

A Composite Stability Index Framework for Routing Stability Analysis in Mobile Ad Hoc Networks

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Abstract

Routing stability continues to be a significant issue in Mobile Ad Hoc Networks (MANETs) because of constant topology alterations resulting from node movement and varying network density. Traditional MANET performance assessment usually depends on various independent metrics, including packet delivery ratio, routing overhead, and latency. Nonetheless, evaluating these metrics individually may fail to sufficiently represent the overall stability performance of routing activities. To overcome this limitation, this document presents a Composite Stability Index (CSI) that combines various routing stability indicators into a cohesive evaluation framework. The suggested CSI integrates normalized metrics of Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL) to create a unified quantitative measure reflecting overall routing stability.

The CSI framework undergoes thorough assessments via extensive simulations in NS2 with different network densities, node mobility rates, and mobility models. Experimental findings indicate that routing stability declines when node density and mobility rise, attributed to greater link breakage rates and elevated routing overhead. A comparative analysis of mobility models reveals that the Gauss-Markov mobility model produces greater CSI values, suggesting more stable routing conditions compared to the Random Waypoint and Random Direction models. Moreover, a robust positive correlation exists between CSI and packet delivery ratio, indicating that greater CSI values lead to enhanced network performance. Heat maps and surface analyses additionally demonstrate the combined effect of node density and mobility on routing stability.

The findings indicate that the suggested CSI framework offers a thorough and understandable measure for assessing routing stability in MANET settings. Combining various stability indicators into one analytical measure, CSI facilitates a more efficient examination of routing behavior in dynamic network environments and provides a valuable resource for assessing and contrasting MANET routing protocols.

Keywords: Mobile Ad Hoc Networks, Routing Stability, Composite Stability Index, AODV, Mobility Models, Network Simulation.

1. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are autonomous wireless networks where mobile nodes interact directly without depending on fixed infrastructure or centralized control. In these networks, nodes actively create multi-hop communication routes that allow data transfer between far-off nodes. Thanks to their adaptable deployment and lack of required infrastructure, MANETs have gained considerable research focus and are often explored for uses including disaster recovery, military communications, environmental surveillance, and temporary network setups in isolated regions [2], [3], [6].

Even with these benefits, ensuring dependable communication in MANET settings continues to be a difficult issue. The main challenge stems from the changing topology due to node movement, which often alters network connectivity and interrupts established communication paths. As nodes move in relation to one another, wireless connections can unexpectedly fail, initiating route rediscovery processes and rising routing overhead. Frequent changes in topology can impair network performance by lowering packet delivery rates, raising end-to-end delay, and creating extra control traffic within the network [1], [4].

To tackle these challenges, many routing protocols have been suggested for MANET settings. Reactive routing protocols like the Ad hoc On Demand Distance Vector (AODV) protocol create routes only when needed, thus minimizing unnecessary routing overhead in contrast to proactive methods [1]. Alternative routing methods include stability aware approaches, multipath routing techniques, or adaptive route discovery strategies to enhance reliability in changing network conditions [4], [8]. Nonetheless, assessing the effectiveness of these routing protocols continues to be a complicated endeavor because of the ever-changing characteristics of MANET environments.

Most current research evaluates routing performance through various independent metrics like packet delivery ratio, routing overhead, delay, throughput, and route lifetime. Although these metrics offer important insights into particular elements of network behavior, they are generally examined in isolation, which complicates achieving a holistic view of routing stability in dynamic networks. In practice, many of these metrics are closely connected. For instance, constant link failures shorten route lifespans, leading to higher routing overhead and ultimately impacting packet delivery efficiency. As a result, examining these indicators separately might not entirely reflect the comprehensive stability traits of routing operations in MANET environments.

A significant aspect affecting routing performance is the interplay among network parameters like node density, node mobility, and mobility patterns. Greater node densities can enhance network connectivity but may also result in heightened contention and routing overhead. Likewise, increased node mobility may lead to frequent link failures and route interruptions. Various mobility models can additionally affect routing stability by generating distinct movement patterns and characteristics of link duration [5], [7]. Thus, grasping the collective influence of these factors is vital for assessing routing behavior in MANETs.

