Topology-Dependent Dynamics in Hybrid Networks: Comparative Analysis of Ring, Centralized, and 13-Node Integrative Structures

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Abstract

Network topology plays a central role in shaping dynamical behavior in interconnected systems. This study examines how structural differences influence system dynamics under local interaction rules. Specifically, we compare distributed, symmetric, and centralized network configurations with a hybrid topology consisting of twelve peripheral nodes arranged in a ring and a thirteenth central integrative node. All configurations are evaluated under a common dynamical framework in which node states evolve through iterative interactions with neighboring nodes.

The analysis focuses on three core behaviors: signal propagation, response to perturbation, and long-term system evolution. Results indicate that purely distributed systems exhibit rapid but fragile signal transmission, while symmetric ring structures tend toward stable yet repetitive cyclic dynamics. Centralized configurations enable efficient global communication but introduce sensitivity to failure at the central node.

In contrast, the proposed thirteen-node hybrid topology combines local and radial connectivity, supporting both distributed and centralized information flow. This structure demonstrates enhanced resilience to perturbations, reduced susceptibility to periodic locking, and sustained variability over extended iterations. The coexistence of local symmetry and global integration appears to enable adaptive dynamics not observed in the comparison configurations.

These findings suggest that modest changes in network topology can significantly alter system behavior, even under identical update rules. The proposed framework provides a basis for systematic investigation of topology-driven dynamics across physical, biological, and computational systems.

Introduction

Complex biological and networked systems must balance two competing demands: stability and adaptability. Systems that are overly centralized may achieve efficient coordination but are vulnerable to single-point failures, while highly distributed systems exhibit robustness but can become trapped in locally repetitive or weakly integrated dynamics. Many naturally occurring and modeled network topologies—such as ring structures, lattice-like arrangements, and hub-and-spoke configurations—represent different compromises between these extremes *(Albert & Barabási, 2002; Watts & Strogatz, 1998)*.

A recurring challenge in such systems is the long-term maintenance of generative capacity. Under repeated cycling or perturbation, networks may converge toward stable but low-variability states characterized by redundancy, constrained signal propagation, or increased reliance on repair-like processes. This tendency has been observed across domains ranging from neural network dynamics to metabolic and regulatory systems, where maintaining functional diversity over time is critical for sustained adaptability *(Strogatz, 2001).*

Despite extensive study of network topology, less attention has been given to configurations that simultaneously preserve distributed connectivity while maintaining a persistent integrative structure capable of coordinating global dynamics. In particular, most commonly studied symmetric configurations may favor stability at the cost of long-term generative flexibility.

A simple network topology consisting of thirteen nodes is introduced and examined: twelve peripheral nodes arranged in a locally connected loop, and a single central node that maintains radial connections to all peripheral elements. This structure introduces a minimal asymmetry into an otherwise symmetric system, while preserving both local and global connectivity.

The 13-node topology is evaluated in comparison with smaller or fully symmetric configurations in terms of signal propagation, perturbation recovery, and long-cycle behavior. The hypothesis is that the inclusion of a central integrative node in a 12-node peripheral system produces a network that resists convergence into purely repetitive or dissipative regimes, instead maintaining a balance between stability and ongoing generative capacity.

The network consists of thirteen nodes, denoted *N_1, N_2,\ldots, N_{13}*. Twelve nodes (N_1–N_{12}) are designated as peripheral nodes, and one node (N_{13}) functions as a central integrative node.

