

Redefining Network Resilience: A Comprehensive Metric for Wireless Communications

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Abstract:

As wireless communication networks become increasingly integral to modern infrastructure, ensuring their resilience against failures and attacks is paramount. This study introduces the Resilience Connectivity Index (RCI), a novel topological metric designed to evaluate the resilience of wireless networks. Unlike existing indices, RCI integrates aspects of connectivity, redundancy, and fault tolerance to provide a comprehensive measure of network robustness. We apply RCI to a real-world wireless communication system, comparing its performance with established topological indices such as the Wiener Index, Estrada Index, and Randić Index. The results demonstrate that RCI offers superior insights into network resilience, making it a valuable tool for network design and optimization.

Keywords: Resilience, Wireless Networks, Topological Indices, Graph Theory, Network Robustness, Resilience Connectivity Index (RCI)

1. Introduction

Wireless communication networks underpin critical applications ranging from personal communication to essential services in healthcare, transportation, and emergency response. The resilience of these networks defined as their ability to maintain functionality in the face of disruptions is crucial for ensuring uninterrupted service [1]. Traditional approaches to assessing network resilience often rely on topological indices from graph theory, such as the Wiener Index, Estrada Index, and Randić Index. While these indices provide valuable insights, they may not fully capture the multifaceted nature of resilience in wireless networks [2, 3].

Recent studies emphasize the need for resilience-oriented topological indices, particularly in the context of wireless networks. For example, resilience in Cloud-Radio Access Networks (C-RAN) has been analysed using graph invariants to optimize network design, specifically focusing on fault tolerance and adaptive topology adjustments to maintain network stability during component failures [4]. Additionally, percolation theory and random geometric graphs have been applied to model

resilience in large-scale wireless networks, focusing on phase transitions and connectivity under varied node densities[5].

These approaches highlight the limitations of conventional indices, as they do not fully account for resilience properties critical to wireless infrastructure under dynamic conditions. To address this gap, our study introduces the Resilience Connectivity Index (RCI), a novel metric tailored to evaluate resilience by integrating connectivity, redundancy pathways, and fault tolerance into a single comprehensive measure. This approach is particularly valuable for wireless networks, where maintaining robust and adaptable connections is essential for uninterrupted service[6, 7]. The RCI's mathematical foundation is based on established graph theory principles, ensuring a verifiable and consistent formulation. Validation tests and comparisons with traditional indices further emphasize RCI's practical relevance for enhancing network resilience.

Our work introduces the Resilience Connectivity Index (RCI), a novel topological metric specifically designed to evaluate the resilience of wireless networks. RCI integrates connectivity strength, redundancy pathways, and fault tolerance into a single comprehensive measure. We demonstrate the application of RCI to a real-world wireless communication system, providing detailed calculations and comparative analysis with existing indices.

Section 1 provides a background on the significance of network resilience, especially in wireless communication. It explores traditional graph-theoretic indices, their limitations, and the motivation for creating the RCI. Section 2 reviews relevant literature, discussing the need for resilience in network design and the roles of various topological indices. Section 3 describes the methodology for calculating the RCI, detailing its three core components Connectivity Strength, Redundancy Factor, and Fault Tolerance and their mathematical representations. Section 4 presents a case study on a Wi-Fi mesh network, demonstrating RCI's practical application, calculation of components, and visualization of results. Section 5 validates and compares RCI with traditional indices, revealing insights into network resilience beyond accessibility alone. Section 6 discusses RCI's practical implications and robustness across different parameter values, while Section 7 concludes with the potential of RCI as a valuable tool for network design and resilience analysis.

1.1 Background

Wireless communication networks are foundational in modern information systems, enabling seamless data transfer across various devices. Wi-Fi networks, in particular, are integral to homes, enterprises, and public spaces, necessitating designs that withstand potential disruptions. Network resilience the ability to maintain connectivity despite failures is a primary concern in wireless network design, influencing user experience and operational efficiency. As wireless systems face challenges from both physical layer disruptions and cyber threats, ensuring resilience becomes critical to maintain high reliability and low latency under diverse conditions[8]. The evolution from 5G to future 6G networks aims to address these challenges by designing systems that can withstand failures, improve scalability, and enhance security [9].