Inspired by these findings, this paper introduces a Composite Stability Index (CSI) that combines various routing stability indicators into a single assessment metric. The CSI integrates three essential metrics concerning routing stability: Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL). Through the consolidation of these metrics into one index, the CSI offers a complete depiction of routing stability and facilitates a more efficient examination of routing patterns in fluctuating network environments.

To assess the suggested framework, simulation tests are performed using the NS-2 network simulator across different network densities, levels of node mobility, and mobility models. The research explores the impact

of these factors on routing stability and analyzes the connection between CSI and network performance metrics like packet delivery ratio. Supplementary analyses utilizing heat maps and surface visualizations are conducted to investigate the joint effect of density and mobility on routing stability

The main contributions of this work can be summarized as follows:

1. A Composite Stability Index (CSI) is introduced to provide a unified measure of routing stability in MANET environments.
2. A systematic evaluation framework is developed that integrates routing stability indicators obtained from simulation experiments.
3. The proposed CSI metric is analyzed under varying node densities, mobility levels, and mobility models to examine routing stability behavior.
4. The relationship between CSI and network performance metrics such as packet delivery ratio is investigated to demonstrate the effectiveness of the proposed approach.

The rest of this paper is structured in the following manner. Section 2 examines previous research on MANET routing and its performance assessment. Section 3 introduces the suggested Composite Stability Index framework and its mathematical model. Section 4 outlines the experimental setup and the simulation environment. Section 5 examines the experimental findings and evaluates routing stability across various network scenarios. Lastly, Section 6 wraps up the paper and highlights avenues for future study.

2. RELATED WORK

Routing in Mobile Ad Hoc Networks (MANETs) has been extensively researched because of the fundamental challenges created by dynamic topology, node movement, and lack of centralized infrastructure. Initial studies concentrated on creating routing protocols that could ensure dependable communication in environments without infrastructure. The Ad hoc On-Demand Distance Vector (AODV) protocol features a route discovery mechanism that creates routes solely when required, minimizing unnecessary control overhead [1]. Later, a number of extensive studies have investigated the traits and performance compromises of MANET routing protocols, encompassing proactive, reactive, and hybrid routing methods [2], [3]. These studies emphasize significant issues including routing scalability, route upkeep, and control overhead in very dynamic networks.

An additional key area of study has explored how mobility and network dynamics influence routing behavior. Mobility models applied in simulation research greatly impact the performance of routing protocols, and it has been demonstrated that frequently utilized models like the random waypoint model can create unrealistic node distribution patterns, which influence experimental outcomes [7]. In a similar manner, the scalability of routing protocols across different node densities and diverse network environments has been analyzed to assess the behavior of routing mechanisms as the size of the network expands [5]. These studies highlight that routing efficiency is significantly affected by network characteristics like node mobility, traffic volume, and network density

Link stability is also acknowledged as a crucial element influencing routing reliability in MANETs. Frequent link disruptions due to node movement initiate route rediscovery processes, resulting in higher routing overhead and decreased communication effectiveness. To tackle this concern, multiple routing mechanisms that consider stability have been suggested, integrating link stability metrics into route selection choices [4], [9]. Multipath routing protocols, like the Ad hoc On demand Multipath Distance Vector (AOMDV), enhance route dependability by sustaining several alternate paths among communicating nodes, thus lessening the effects of link failures on communication efficiency [8]

Besides fundamental routing methods, numerous investigations have examined improvements and optimization strategies designed to enhance routing efficiency and strengthen network resilience. In integrated Internet MANET settings, mechanisms for gateway selection are necessary to enable communication between mobile nodes and outside networks. Gateways that consider traffic conditions have been suggested to enhance service quality and alleviate congestion in these settings [10]. Likewise, fuzzy control-based adaptive gateway discovery methods have been implemented to enhance load balancing and routing effectiveness [11]. Various research efforts have suggested alterations to traditional routing protocols to improve route discovery effectiveness, energy awareness, and routing dependability [12], [14], [17]. Approaches focused on trust-based routing and secure routing mechanisms have been explored to enhance the security and reliability of networks [15]

Recent studies have investigated smart and flexible routing methods that can adapt to changing network conditions. Techniques in machine learning, such as reinforcement learning, have been utilized to create routing systems that adjust to changes in topology and fluctuations in traffic patterns [18]. Research on elements influencing MANET performance highlights that routing effectiveness relies on various interconnected factors, including mobility patterns, node density, and traffic load [19]. Comparative analyses assessing various routing protocols across diverse simulation scenarios consistently deliver meaningful perspectives on protocol effectiveness and design compromises [20].