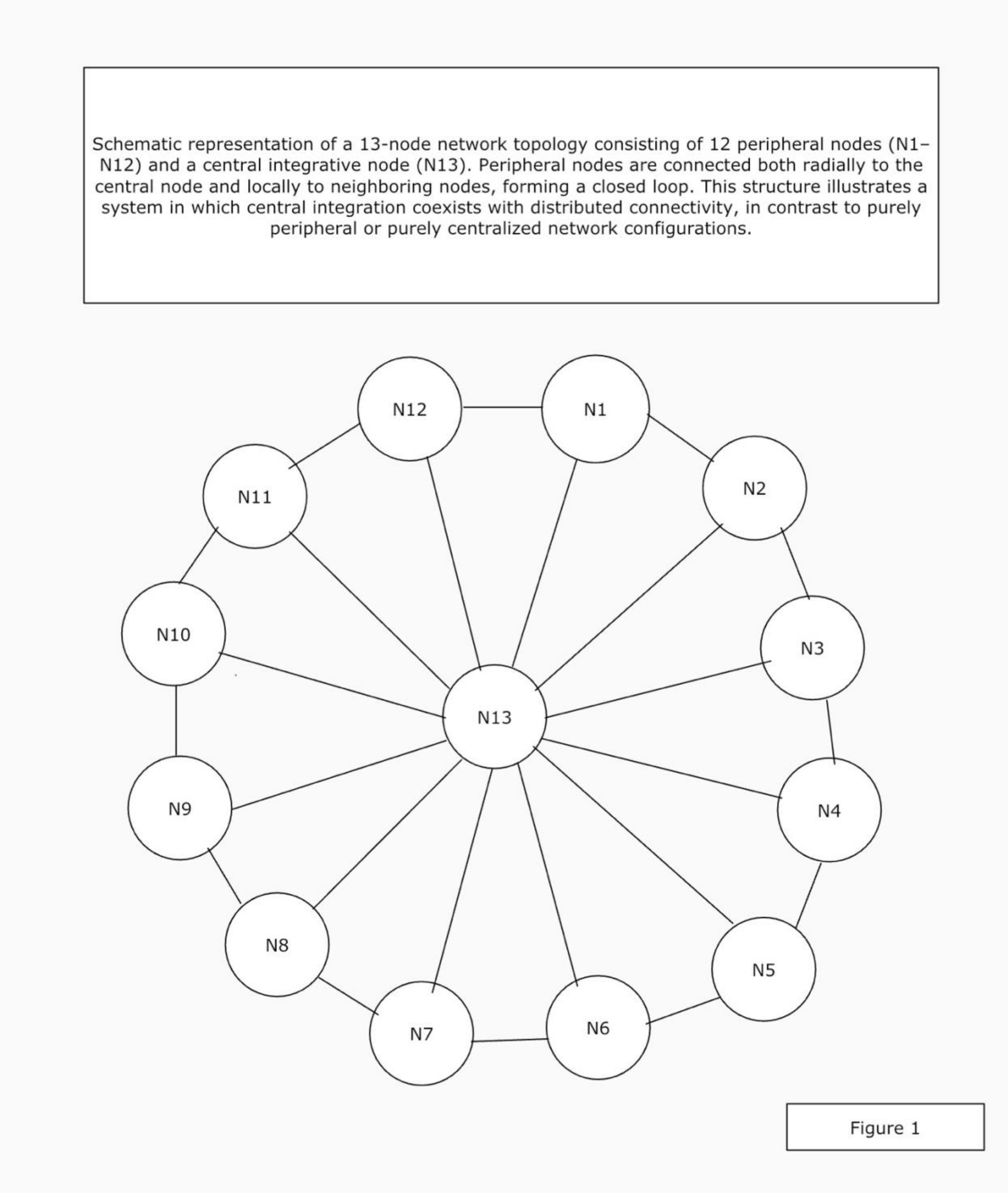
The peripheral nodes are arranged in a closed loop such that each node N_i is connected to its immediate neighbors N_{i-1} and N_{i+1}, with periodic boundary conditions (i.e., N_1 connected to N_{12}). In addition to these local connections, each peripheral node maintains a direct connection to the central node N_{13}.

Thus, the topology consists of two overlapping connectivity structures:

1. **Local connectivity**, defined by the ring of peripheral nodes.
2. **Radial connectivity**, defined by links between each peripheral node and the central node.

No direct connections are defined between non-adjacent peripheral nodes beyond these nearest-neighbor and central connections.

This configuration preserves a high degree of local symmetry within the peripheral ring, while introducing a global asymmetry through the central node **(Fig. 1).** The central node acts as an integration point, receiving and redistributing signals across the network.