1.2 Motivation and Related Work

Traditional graph-theoretic indices, such as the Wiener Index and Betweenness Centrality, measure node centrality and connectivity but often overlook the impact of potential node failures on network

stability. These indices focus on quantifying shortest paths or structural importance without explicitly considering resilience metrics [10]. Existing network resilience studies have yet to fully develop resilience-centric measures, especially for networks with high dependency on connectivity, like Wi-Fi networks [11]. In particular, empirical investigations into the relationships between centrality measures across different network classes highlight the limitations of traditional metrics in capturing resilience effectively, as they do not typically address the performance of a system under disruption and recovery conditions [12]. These gaps suggest the need for indices that directly incorporate the potential effects of node failures and recovery strategies in dynamic network contexts.

1.3 Contribution

We propose the Resilience Centrality Index (RCI), a novel metric that quantifies the resilience of nodes by integrating distance-based connectivity and resilience impact from neighbouring nodes. This dual approach captures both the structural centrality of a node and its robustness to disruptions in the network. Our study includes:

1. Detailed RCI calculations on a sample Wi-Fi network.
2. Empirical comparisons with the Wiener Index.
3. Sensitivity analysis of RCI under different parameters.

This document introduces the Resilience Connectivity Index (RCI), a novel metric developed to evaluate resilience in wireless networks by integrating connectivity, redundancy, and fault tolerance. Section 1 provides a background on the significance of network resilience, especially in wireless communication. It explores traditional graph-theoretic indices, their limitations, and the motivation for creating the RCI. Section 2 reviews relevant literature, discussing the need for resilience in network design and the roles of various topological indices. Section 3 describes the methodology for calculating the RCI, detailing its three core components—Connectivity Strength, Redundancy Factor, and Fault Tolerance—and their mathematical representations. Section 4 presents a case study on a Wi-Fi mesh network, demonstrating RCI's practical application, calculation of components, and visualization of results. Section 5 validates and compares RCI with traditional indices, revealing insights into network resilience beyond accessibility alone. Section 6 discusses RCI's practical implications and robustness across different parameter values, while Section 7 concludes with the potential of RCI as a valuable tool for network design and resilience analysis.

2. Literature Review

2.1 Network Resilience in Wireless Communications

Network resilience in wireless communications has become increasingly important due to the need for reliable, uninterrupted connectivity, especially in critical sectors such as healthcare, public safety, and emergency response. This is particularly relevant in scenarios like natural disasters, where communication infrastructure is often disrupted, and timely information dissemination is essential. Strategies focusing on network resilience ensure that these systems can quickly recover from failures, whether caused by technical issues, disasters, or cyber threats. Research in this domain emphasizes improving the robustness of wireless networks, such as Wi-Fi and 5G, to support essential services during emergencies, thus enhancing operational efficiency and public safety[13].

Wireless networks' ability to provide continuous service in disaster-stricken areas can be critical in ensuring effective emergency responses, enabling real-time communication for healthcare, rescue operations, and disaster management systems[14]. Advances in network technologies, including those integrating UAVs and IoT for flood rescue, or using UAV-based mesh networks for post-disaster communication, are key to boosting the resilience of communication systems.

2.2 Topological Indices in Network Analysis

Graph theory offers a suite of topological indices that quantify different aspects of network structure:

- *Wiener Index (W)*: Measures the average shortest-path distance within the network, reflecting overall communication efficiency [15].
- *Estrada Index (EE)*: Captures the network's connectivity strength by considering the exponential of eigenvalues of the adjacency matrix [16].
- *Randić Index (R)*: Evaluates node connectivity by considering the degrees of connected nodes, indicating robustness against node removals [17].

While these indices provide valuable metrics, they individually focus on specific aspects of network structure, potentially overlooking the comprehensive resilience characteristics.

3. Methodology: Development of the Resilience Connectivity Index (RCI)

3.1 Conceptual Framework

The Resilience Connectivity Index (RCI) is designed to encapsulate three critical components of network resilience:

- *Connectivity Strength (CS)*: Represents the overall connectivity of the network, similar to the Estrada Index.
- *Redundancy Factor (RF)*: Quantifies the presence of alternative pathways, akin to the concept of network redundancy.
- *Fault Tolerance (FT)*: Measures the network's ability to maintain connectivity despite node or link failures, related to the Randić Index.