Furthermore, new routing methods have integrated delay-aware and opportunistic communication approaches to enhance packet delivery efficiency in fast-changing settings [21]. Recent studies have suggested resilient routing architectures and improved protocol designs to enhance network robustness amidst frequent topology changes [22]. Additionally, recent research assessing routing protocols in dynamic network environments underscores the intricate connection between routing overhead, mobility, and overall network efficiency [23], [24]

A summary of representative MANET routing studies is presented in Table1, which highlights the primary focus areas and limitations of existing research.

Table1: Summary of Representative MANET Routing Studies

Ref.	Focus Area	Key Contribution	Limitation
[1]	AODV routing	Implementation and analysis of on-demand routing protocol	Focus on protocol behavior
[2], [3]	MANET routing surveys	Comprehensive classification of routing protocols	Lack unified stability framework
[4], [9]	Link-stability routing	Incorporate link stability into route selection	Stability metrics evaluated individually
[5]	Routing scalability	Analysis of scalability in heterogeneous networks	Limited focus on routing stability
[7]	Mobility modeling	Demonstrates influence of mobility models on routing evaluation	Does not propose stability metrics
[8]	Multipath routing	Introduces AOMDV protocol with multiple route options	Metrics evaluated independently
[10], [11]	Internet–MANET integration	Gateway selection and adaptive gateway discovery mechanisms	Focus on connectivity management
[12], [14], [17]	Routing optimization	Enhanced routing mechanisms considering energy, stability, and security	No unified performance indicator
[18]	Intelligent routing	Reinforcement learning–based routing strategies	Higher computational complexity

[19], [20]	Performance surveys	Comparative evaluation of routing protocols	Metrics considered separately
[21], [22]	Recent routing enhancements	Delay-aware and resilient routing mechanisms	Limited integrated performance analysis
[23], [24]	Performance evaluation studies	Protocol evaluation under dynamic network conditions	Lack unified stability evaluation
This Work	Composite stability analysis	Introduces a Composite Stability Index (CSI) integrating multiple routing stability indicators into a unified evaluation framework	-

While these studies offer important perspectives on routing performance, the majority of current research assesses network behavior through single performance metrics. Common assessment metrics consist of packet delivery ratio, end-to-end latency, throughput, routing overhead, and indicators of route stability. Although these metrics reflect particular features of network behavior, examining them separately might not sufficiently convey the comprehensive stability attributes of routing activities in MANET settings. Table2 presents the performance metrics frequently utilized in previous studies on MANET routing

Table2. Routing Performance Metrics Used in Prior MANET Studies

Ref.	Metrics Used	Evaluation Focus
[1]	Routing overhead, packet delivery ratio	Evaluation of AODV routing performance
[4], [9]	Link stability, route lifetime	Stability-aware routing
[8]	Packet delivery ratio, delay, routing overhead	Multipath routing performance
[12]	Throughput, delay, routing overhead	Evaluation of AODV modifications
[14]	Energy consumption, route stability	Energy-efficient routing
[15]	Trust level, packet delivery ratio	Secure routing decisions
[18]	Throughput, delay, learning efficiency	Reinforcement-learning routing
[20]	Packet delivery ratio, throughput, delay	Comparative protocol analysis
[21]	Delay, packet delivery ratio	Opportunistic routing evaluation
[23], [24]	Throughput, delay, routing overhead	Protocol performance evaluation

As illustrated in Table2, earlier research usually assesses routing protocols by utilizing various separate performance metrics. Nevertheless, these metrics are frequently examined independently, which might not completely reflect the collective impact of link stability, route persistence, and routing overhead on total network performance. In highly dynamic MANET environments, these elements closely interact and collectively influence the stability of routing operations. Thus, there is a requirement for analytical methods that combine various stability-related metrics into a cohesive framework that can depict overall routing behavior in a more thorough manner.

