Toward a First-Principles Theory of Resilience for Complex Quantum Networks

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Extended Abstract

Resilience—the capacity of a system to absorb, adapt to, and recover from perturbations—has a rich mathematical footing in dynamical systems [1] (e.g., recovery rates, reactivity, amplification envelopes, basin geometry, and invariability measures). Yet these ideas have not been unified for complex networks, and are virtually absent for complex quantum networks (CQNs), despite the imminent push toward a quantum internet. Our work is the first and only effort in providing a first-principles resilience theory for CQNs, following in the vein of the modern dynamical-systems treatment of resilience (local vs. global indicators and their interrelations) and adapting it to the operational realities of CQNs (entanglement distribution, repeater chains, noisy links, switching/routing).

Foundational results on robustness in classical complex networks (including, but not limited to: error/attack tolerance; percolation-driven collapse; macroscopic resilience patterns) underscore both the opportunity and the risk when topology, dynamics, and perturbations interact. However, not only have these lessons not yet been systematically ported to quantum networks, but there is also a complete absence in accounting for the emergent phenomena arising at the network layer of communication engineering as a result of utilizing quantum technology at the physical layer and methodologically analyzing the beyond-Shannon nuance of transfer of quantum information between quantum devices (quantum state generators, bell state analyzers, quantum circuits, quantum repeaters, etc.) in the networks.

In order to achieve this, our methodology reinterprets dynamical-systems resilience theory in the context of network theory using a variety of sophisticated mathematical tools - more specifically, a combination of symmetric fibrations and concepts from spectral graph theory & control theory are used to lift state spaces, attractors, basins, return rates, and rare transitions into a network theory context by discussing performance maps, 'structural robustness'-guided (Cheeger bounds and interlacing inequalities) network flows under specified percolation classes, and tracking of a variety of network-wide phenomena such as epidemic tipping and imperfect synchronization. We conclude by providing the pathway to re-deriving the various resilience metrics that are currently in use today for resilience engineering of both classical and quantum complex communication networks.

Quantum networking roadmaps [2] and percolation-style analyses emphasize that end-to-end entanglement scales through fragile phases and thresholds, strongly shaped by topology, channel noise, and repeater operations— all prime territory for a principled resilience calculus. Additionally, integration of these quantum networks, and eventually the quantum internet, into larger legacy classical telecommunication architectures for future communication standards like 6G and 7G will rely on a mathematically sound development of various resilience metrics that be used to ensure adherence to key performance indicators (KPIs) that will be required by the clients when they make their demands/requests for transfers of information across a large global network of immense complexity and sophistication. This requires the foundational basis of an underlying resilience theory that can yield the development of insightful, useful and

timely resilience metrics, thus positioning our work to be the key to unlocking the full potential of future communication networks while remaining safe and sustainable during operation.

Ethics

Resilience analysis may be dual-use: it can inform both defense (hardening critical quantum links) and offense (targeting fragile components). We explicitly commit to publishing defensive design rules and to withhold actionable attack heuristics. We also discuss: (i) privacy/security in telemetry for early-warning tools; (ii) sustainability—quantifying additional energy/footprint of resilience mechanisms (redundancy, purification) and encouraging resource-aware design.

Preference for Medium of Dissemination

The authors would like to note a preference for delivering an oral presentation over lightning talks/poster presentation.

References

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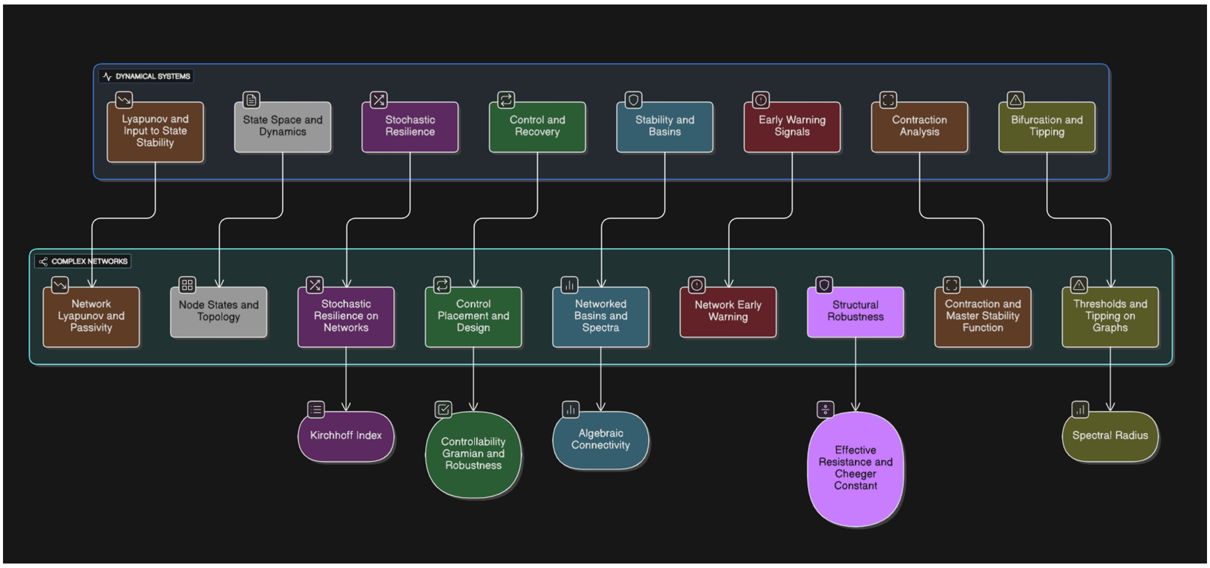

Figure 1: **Resilience Parallels.** Denoted here are the parallels between the concepts of resilience in dynamical systems and complex networks, with recognizable system parameters being highlighted.