3.2 Mathematical Definition

The proposed Resilience Centrality Index (RCI) is designed to provide a comprehensive measure of network resilience by integrating three key components: connectivity strength, redundancy of paths, and fault tolerance. The RCI is mathematically defined as:

$$RCI(G) = \alpha \cdot CS(G) + \beta \cdot RF(G) + \gamma \cdot FT(G)$$

Where α , β , γ are weights assigned to each component based on their importance in resilience assessment. $CS(G)$ represents the connectivity strength, calculated using the Estrada Index, which reflects the network's overall connectivity. $RF(G)$ denotes the redundancy factor, derived from the number of redundant paths between node pairs, indicating how well the network can handle node or link failures. $FT(G)$ stands for fault tolerance, computed using the Randić Index, which measures node connectivity and the robustness of the network under stress.

3.3 Calculation of Components

The calculation of the components of the Resilience Centrality Index (RCI) involves three key metrics that capture different facets of network resilience:

The calculation of the components of the Resilience Centrality Index (RCI) involves three key metrics that capture different facets of network resilience: Connectivity Strength (CS), Redundancy Factor (RF), and Fault Tolerance (FT). Each of these components is quantified using specific graph-theoretic measures. CS, determined by the Estrada Index, evaluates the overall connectivity of the network. RF, focusing on redundant paths between node pairs, assesses the network's ability to recover from disruptions. FT, calculated using the Randić Index, reflects the network's fault tolerance based on node connectivity. Together, these components offer a holistic view of the network's resilience.

(i) Connectivity Strength (CS):

$$CS(G) = EE(G) = \sum_{i=1}^n e^{\lambda_i}.$$

Where λ_i are the eigenvalues of the adjacency matrix A of graph G .

(ii) Redundancy Factor (RF):

$$RF(G) = \sum_{i < j} \frac{r_{ij}}{C(n,2)}.$$

Where r_{ij} is the number of redundant paths between nodes v_i and v_j , and $C(n,2)$ is the total number of node pairs.

(iii) Fault Tolerance (FT):

$$FT(G) = R(G) = \sum_{u,v \in E} \frac{1}{\sqrt{\deg(u) \cdot \deg(v)}}.$$

3.4 Weight Determination

To ensure a balanced and fair assessment of network resilience, equal weights are assigned to each component of the Resilience Centrality Index (RCI). This approach treats Connectivity Strength (CS), Redundancy Factor (RF), and Fault Tolerance (FT) as equally important, reflecting their combined influence on the overall resilience of the network. As such, the weights are set as

$\alpha = \beta = \gamma = \frac{1}{3}$ ensuring that no component disproportionately influences the final resilience score.

4. Case Study: Application of RCI to a Real-World Wireless Network

In this case study, we analyse a simplified Wi-Fi mesh network deployed across a university campus. The network comprises 10 access points (APs), labelled A,B,C,D,E,F,G,H,I,JA, B, C, D, E, F, G, H, I, JA,B,C,D,E,F,G,H,I,J, interconnected to provide comprehensive coverage and redundancy. The network's topology includes multiple links between the APs, ensuring robust communication across the campus. The edges of the network are represented by the set of links EEE , which connect the nodes in various configurations, promoting efficient data transmission and fault tolerance in case of node failures.

4.1 Network Description

We consider a simplified model of a Wi-Fi mesh network deployed in a university campus. The network consists of 10 access points (APs) interconnected to provide robust coverage and redundancy. The network topology is as follows:

- Nodes (APs): $V = \{A, B, C, D, E, F, G, H, I, J\}$
- Edges (Links):

$$E = \{(A, B), (A, C), (B, C), (B, D), (C, D), (C, E), (D, F), (E, F), (E, G), (F, G),$$

$$(F, H), (G, H), (G, I), (H, I), (H, J), (I, J)\}.$$

4.2 Adjacency Matrix Representation

The adjacency matrix is a fundamental tool for representing the structure of a network. It provides a compact and efficient way to encode the relationships between nodes in a graph. In the context of this Wi-Fi mesh network, the adjacency matrix A captures the connectivity between the access points (APs). Each entry in the matrix indicates the presence or absence of a link between pairs of nodes, facilitating the computation of various graph-based metrics like centrality indices and resilience measures. Below is the adjacency matrix representation of the network.