Inspired by this finding, the current research presents a Composite Stability Index (CSI) that consolidates various routing stability metrics into a unified measurement for assessing routing efficiency in MANETs. The CSI offers a consolidated view of routing stability by merging essential metrics associated with route persistence, link failure patterns, and routing costs, thus facilitating a comprehensive assessment of network performance in fluctuating environments

3. METHODOLOGY

3.1 Network Simulation Framework

Assessing routing stability in mobile ad hoc networks necessitates a structured framework that reflects the relationship among node mobility, link dynamics, and the functioning of routing protocols. This study employs a simulation-driven evaluation framework to assess routing stability in dynamic network environments.

The simulated environment includes mobile nodes positioned within a specified network region. Nodes interact via multi-hop wireless connections employing a reactive routing protocol. Because of node movement, connections can fail, requiring the dynamic discovery of new paths. Throughout the simulation, various routing performance metrics are gathered and subsequently utilized to calculate the Composite Stability Index (CSI)

The evaluation framework consists of four stages: network simulation, metric collection, metric normalization, and CSI computation.

3.2 Routing Stability Metrics

Routing stability in MANETs is primarily affected by link reliability and routing overhead. In this study, three indicators are used to characterize routing stability.

Path Stability Time (PST): Path Stability Time indicates the length of time a communication pathway stays valid without disruption. Higher PST values signify consistent routes and lower route rediscovery costs.

Link Breakage Rate (LBR): Link Breakage Rate indicates how often link failures take place while the network is in operation. Elevated LBR values usually suggest unstable network situations due to the movement of nodes

Normalized Routing Load (NRL): Normalized Routing Load calculates the proportion of routing control packets to data packets that are successfully delivered, indicating the overhead of the routing protocol

3.3 Mathematical Model of Routing Stability

In a MANET setting, link disruptions mainly happen because of node movement. Let N denote the total count of nodes in the network and v signify the average speed of the nodes. The likelihood of a link disruption between two nodes depends on their mobility in relation to each other and their communication range.

The expected link breakage rate can be approximated as

$$LBR \propto \rho v$$

Where, ρ represents node density and v represents average node velocity.

Higher mobility and node density increase the likelihood of link breakages, which leads to frequent route rediscovery events and increased routing overhead

Path stability time is inversely related to link breakage behavior and can be expressed as

$$PST \propto \frac{1}{LBR}$$

As link failures become more frequent, route lifetimes decrease, resulting in lower path stability.

Link breakages also impact routing overhead because route discovery packets are sent each time a route fails. Therefore, the normalized routing load can be estimated as

$$NRL \propto LBR$$

These relationships indicate that routing stability in MANETs depends on the interaction between route persistence, link failure dynamics, and routing overhead.

3.4 Composite Stability Index (CSI)

A Composite Stability Index (CSI) is introduced to represent the collective effect of routing stability indicators. Because the metrics are in various units, they are initially standardized using min-max normalization

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

After normalization, the CSI is defined as,

$$CSI = \alpha PST' - \beta LBR' - \gamma NRL'$$

Where, PST' is normalized path stability time, LBR' is normalized link breakage rate and NRL' is normalized routing load. Higher CSI values indicate more stable routing conditions. The weighting parameters satisfy:

$$\alpha + \beta + \gamma = 1$$

3.5 CSI-Based Stability Analysis Framework

Upon calculating the Composite Stability Index (CSI), the suggested framework assesses routing stability across various network scenarios. The evaluation is conducted by analyzing the fluctuations of CSI values across various simulation settings like node mobility, network density, and traffic load.

In the course of simulation, routing activities produce measurements for the previously established stability indicators, specifically Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL). These metrics are gathered for every simulation scenario and then normalized via the min-max normalization technique outlined in Section 3.4. Normalization guarantees that metrics with varying units and value ranges contribute equally to the CSI computation

The entire CSI calculation procedure is depicted in Figure1. The figure illustrates that routing stability indicators derived from the simulation environment are initially normalized and subsequently merged to calculate the CSI value

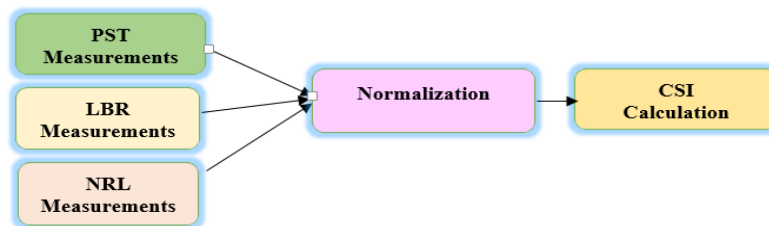


Figure1. CSI Computation Process

The calculated CSI values are then examined to assess routing stability across various network conditions. Increased CSI values indicate stable routing conditions marked by extended route lifetimes, reduced link failures, and diminished routing overhead. On the other hand, reduced CSI values suggest erratic routing activity resulting from regular topology alterations and heightened control traffic.