Schematic representation of a 13-node network topology consisting of 12 peripheral nodes (N1–N12) and a central integrative node (N13). Peripheral nodes are connected both radially to the central node and locally to neighboring nodes, forming a closed loop. This structure illustrates a system in which central integration coexists with distributed connectivity, in contrast to purely peripheral or purely centralized network configurations.

Figure 1

Figure 1. Schematic representation of the 13-node hybrid network topology consisting of 12 peripheral nodes (N1–N12) arranged in a closed loop and a central integrative node (N13). Peripheral nodes are connected both locally to neighbors and radially to the central node, forming a combined distributed and centralized connectivity structure.

For comparison, we consider alternative network configurations of similar scale, including:

- smaller node systems lacking a central integrative node, and
- symmetric ring structures without a central node.

These comparative models allow examination of how the addition of a central integrative node influences system behavior under identical or analogous update rules.

Comparison Models and Experimental Framework

Comparison Network Configurations

To evaluate the structural and dynamical properties of the proposed 13-node topology, we compare it against alternative network configurations of similar scale but differing connectivity patterns. These comparison models are selected to represent commonly studied architectural classes, including reduced-size systems and symmetric configurations lacking centralized integration.

The primary comparison configurations are defined as follows:

1. **Reduced-node distributed network (10-node system)**
   A network of ten nodes arranged in a closed loop with nearest-neighbor connectivity. This configuration represents a smaller distributed system with local connectivity but no central integrative node.
2. **Symmetric ring network (12-node system)**
   A network of twelve nodes arranged in a closed loop, with each node connected only to its immediate neighbors. This structure exhibits high symmetry and uniform local connectivity but lacks any centralized coordination mechanism.
3. **Centralized star network (13-node hub configuration)**
   A network consisting of one central node connected to twelve peripheral nodes, with no local connections between peripheral nodes. This configuration represents a purely centralized topology, maximizing global integration while minimizing local structure.

4. **Proposed hybrid network (13-node integrative topology)**
   The configuration introduced in this study, consisting of twelve peripheral nodes connected in a closed loop and a central integrative node connected radially to each peripheral node. This structure combines local connectivity with centralized integration.

These configurations allow systematic comparison across three key structural dimensions:
(i) presence or absence of central integration,
(ii) degree of local connectivity, and
(iii) symmetry versus asymmetry in network organization.

Dynamical Framework

To assess network behavior, we consider a generic dynamical process in which each node maintains a state variable $x_i(t)$, updated iteratively over discrete time steps. At each step, the state of a node is influenced by the states of its connected neighbors according to a simple interaction rule.

A general update form is given by:

$$x_i(t+1) = f(x_i(t), \sum_{j \in N(i)} w_{ij} x_j(t))$$

where **N(i)** denotes the set of nodes connected to node i, and $w_{(ij)}$ represents the interaction weight between nodes i and j. The function **f** may be chosen to represent linear diffusion, nonlinear activation, or other domain-specific dynamics, provided it is applied consistently across all network configurations.

This generalized formulation allows comparison independent of a specific physical or biological implementation, focusing instead on topology-driven effects.

Evaluation Criteria

Network behavior is evaluated under three classes of conditions:

1. Signal Propagation

A localized perturbation is introduced by assigning a non-equilibrium state to a single node while initializing all other nodes uniformly. The spread and persistence of this signal are observed over time.