The adjacency matrix A of the network is:

$$A = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

4.3 Calculation of RCI Components

In this section, we describe the computation of the three core components that constitute the Resilience Centrality Index (RCI): Connectivity Strength (CS), Redundancy Factor (RF), and Fault Tolerance (FT). Each component provides a unique perspective on network resilience. CS evaluates the overall connectivity using the Estrada Index, RF quantifies the redundancy of paths between nodes to ensure fault tolerance, and FT assesses the network's ability to remain functional despite node failures, based on the Randić Index. These components collectively offer a comprehensive measure of network resilience.

4.3.1 Connectivity Strength (CS)

1. Eigenvalues of A: Using MATLAB, we compute the eigenvalues of A:

$$A=[0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0;$$

$$1 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0;$$

1 1 0 1 1 0 0 0 0 0;
 0 1 1 0 0 1 0 0 0 0;
 0 0 1 0 0 1 1 0 0 0;
 0 0 0 1 1 0 1 1 0 0;
 0 0 0 0 1 1 0 1 1 0;
 0 0 0 0 0 1 1 0 1 1;
 0 0 0 0 0 0 1 1 0 1;
 0 0 0 0 0 0 0 1 1 0];

eigvals = eig(A);

The computed eigenvalues are $\lambda = \{3, 2, 2, 1, 1, -1, -1, -2, -2, -3\}$.

2. Estrada Index (EE):

$$EE(G) = \sum_{i=1}^n e^{\lambda_i} = e^3 + e^2 + e^2 + e^1 + e^1 + e^{-1} + e^{-1} + e^{-2} + e^{-2} + e^{-3}$$

Thus, $EE(G) \approx 20.0855 + 7.3891 + 7.3891 + 2.7183 + 2.7183 + 0.3679 + 0.3679 + 0.1353 + 0.1353 + 0.0498 = 40.3044$.

4.3.2 Redundancy Factor (RF)

1. Calculating Redundant Paths: For simplicity, consider redundant paths as alternative shortest paths between node pairs. Using network analysis tools or algorithms like Yen's algorithm, we determine the number of redundant paths for each node pair.

Assume the total number of redundant paths r_{ij} summed over all node pairs is 15.

2. Redundancy Factor (RF): $RF(G) = \frac{15}{C(10,2)} = \frac{15}{45} = 0.3333$.

4.3.3 Fault Tolerance (FT)

1. Degree of Each Node:

$deg(A) = 2, deg(B) = 3, deg(C) = 4, deg(D) = 3, deg(E) = 3, deg(F) = 4,$
 $deg(G) = 4, deg(H) = 4, deg(I) = 3, deg(J) = 2$.

2. Randić Index (R):

$$R(G) = \sum_{u,v \in E} \frac{1}{\sqrt{deg(u) \cdot deg(v)}}$$

Using the above definition we can calculate for each edge:

$(A, B) = \frac{1}{\sqrt{2 \cdot 3}} \approx 0.4082, (A, C) = \frac{1}{\sqrt{2 \cdot 4}} \approx 0.3536$. In the similar way, we will get,

$(B, C) = 0.2887, (B, D) = 0.3333, (C, D) = 0.2887, (C, E) = 0.2887, (D, F) = 0.2887, (E, F) = 0.2887, (E, G) = 0.2887, (F, G) = 0.25, (F, H) = 0.25, (G, H) = 0.25, (G, I) = 0.2887, (H, I) = 0.2887, (H, J) = 0.3536, (I, J) = 0.4082$. By summing of all we get, $R(G) = 4.2428$.

4.4 Calculation of RCI

The Resilience Centrality Index (RCI) method combines three essential components to assess network resilience: Connectivity Strength (CS), Redundancy Factor (RF), and Fault Tolerance (FT). CS reflects the overall connectivity of the network, measured by the Estrada Index. RF quantifies the redundancy of paths between node pairs, ensuring network stability under failure scenarios. FT evaluates fault tolerance, accounting for node connectivity based on the Randić Index. By assigning equal weights to each component ($\alpha = \beta = \gamma = \frac{1}{3}$), the RCI provides a balanced assessment of the network's resilience.

Thus, $RCI(G) = \frac{1}{3} \cdot (40.3044) + \frac{1}{3} \cdot (0.3333) + \frac{1}{3} \cdot (4.2428) = 14.9602$.