Utilizing this framework, the CSI offers a singular metric that reflects the collective impact of essential routing stability factors, facilitating a more thorough assessment of routing performance in mobile ad hoc networks.

3.6 CSI Computation Algorithm

The calculation of the Composite Stability Index (CSI) is formalized via a systematic process that incorporates routing stability metrics derived from simulation experiments. The algorithm analyzes the critical metrics Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL) to generate a CSI value for every simulation scenario.

As these metrics are assessed on varying scales, they are initially standardized through the min–max normalization technique mentioned previously. The weighted formulation is then applied to combine the normalized metrics and calculate the CSI value. In this study, uniform weights are given to each parameter to uphold simplicity and guarantee an equal contribution of the stability indicators.

Greater CSI values signify stable routing scenarios defined by extended route lifetimes, fewer link disruptions, and reduced routing overhead, while lesser CSI values reflect unstable network conditions. The procedure for computing CSI is outlined in Algorithm1

Algorithm 1 Composite Stability Index (CSI) Computation

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1: Input: Simulation scenarios  $S$ , metrics  $PST(s)$ ,  $LBR(s)$ ,  $NRL(s)$ , weights  $\alpha, \beta, \gamma$ 

2: Step 1: Collect Metrics
3: for each scenario  $s \in S$  do
4:   Record  $PST(s)$ ,  $LBR(s)$ ,  $NRL(s)$ 
5: end for

6: Step 2: Compute Min–Max Values
7:  $PST_{min} \leftarrow \min(PST(s))$ ,  $PST_{max} \leftarrow \max(PST(s))$ 
8:  $LBR_{min} \leftarrow \min(LBR(s))$ ,  $LBR_{max} \leftarrow \max(LBR(s))$ 
9:  $NRL_{min} \leftarrow \min(NRL(s))$ ,  $NRL_{max} \leftarrow \max(NRL(s))$ 

10: Step 3: Normalize Metrics
11: for each scenario  $s \in S$  do
12:    $PST'(s) \leftarrow \frac{PST(s) - PST_{min}}{PST_{max} - PST_{min}}$ 
13:    $LBR'(s) \leftarrow \frac{LBR(s) - LBR_{min}}{LBR_{max} - LBR_{min}}$ 
14:    $NRL'(s) \leftarrow \frac{NRL(s) - NRL_{min}}{NRL_{max} - NRL_{min}}$ 
15: end for

16: Step 4: Compute CSI
17: for each scenario  $s \in S$  do
18:    $CSI(s) \leftarrow \alpha \cdot PST'(s) + \beta \cdot LBR'(s) + \gamma \cdot NRL'(s)$ 
19: end for

20: Output:  $CSI(s)$  for all scenarios
  
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4. EXPERIMENTAL SETUP

Simulation experiments were carried out with the Network Simulator NS-2.35 to assess the efficacy of the suggested Composite Stability Index (CSI). The experiments aimed to evaluate routing stability in Mobile Ad Hoc Networks (MANETs) across different network densities, mobility patterns, and node velocities.

The simulation setting includes mobile nodes placed in a rectangular region of 600 m × 400 m, where nodes interact via multi-hop wireless connections. Node mobility causes frequent changes in topology that can result in link failures and the need for route rediscovery, enabling the examination of routing stability in dynamic network scenarios. Every simulation is conducted for 1000 seconds to gather ample network activity and routing behavior.

To examine the impact of network density, the quantity of nodes is adjusted to 25, 50, 75, 100, and 125 nodes. Furthermore, various mobility models are taken into account to represent diverse movement patterns. In the experiments, the mobility models utilized are the Random Waypoint (RWP), Random Direction (RD), and Gauss-Markov (GM). The speeds of the nodes are adjusted to 3 m/s, 6 m/s, and 10 m/s to illustrate various mobility levels. In the RWP model, a pause duration of 100 seconds is implemented, whereas the Gauss-Markov model utilizes a correlation coefficient $\alpha = 0.75$ to regulate movement smoothness.