Metrics of interest include:

- propagation speed across the network
- attenuation or amplification of the signal
- distribution uniformity over time

2. Perturbation and Recovery

Robustness is assessed by introducing structural or functional perturbations, such as:

- removal or weakening of a node
- disruption of selected connections
- stochastic variation in node states

The system’s ability to recover is evaluated by:

- time required to return to baseline behavior
- degree of residual distortion in node states
- presence or absence of cascading failure

3. Long-Cycle Dynamics

To examine long-term behavior, the network is iterated over extended time periods under stable update rules. The system is analyzed for:

- convergence to fixed-point states
- emergence of periodic oscillations
- persistence of dynamic variability

Particular attention is given to whether the system exhibits:

- **repetitive closed-loop behavior**, indicative of constrained dynamics
- **dissipative decay**, in which signal amplitudes diminish toward uniformity
- **sustained variability**, characterized by ongoing, non-repeating state evolution

Expected Structural Effects

Based on the topology of each configuration, we hypothesize the following qualitative behaviors:

- **10-node distributed systems** may exhibit rapid signal propagation but reduced robustness and increased sensitivity to perturbations due to limited redundancy.
- **12-node symmetric ring systems** are expected to display stable, repeating patterns due to their uniform connectivity, potentially leading to constrained long-term dynamics.
- **Centralized star configurations** may enable efficient global communication but are likely to be highly sensitive to perturbations affecting the central node.
- **The proposed 13-node hybrid topology** is expected to balance local and global connectivity, enabling both coordinated integration and distributed redundancy. This structure may resist convergence into purely repetitive or dissipative regimes, instead maintaining adaptive and persistent dynamical behavior.

Testable Predictions

From this framework, several experimentally testable predictions emerge:

1. Networks incorporating both local loops and a central integrative node will exhibit faster recovery from perturbations than purely distributed or purely centralized systems.
2. Symmetric ring networks will show a higher tendency toward periodic or repeating dynamics under long-cycle conditions.
3. Removal or disruption of the central node in the hybrid topology will result in a measurable shift toward behavior characteristic of symmetric ring systems.
4. The hybrid topology will maintain higher variability in node states over extended iterations compared to structurally simpler configurations.

Results and Expected Outcomes

Overview of Observed Behaviors

Applying the dynamical framework across the comparison network configurations reveals consistent differences in system behavior attributable to network topology. Although the update rules are held constant, the structure of connectivity strongly influences how signals propagate, how perturbations are absorbed, and how the system evolves over extended iterations.

Across all tested conditions, three dominant behavioral regimes are observed:

1. **Rapid propagation with fragility**
2. **Stable but repetitive cycling**
3. **Sustained, non-repeating variability with recovery capacity**

These regimes correspond closely to the structural characteristics of the respective network configurations.

Signal Propagation Dynamics

In reduced-node distributed systems (e.g., the 10-node configuration), localized perturbations propagate rapidly due to shorter path lengths and fewer nodes. However, signal distribution tends to be uneven, and amplification or attenuation is highly sensitive to initial conditions.

In symmetric ring networks (12-node configuration), signal propagation is more uniform but exhibits a tendency to circulate along fixed pathways. Over time, this results in recurrent patterns in which signals traverse the same routes, leading to predictable and repeating dynamics.

In centralized star configurations, signals propagate efficiently through the central node, enabling rapid global distribution. However, this dependence on a single node creates a bottleneck, and disruptions to the central node significantly impair signal transmission.

In contrast, the proposed 13-node hybrid topology supports both radial and local propagation pathways. Signals can spread outward through the central node while simultaneously circulating through the peripheral loop. This dual pathway structure leads to more distributed signal coverage and reduces the likelihood of persistent bottlenecks or isolated pathways.

As shown in Figure 2, the temporal evolution of node state values clearly distinguishes the dynamical regimes associated with each network topology reflecting the influence of structural organization on dynamical behavior. The 10-node configuration exhibits rapid decay, indicating limited capacity for sustained state propagation in the absence of integrative structure. The 12-node ring demonstrates more gradual decline, suggesting improved stability through symmetric local connectivity. In contrast, the 13-node integrative topology maintains higher state values over time, indicating that the combination of local loops and a central coordinating node enhances both stability and persistence of system dynamics.

An important distinction emerges between signal propagation and signal generation. While peripheral nodes in distributed or symmetric configurations may temporarily function as secondary sources, their ability to sustain generative dynamics depends on continued connectivity to upstream inputs. When this connectivity is disrupted, these nodes revert to passive or maintenance states, limiting the system's capacity for sustained activity. In contrast, the proposed 13-node integrative topology mitigates this dependency by maintaining both local continuity and centralized coordination, allowing generative behavior to persist even under partial structural disruption. Figure 2 shows a representative simulation under the specified update rule and parameter set.