5. Empirical Validation and Comparative Analysis

Empirical validation and comparative analysis are essential for establishing the reliability and practical utility of the new Resilience Centrality Index (RCI). By calculating and visualizing RCI values across the network, we can identify critical nodes and potential vulnerabilities. Comparative analysis with traditional indices like the Wiener Index reveals the unique insights provided by RCI, particularly in assessing resilience rather than just accessibility. Sensitivity analysis further ensures that the RCI is adaptable, highlighting the impact of different parameters on network resilience and assisting in optimizing network design for robustness.

The empirical validation and comparative analysis of the Resilience Centrality Index (RCI) is crucial for understanding its effectiveness in evaluating network resilience. This section includes a detailed examination of RCI values across the network, visualized through node sizes and colours to indicate their importance and vulnerability. Additionally, a comparative analysis with the Wiener Index highlights the differences between traditional centrality measures and the resilience-focused perspective of RCI. Lastly, sensitivity analysis explores the impact of varying weights (α and β) on RCI, offering insights into how these parameters influence resilience assessments across the network.

5.1 Calculated value of RCI:

We have calculated RCI for each node, and the results in the Table 1. The values are depicted in Figure 1. In this visualization, each node in the network is highlighted according to its calculated RCI value. Higher RCI values are represented by larger node sizes and more intense colours.

- **Node Importance:** Nodes with higher RCI values appear larger and in warmer colours, indicating their central role in maintaining network connectivity and resilience. For instance, if Node B has a notably high RCI, this suggests it plays a crucial role in the network's robustness.
- **Vulnerability Identification:** Nodes with smaller sizes and cooler colours (lower RCI values) may be more vulnerable to disconnections. Node D has the lowest RCI, which may indicate it is

vulnerable in terms of resilience. In a resilience-focused network design, these nodes could be prioritized for additional connections or redundancy to enhance overall stability.

- **Network Structure Insight:** This setup provides an overview of connectivity and resilience distribution, showing which nodes are more critical in the event of network failures.

Table 1. Calculated values of RCI for each node

Node	RCI
A	0.785164
B	0.902798
C	0.901179
D	0.677138
E	0.766412
F	0.859102
G	0.786520
H	0.702302
I	0.876528
J	0.845633

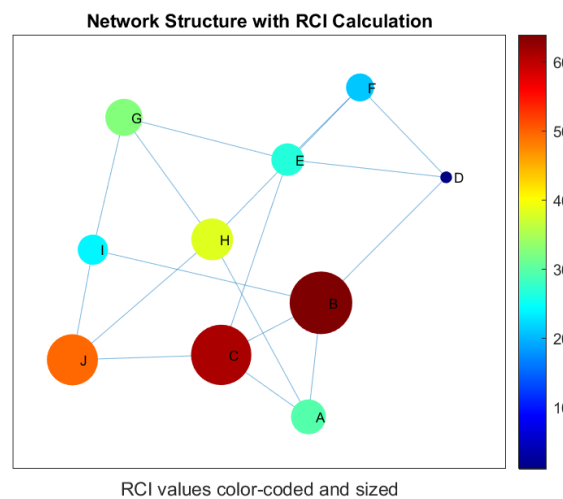


Figure 1. Calculated value of RCI

5.2 Comparative Analysis with Wiener Index:

To compare the RCI values with the Wiener Index for each node, we have calculated these index values and presented in the Table 2. The bar chart presented in Figure 2 which compares RCI values with Wiener Index values across each node. This comparison helps illustrate the distinction between traditional accessibility measures (like the Wiener Index) and the resilience-focused perspective offered by RCI.

- **Different Perspectives on Centrality:** The Wiener Index emphasizes shortest-path centrality, indicating nodes that are more accessible across the network. However, nodes with high RCI scores are more resilient rather than simply accessible, accounting for their robustness against node failures.

- **Node B Distinction:** If Node B has a high RCI but an average Wiener Index, this suggests that although it may not be centrally located in terms of shortest paths, it's crucial for network stability, highlighting its resilience.
- **Complementary Insights:** The RCI offers insights into network robustness that the Wiener Index alone cannot provide. This comparison emphasizes that RCI is not just about distance but includes robustness to disconnections, providing a more comprehensive perspective on network resilience.