Traffic flow adheres to a Constant Bit Rate (CBR) model using UDP transport, featuring a packet size of 512 bytes and a traffic rate of 128 kbps. Five simultaneous traffic flows are created between randomly chosen source-destination pairs to illustrate standard communication patterns.

The IEEE 802.11 MAC protocol is utilized by the wireless communication layer, and the TwoRayGround model is employed to simulate signal propagation. The interface queue is set up as DropTail or PriQueue, with a maximum limit of 50 packets. To guarantee statistical reliability and minimize randomness in the simulation results, five distinct random seeds are employed for every scenario

The routing protocol examined in the experiments is AODV, known for its reactive routing characteristics and effective route discovery process, making it popular in MANET performance research

In the simulation, routing stability metrics such as Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL) are documented. These metrics are then analyzed using the Composite Stability Index framework outlined in Section 3 to assess routing stability in various network scenarios.

The key simulation parameters used in the experiments are summarized in Table3.

Table3: Simulation Parameters

Parameter	Value
Simulator	NS-2.35
Simulation Area	600 m × 400 m
Simulation Time	1000 s
Node Counts	25, 50, 75, 100, 125
Mobility Models	RWP, RD, GM
Node Speed	3, 6, 10 m/s
RWP Pause Time	100 s
GM Correlation Factor (α)	0.75
Traffic Type	CBR over UDP
Packet Size	512 bytes
Traffic Rate	128 kbps
Number of Flows	5
MAC Protocol	IEEE 802.11
Propagation Model	TwoRayGround
Interface Queue	DropTail/PriQueue (50 packets)
Random Seeds	5
Routing Protocol	AODV

5. RESULTS AND DISCUSSIONS

This section details the experimental assessment of the suggested Composite Stability Index (CSI) across varying network conditions. The study examines how node density, node mobility, and mobility models affect routing stability. Furthermore, the influence of various CSI weighting setups is analyzed to determine how specific routing stability metrics affect the overall stability performance of the network

5.1 Effect of Node Density on Routing Stability

Figure 2 depicts how the Composite Stability Index (CSI) changes as the quantity of nodes in the network rises. The evaluation examines four distinct weight setups that reflect varying relative impacts of the stability metrics: Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL).

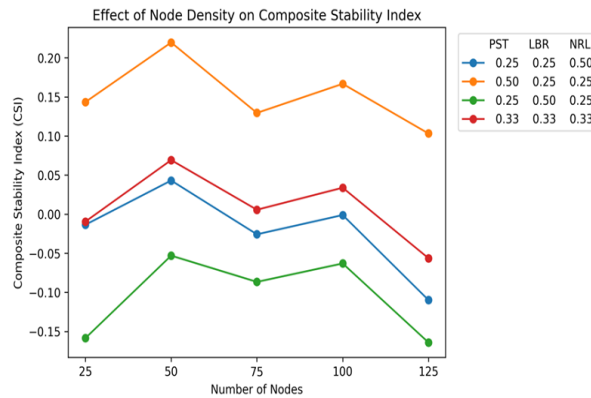


Figure2: Effect of Node Density on Composite Stability Index

The findings suggest that routing stability typically diminishes with rising node density. With a small number of nodes, the network faces fewer link failures and decreased routing overhead, leading to increased CSI values. With a rise in node density, the number of possible link interactions expands considerably, resulting in heightened competition in the wireless medium and more frequent changes in topology. As a result, the rate of link failures rises, and the routing overhead increases because of the more frequent need for route rediscovery.

The illustration likewise shows the impact of the CSI weighting factors. Configurations that prioritize routing overhead (NRL) show marginally reduced CSI values in dense networks, suggesting that routing overhead becomes a key element influencing routing stability in high-density scenarios. In contrast, setups that prioritize path stability time generally preserve relatively higher CSI values, indicating that consistent routes can somewhat alleviate the adverse impacts of greater node density.

Overall, the results confirm that node density plays a significant role in determining routing stability in MANET environments.