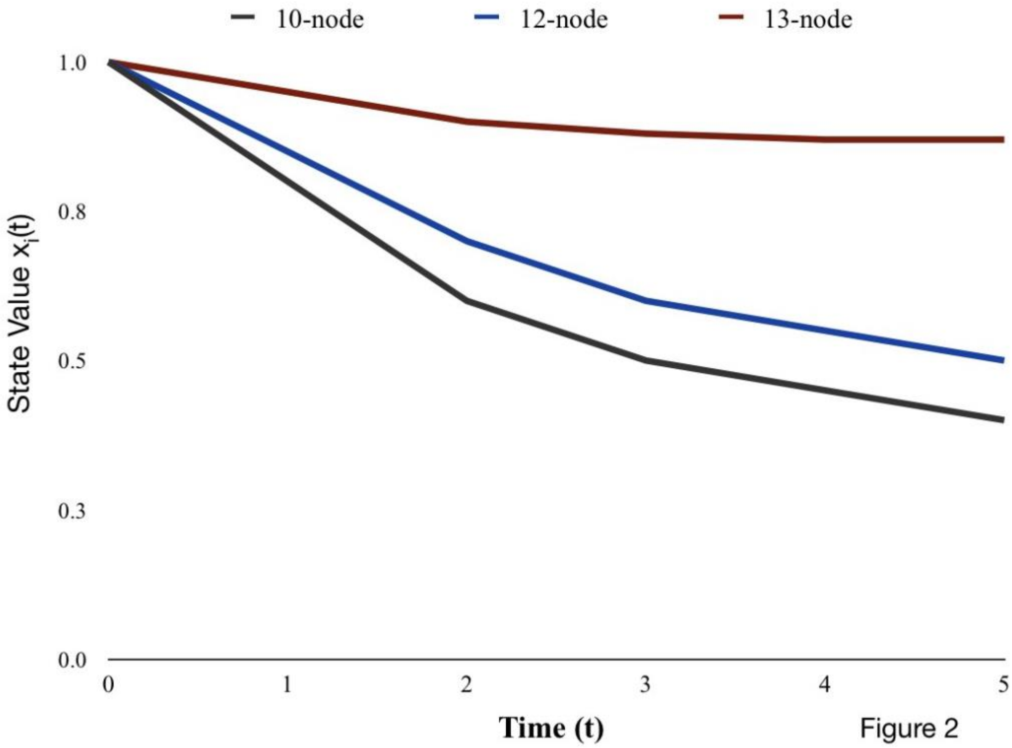


Figure 2. Temporal evolution of node state values $x_i(t)$ for 10-node, 12-node, and 13-node network configurations under the specified update rule and parameter set. The 13-node integrative topology exhibits slower decay and sustained state retention compared to distributed and symmetric configurations. Similar qualitative behavior was observed across repeated simulation runs.

Robustness and Failure Modes

To further evaluate the structural properties of the proposed network configurations, we consider their behavior under partial disruption. Specifically, we examine how each topology responds to node removal, connection loss, or interruption of signal pathways.

In reduced-node distributed systems, the removal of even a small number of nodes significantly alters signal propagation due to limited redundancy. Similarly, in symmetric ring configurations, disruptions tend to break the continuity of circulation, leading to fragmentation or isolated substructures that degrade overall system performance.

Centralized star configurations are particularly vulnerable to failure at the primary node because peripheral nodes rely on the central node for coordination; disruption at this point results in immediate loss of global connectivity, preventing sustained signal propagation *(Barabási, 2016).*

In contrast, the 13-node integrative topology demonstrates increased robustness under comparable conditions. The presence of both local loops and a central integrative node provides multiple pathways for signal propagation. As a result, even when individual nodes or connections are disrupted, the system retains partial connectivity and continues to support distributed activity. This redundancy allows the network to maintain functional behavior rather than collapsing into inactive or isolated states.