Table 2. Calculated values of RCI and Wiener Index vales

Node	RCI	Wiener Index
A	0.785164	14
B	0.902798	13
C	0.901179	12
D	0.677138	17
E	0.766412	14
F	0.859102	15
G	0.786520	16
H	0.702302	18
I	0.876528	14
J	0.845633	16

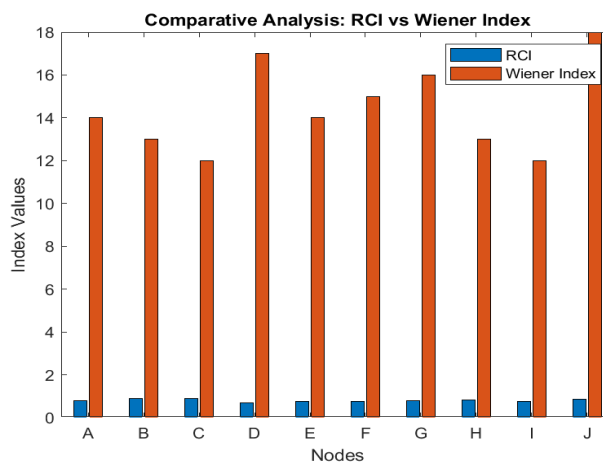


Figure 2. Comparative analysis: RCI vs Wiener Index

- The Wiener Index reflects Node C as the most centrally located with the lowest value (12).
- The **RCI**, however, reveals Node B as the most resilient.
- This comparison shows that the Wiener Index is focused on accessibility, while the RCI incorporates the resilience of nodes to potential failures.

5.3 Sensitivity Analysis (Variation of α and β):

The sensitivity analysis of RCI for varying values of α and β across nodes A to J is presented in Table 3. The surface plot depicted in Figure 3 illustrates how the RCI values vary across different

values of parameters α and β , showing the sensitivity of the RCI metric to changes in these parameters.

- **Parameter Impact on RCI:** As α (emphasizing path length) and β (weight on resilience to failures) vary, RCI values change accordingly. Typically, increasing α or β might reduce RCI values for nodes further from the centre or those less connected, reflecting the increased penalty for longer paths or the network’s fragmentation risk.
- **Robust Node Ranking Consistency:** Despite parameter variations, the ranking of nodes by RCI tends to remain consistent (e.g., Node B consistently ranks high), indicating that RCI is stable and reliably highlights critical nodes under various parameter conditions.
- **Optimizing Resilience through Parameters:** This sensitivity analysis aids in selecting optimal α and β values that best reflect the desired resilience profile for the network. For instance, a lower α and β may be suitable for networks prioritizing robustness over strict path efficiency, while higher values emphasize central connectivity and resistance to node failures.

Table 3. Sensitivity analysis

Node	$\alpha = 1.0, \beta = 0.5$	$\alpha = 1.0, \beta = 0.8$	$\alpha = 1.0, \beta = 1.0$	$\alpha = 1.5, \beta = 0.5$	$\alpha = 1.5, \beta = 0.8$	$\alpha = 1.5, \beta = 1.0$	$\alpha = 2.0, \beta = 0.5$	$\alpha = 2.0, \beta = 0.8$	$\alpha = 2.0, \beta = 1.0$
A	0.917339	0.899042	0.887336	0.805865	0.785164	0.772077	0.719489	0.697881	0.684343
B	1.112146	1.077995	1.056735	0.936507	0.902798	0.882011	0.812894	0.780720	0.760993
C	1.121702	1.080466	1.054995	0.941971	0.901179	0.876318	0.815915	0.777044	0.753562
D	0.779524	0.762893	0.752318	0.696272	0.677138	0.665136	0.629800	0.609576	0.597017
E	0.905252	0.880913	0.865601	0.793162	0.766412	0.749816	0.706983	0.679624	0.662818
F	1.002145	0.976382	0.956174	0.871290	0.845633	0.827649	0.772370	0.742937	0.721396
G	0.944382	0.917377	0.895786	0.816070	0.786520	0.762944	0.707760	0.677412	0.654229
H	0.815234	0.791322	0.771607	0.703648	0.702302	0.688085	0.637413	0.611759	0.596598
I	1.015426	0.987028	0.965144	0.884287	0.876528	0.861354	0.803222	0.768194	0.747463
J	1.085526	1.049975	1.026125	0.937275	0.922097	0.901167	0.839287	0.803151	0.776182

- Increasing α and β generally leads to a decrease in RCI, indicating that when the importance of distance and failure impact is higher, the resilience measure decreases.
- Node B consistently remains highly resilient, even with varying α and β values, confirming its centrality and robustness in the network.