5.2 Impact of Node Mobility on Routing Stability

Figure3 illustrates how CSI changes in relation to levels of node mobility. Node velocities of 3 m/s, 6 m/s, and 10 m/s are viewed as indicative of low, moderate, and high mobility scenarios respectively.

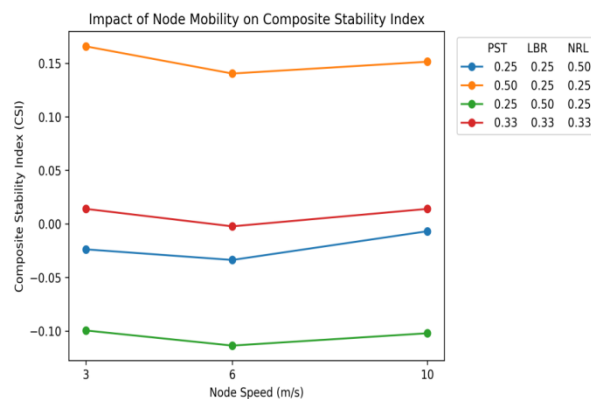


Figure3: Impact of Node Mobility on Composite Stability Index

The findings clearly indicate that CSI diminishes with an increase in node mobility. At reduced speeds, nodes shift gradually in relation to one another, leading to extended route durations and a decrease in link failures. In these circumstances, the network undergoes minimized routing overhead and enhanced path stability, resulting in elevated CSI values.

With the rise in node speed, the frequency of link failures increases because of swift topology alterations. Frequent route failures initiate extra route discovery processes, leading to higher routing overhead and diminishing path stability duration. As a result, the total CSI value drops, indicating diminished routing stability.

The findings align with the theoretical correlation outlined in Section 3.3, indicating that the rate of link breakage rises in proportion to the velocity of nodes. These results emphasize how node mobility affects the stability of MANET routing and showcase the CSI framework's ability to effectively capture this phenomenon.

5.3 Influence of Mobility Models on Routing Stability

Figure 4 illustrates routing stability across three frequently utilized mobility models: Random Waypoint (RWP), Random Direction (RD), and Gauss-Markov (GM). Every mobility model signifies various movement patterns and consequently results in unique topology dynamics

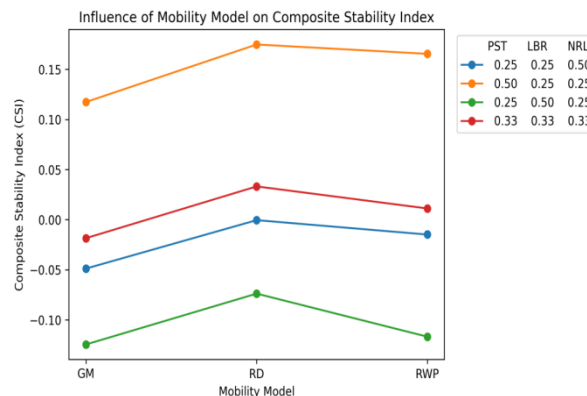


Figure4: Influence of Mobility Model on Composite Stability Index

The findings show that the Gauss-Markov mobility model typically yields greater CSI values than the other models. This behavior can be linked to the temporal correlation inherent in the Gauss-Markov model, leading to smoother node transitions and more consistent link durations. As a result, paths usually stay valid for extended durations, minimizing link failures and routing overhead.

Conversely, the Random Waypoint model features frequent alterations in direction and varying node velocities, raising the chances of link disruptions. Likewise, the Random Direction model can lead to nodes spreading out toward the edges of the simulation space, producing uneven node distributions and heightened route instability.

These findings validate that mobility patterns have a considerable impact on routing behavior in MANETs,

and the CSI framework successfully reflects the stability variations caused by different mobility models.