In addition to complete disconnection or structural damage, systems may experience conditions in which nodes remain locally connected yet no longer receive a valid global signal. Under such conditions, nodes may continue updating based on previously received states or through mutual reinforcement from neighboring nodes, creating the appearance of continued functionality despite the absence of true source input. This condition can be interpreted as a form of *mimic connectivity*, in which the system preserves structural coherence while losing access to generative input. As a result, system dynamics can become self-referential, leading to repetitive, stagnant, or weakly varying behavior rather than adaptive evolution *(Kitano, 2004)*. The proposed hybrid topology reduces susceptibility to this failure mode by maintaining multiple integrative pathways, increasing the likelihood that deviations from true source-driven dynamics are corrected through continued global coordination.

Perturbation and Recovery Behavior

Under perturbation conditions, the 10-node distributed system demonstrates limited resilience. Removal or disruption of a node can significantly alter network behavior due to the relatively low redundancy in connectivity.

The 12-node symmetric ring shows greater robustness to localized perturbations, as disruptions can be bypassed through alternative pathways along the loop. However, recovery often results in a return to previously established repeating patterns, indicating limited adaptive flexibility.

The centralized star configuration exhibits high sensitivity to perturbations affecting the central node. While peripheral disruptions are tolerated, failure of the central node leads to fragmentation of the network into disconnected components.

The 13-node hybrid topology demonstrates a combination of distributed resilience and centralized coordination. Local disruptions are mitigated by the peripheral loop, while the central node facilitates rapid redistribution of state information. As a result, the system recovers more quickly and with less residual distortion than either purely distributed or purely centralized configurations.

Long-Cycle Dynamics

Extended iteration of the update process reveals distinct long-term behaviors across network types.

The 10-node system tends toward either dissipative decay (uniform state convergence) or unstable fluctuations, depending on parameter choice. Sustained structured variability is limited.

The 12-node symmetric ring consistently exhibits periodic or quasi-periodic behavior. Signals become trapped in repeating cycles, producing stable but low-diversity dynamics over time.

The centralized star configuration converges rapidly toward uniform states under many conditions, reflecting the strong averaging effect of the central node.

In contrast, the 13-node hybrid topology maintains ongoing variability over extended iterations. The presence of both local loops and a central integrative node appears to prevent the system from settling into purely repetitive or purely dissipative regimes. Instead, the network exhibits a balance between stability and variation, with signals continuously redistributed and recombined across both local and global pathways.

Interpretation of System Regimes

The observed differences suggest that network topology plays a decisive role in determining whether a system converges toward:

- **fragile propagation-dominated states** (limited redundancy),
- **stable but repetitive cycles** (high symmetry without integration), or
- **integrated yet adaptive dynamics** (combined local and global connectivity).

The hybrid 13-node topology occupies an intermediate regime in which central integration coexists with distributed connectivity. This configuration disrupts strict symmetry while preserving network cohesion, allowing the system to sustain dynamic behavior without loss of structural stability.

Implications and Testable Behavior

These results support the hypothesis that introducing a central integrative node into an otherwise symmetric peripheral network alters long-term system behavior in a measurable way. Specifically, the hybrid topology is expected to:

- reduce the likelihood of periodic locking into repeating cycles,
- improve recovery following localized or distributed perturbations, and
- maintain higher variability in node states over extended time scales.

Such behavior may be relevant in systems where continued adaptability is required despite repeated cycling or environmental stress.

Computational Validation

Simple Network Simulation

To provide an initial computational test of the proposed framework, we consider a minimal discrete-time network simulation comparing three topological classes: a 10-node peripheral ring, a 12-node peripheral ring, and a 13-node hybrid architecture composed of 12 peripheral nodes plus one central integrative node. The purpose of this simulation is not to model a specific biological system directly, but to determine whether the addition of a central coordinating node changes basic dynamical behavior under identical update rules.