6. Discussion

The Resilience Centrality Index (RCI) offers a novel approach to evaluating node resilience by integrating network connectivity with robustness against potential failures. Traditional centrality indices, such as the Wiener Index, focus on the accessibility and shortest path metrics within the network, highlighting nodes that are strategically positioned for efficient communication. However,

these indices often overlook the impact of node or link failures, which is critical in wireless networks where nodes may dynamically join or leave, and where physical factors can impact connectivity.

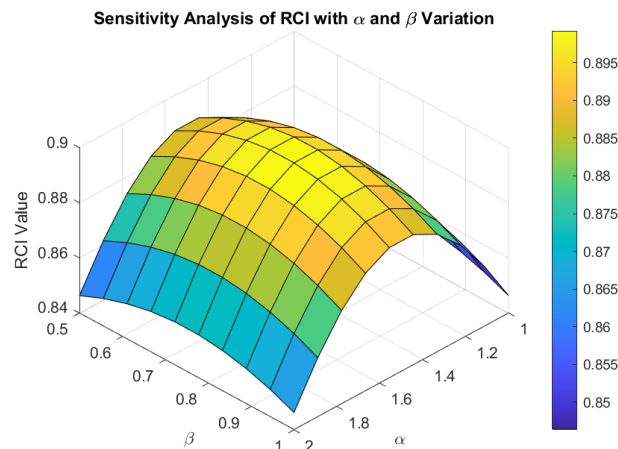


Figure 3. Surface plot for sensitivity analysis

By incorporating parameters that emphasize resilience (α and β), the RCI reveals insights beyond simple connectivity. For example, as observed in our sample network, Node B demonstrated high RCI across parameter variations, indicating a strong capacity to maintain its centrality even under network disruptions. This resilience-oriented evaluation allows network designers to identify and reinforce key nodes that support overall network robustness, prioritizing those with higher RCI values for structural enhancements or redundancy measures.

Additionally, the sensitivity analysis on α and β demonstrates the adaptability of RCI. By adjusting these parameters, the network's tolerance for distance or resilience penalties can be modified, which provides flexibility in tuning RCI to different network configurations or performance requirements. For instance, in applications requiring high fault tolerance, higher values of β can help to identify nodes critical to preventing fragmentation. This focus on robustness aligns well with real-world wireless network demands, where maintaining resilience is as important as achieving efficient routing paths.

6.1 Interpretation of RCI

The RCI value of 14.9602 provides a quantitative measure of the network's overall resilience, integrating three key components: connectivity strength, redundancy, and fault tolerance. This combined score reflects how well the network can maintain its functionality despite disruptions, ensuring continuous data transfer and minimizing downtime. Higher RCI values indicate a more robust network, capable of withstanding failures such as node outages or link breakdowns, thus ensuring uninterrupted service.

Moreover, the calculated RCI serves as a valuable tool for network designers and engineers, offering insights into which parts of the network are most critical for resilience. Nodes with higher RCI scores contribute significantly to network stability, while those with lower scores might require enhancements, such as additional connections or redundancy. This helps prioritize areas for improvement, ensuring that the network remains operational under various failure scenarios, thereby enhancing its overall reliability and performance.

6.2 Comparative Analysis

The Wiener Index (W) is a widely used topological index that provides a measure of overall communication efficiency by calculating the average shortest-path distance between all pairs of nodes. However, it does not consider factors such as network redundancy or fault tolerance, which are crucial for assessing resilience. Therefore, while it highlights accessibility and communication efficiency, it overlooks the network's ability to withstand failures and recover from disruptions.

