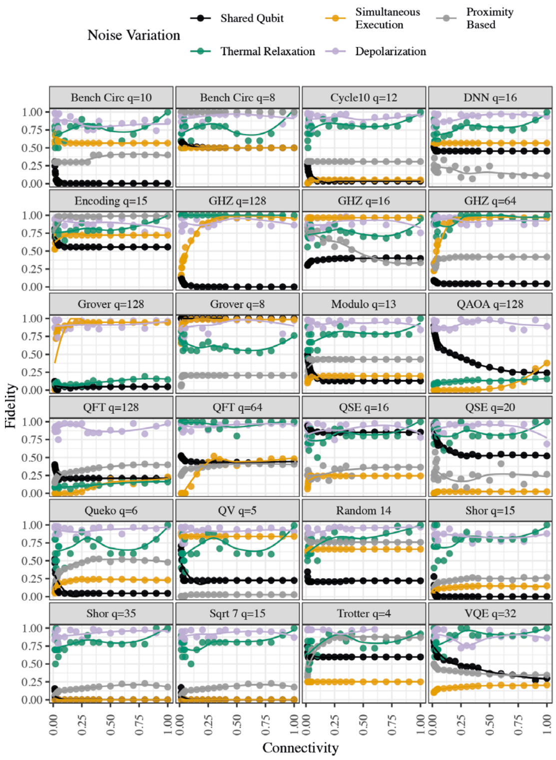
Over the past few years, advances in quantum computing have pushed it steadily closer to practical, real-world applications. But before this goal can be reached, greater standardisation will be needed across the entire quantum 'stack' – from user-facing software, all the way down to the underlying hardware.

In new research published in *EPJ Quantum Technology*, a team led by Hila Safi at the Technical University of Applied Sciences Regensburg investigates how this full-stack design challenge might be addressed. By systematically exploring the interplay between software hardware, the researchers show that improving quantum performance will depend on carefully co-designing both layers together.

Compared with classical computers, quantum hardware operates according to fundamentally different physical principles, meaning established design approaches can't simply be reused when building full-stack quantum systems. As well as being highly sensitive to noise, which can rapidly destroy fragile quantum information, quantum states also cannot be copied, placing strict limits on how information is processed and moved through a system.

At the same time, current quantum devices face severe practical constraints, including unavoidable noise and restricted qubit connectivity, which limits how many qubits can directly interact. As a result, quantum computing architectures must be rethought to integrate seamlessly with existing classical infrastructure, overlapping where possible but diverging where quantum-specific requirements demand it.

To work within these constraints, developers of quantum systems need to adapt classical design ideas wherever possible. In practice, this means carefully choosing how qubits are arranged and how operations are routed between them. Ideally, this would ensure that limited quantum resources are used as efficiently as possible, while still operating within a largely classical computing infrastructure. Practically, however, configurations of possible designs are often vast – presenting a daunting challenge for developers.



▲ Illustration of fidelity vs. connectivity across benchmarks as facets comparing three crosstalk models, thermal relaxation, and depolarisation noise for the heavy-hex back-end topology.

In their study, Safi's team tackled this problem using a technique known as design space exploration (DSE). Widely used in engineering and computer science, DSE involves systematically testing many different system configurations to understand how design choices affect the performance of the overall system. Here, the approach allowed the researchers to explore a wide range of ways to compile and execute quantum circuits, using methodologies inspired by classical system design.

Using computationally noisy simulations, the researchers varied both software-level decisions – such as qubit placement and routing strategies – and hardware-related features, including noise levels and connectivity patterns. This systematic approach revealed which combinations of choices led to the most accurate execution in the final circuit configuration.

The results show that by carefully selecting software strategies and hardware configurations, developers can substantially improve quantum circuit fidelity, even beyond what standard error mitigation techniques can achieve on their own. Importantly, these gains persist when quantum error correction schemes are included, rather than replacing their benefits.

Overall, the study highlights the critical role of a full-stack approach to optimising quantum systems, where hardware and software are designed in tandem with each other. By building on these insights, Safi and colleagues hope future work will further improve the accuracy and scalability of quantum computing architectures, potentially bringing widespread use a step closer to our everyday lives. ■

Reference

[1] S H. Safi, M. Bandic, C. Niedermeier *et al.*, *EPJ Quantum Technol.* **12**, 117 (2025). https://doi.org/10.1140/epjqt/s40507-025-00413-7