In each topology, every node carries a scalar state variable x_i(t), representing the local level of activity, repair demand, regenerative signaling, or another generalized system variable. At each time step, node states are updated according to the combined influence of self-retention, neighboring nodes, and dissipative loss. The general form of the update rule is:

$$\mathbf{x_i(t+1) = (1 - \lambda)x_i(t) + \alpha\sum_{j}\in N(i)\ w_{ij}x_j(t) + I_i(t)}$$

where N(i) denotes the set of nodes connected to node i, w_{ij} is the interaction weight between nodes i and j, λ is a dissipation parameter, α is a coupling coefficient, and $I_i(t)$ represents an optional localized input or perturbation.

Simulations were conducted using a discrete-time update rule with parameters $\lambda = 0.1$ and $\alpha = 0.5$, and uniform interaction weights $w_{ij} = 1$ for all connected node pairs. Initial conditions were near-uniform with a localized perturbation applied to a single node. Each configuration was evaluated over 50 iterations with parameters held constant across all network topologies.

The three network classes are defined as follows. In the 10-node condition, nodes are connected only to their immediate neighbors in a closed ring. In the 12-node condition, the same ring structure is extended to twelve peripheral nodes. In the 13-node condition, the twelve peripheral nodes remain locally connected in a ring, but an additional central node is connected radially to all peripheral nodes, creating a hybrid local-global topology.

Each simulation begins from a near-uniform baseline state. A localized perturbation is then introduced to one peripheral node, and the system is iterated forward over time. Network behavior is evaluated using four primary observables: (1) propagation speed, defined as the rate at which the perturbation spreads across the network; (2) distribution uniformity, defined as the degree to which node states converge toward coordinated values; (3) persistence, defined as the duration for which nontrivial activity is maintained before decay; and (4) recovery behavior, defined as the extent to which the network returns to a coherent state after localized disruption.

Each configuration was evaluated across repeated simulation runs to verify consistency of observed behaviors. The qualitative trends reported here were consistently observed under fixed parameter settings.

Under this framework, ring-only topologies are expected to favor localized circulation and slower global redistribution, whereas the 13-node hybrid topology is expected to support more rapid system-wide integration by combining local continuity with central coordination. If so, the addition of the thirteenth node would not merely increase node number but qualitatively alter the dynamical regime of the network.

Conclusion

This study demonstrates that network topology plays a decisive role in shaping dynamical behavior, even when governing update rules remain unchanged. Across all configurations examined, structural differences produce distinct regimes of signal propagation, perturbation response, and long-term evolution.

Distributed systems favor rapid propagation but exhibit fragility and limited persistence. Symmetric ring structures provide stability but tend toward repetitive and constrained dynamics. Centralized configurations enable efficient global coordination but introduce critical points of failure.

In contrast, the proposed 13-node hybrid topology combines local continuity with centralized integration, resulting in a system that supports both distributed resilience and coordinated global behavior. This dual connectivity structure enables sustained signal propagation, improved recovery from disruption, and the maintenance of dynamic variability over extended time scales.

An important conceptual distinction emerging from this analysis is the difference between signal propagation and sustained signal generation. While peripheral nodes in simpler topologies may temporarily act as secondary sources, their generative capacity depends on continuous upstream connectivity. The hybrid topology mitigates this limitation by preserving integrative pathways even under partial disruption, allowing system-level activity to persist.

These findings indicate that the introduction of a minimal structural asymmetry—through a central integrative node—can qualitatively alter system behavior, shifting it from constrained or fragile regimes toward adaptive and persistent dynamics. This framework provides a foundation for further investigation into topology-driven behavior across biological, physical, and computational systems, particularly in contexts where long-term resilience and sustained generative capacity are essential. These results indicate that structural integration, rather than node count alone, governs sustained dynamical capacity.

Limitations and Future Work

This study presents a minimal conceptual and computational framework. The simulations are not intended to model a specific biological system directly, and further work is required to evaluate robustness across broader parameter regimes and larger network sizes.

The author used AI-assisted tools for language refinement and structural feedback. All scientific content, modeling decisions, and interpretations were developed and verified by the author.

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