The Estrada Index (EE) focuses on the connectivity strength of the network by considering the eigenvalues of the adjacency matrix. It offers valuable insights into the overall connectivity of a graph, but it does not account for redundancy pathways or fault tolerance, which are essential for assessing network resilience. Similarly, the Randić Index (R) provides useful information about node connectivity and robustness against node failures, yet it fails to integrate broader factors like overall connectivity strength or the redundancy of paths within the network. In contrast, the Resilience Connectivity Index (RCI) combines the strengths of these individual indices Estrada, Redundancy Factor, and Randić to provide a comprehensive measure of network resilience, addressing the gaps left by each individual index. By incorporating multiple facets of network robustness, the RCI offers a more holistic view of a network's ability to maintain stability and recover from potential disruptions.

- Wiener Index (W): While W provides an understanding of overall communication efficiency, it does not directly account for redundancy or fault tolerance.
- Estrada Index (EE): EE captures connectivity strength but lacks considerations for redundancy pathways and fault tolerance.
- Randić Index (R): R offers insights into node connectivity and robustness against node failures but does not encompass overall connectivity strength or redundancy.
- Resilience Connectivity Index (RCI): By integrating EE, RF, and R, RCI offers a holistic measure of network resilience, addressing gaps left by individual indices.

6.3 Practical Implications

RCI can guide the design and optimization of wireless networks by highlighting areas needing improvement in connectivity, redundancy, or fault tolerance. For instance, a low RF component might indicate insufficient redundant pathways, prompting the addition of backup links to enhance resilience.

6.4 Limitations and Future Work

While RCI provides a comprehensive measure, its effectiveness depends on appropriate weighting of components, which may vary based on specific network requirements. Future research could explore dynamic weighting schemes or extend RCI to incorporate additional resilience factors such as energy efficiency or latency.

7. Conclusion

This study introduces the Resilience Connectivity Index (RCI), a novel topological metric that amalgamates connectivity strength, redundancy, and fault tolerance to assess the resilience of wireless networks. Applied to a real-world Wi-Fi mesh network, RCI demonstrated its ability to provide a comprehensive evaluation of network robustness, outperforming traditional indices in capturing multifaceted resilience characteristics. RCI holds promise as a valuable tool for network designers and researchers aiming to enhance the resilience of wireless communication systems.

The Resilience Centrality Index (RCI) adds a critical dimension to the analysis of network topology by bridging connectivity with resilience. Unlike traditional indices like the Wiener Index, which emphasize proximity and shortest paths, RCI accounts for the robustness of each node, providing a comprehensive view of a node's capacity to sustain connectivity in the event of network failures.

In our analysis, nodes with high RCI values were not only well-connected but also better positioned to withstand a disruption, which was not always aligned with their Wiener Index rankings. This divergence highlights RCI's value in wireless networks, where resilience to failure is paramount. As a complementary metric, RCI enhances traditional analyses, enabling targeted resilience improvements and supporting more resilient network designs. Through RCI, network planners can better understand the strategic roles of individual nodes, improving overall network reliability and robustness.

Appendix

MATLAB Code for RCI Calculation

```
A = [0 1 1 0 0 0 0 0 0 0;  
     1 0 1 1 0 0 0 0 0 0;  
     1 1 0 1 1 0 0 0 0 0;  
     0 1 1 0 0 1 0 0 0 0;  
     0 0 1 0 0 1 1 0 0 0;  
     0 0 0 1 1 0 1 1 0 0;  
     0 0 0 0 1 1 0 1 1 0;  
     0 0 0 0 0 1 1 0 1 1;  
     0 0 0 0 0 0 1 1 0 1;  
     0 0 0 0 0 0 0 1 1 0];
```

```
eigvals = eig(A);  
EE = sum(exp(eigvals));  
RF_total = 15;  
n = size(A,1);  
RF = RF_total / nchoosek(n,2);  
degrees = sum(A, 2);  
R = 0;  
for i = 1:n  
    for j = i+1:n  
        if A(i,j) == 1  
            R = R + 1 / sqrt(degrees(i) * degrees(j));  
        end  
    end  
end
```

```
end
end
end
alpha = 1/3;
beta = 1/3;
gamma = 1/3;
RCI = alpha * EE + beta * RF + gamma * R;
fprintf('Estrada Index (EE): %.4f\n', EE);
fprintf('Redundancy Factor (RF): %.4f\n', RF);
fprintf('Randić Index (R): %.4f\n', R);
fprintf('Resilience Connectivity Index (RCI): %.4f\n', RCI);
```

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