5.4 Relationship between Packet Delivery Ratio and CSI

Figure5 shows the correlation between the packet delivery ratio (PDR) and the Composite Stability Index. The illustration shows a favorable relationship between the two measures. Elevated CSI values typically indicate enhanced packet delivery performance

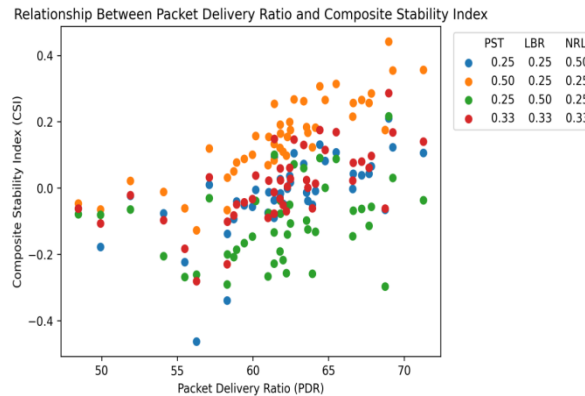


Figure5: Relationship between Packet Delivery Ratio and Composite Stability Index

This connection is anticipated since stable pathways decrease the chances of packet losses due to route failures. When routes stay valid for extended durations, data packets can be transmitted successfully without disruption, leading to increased PDR values. On the other hand, unstable pathways result in packet losses and more retransmissions, diminishing delivery performance.

The noted correlation demonstrates that CSI accurately reflects routing stability features that directly affect packet delivery performance.

5.5 Joint Impact of Node Density and Mobility

A two dimensional stability analysis, illustrated in Figure6 with a CSI heat map, is provided to explore the joint effect of node density and node mobility. The heat map offers a graphical depiction of CSI values for various combinations of node counts and node speeds

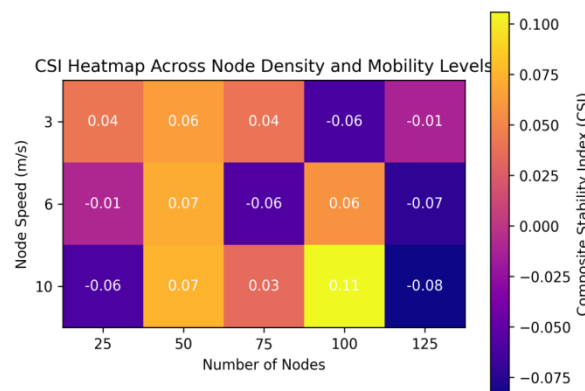


Figure6: Composite Stability Index heat map across Node Density and Mobility Levels

The findings show that the peak CSI values appear in situations of low mobility and moderate node density. With rising node speed, CSI values drop at every density level, verifying the adverse effect of mobility on routing stability. Likewise, very high node densities diminish CSI as a result of heightened contention and routing overhead.

The heat map distinctly shows the relationship between density and mobility parameters, indicating that routing stability is affected by the interplay of these factors rather than by an isolated parameter.

5.6 CSI Surface Analysis

Figure7 shows a three-dimensional surface representation of CSI based on node density and node speed. The surface plot offers a clear visualization of how routing stability changes with different network conditions

CSI Surface Plot Across Node Density and Mobility

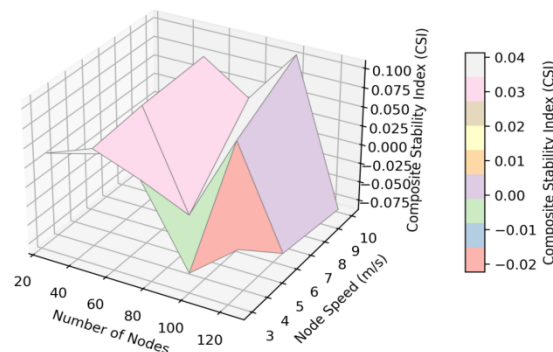


Figure7: Composite Stability Index Surface Plot across Node Density and Mobility Levels

The surface demonstrates a steady reduction in CSI as the density of nodes and their speed rise. This trend indicates the joint impact of more link failures and elevated routing overhead due to frequent changes in topology. The contour projection on the base plane emphasizes stable regions in the parameter space, facilitating the straightforward identification of operating conditions that offer comparatively stable routing performance.

In summary, the surface analysis indicates that the suggested CSI framework successfully identifies the relationship between network density and node mobility, offering an extensive perspective on routing stability under various MANET operating conditions.

6. CONCLUSION

This research presented a Composite Stability Index (CSI) as a single measure for assessing routing stability in Mobile Ad Hoc Networks. In contrast to conventional performance evaluation methods that depend on separate metrics, the suggested CSI combines three essential routing stability indicators: Path Stability Time (PST), Link Breakage Rate (LBR), and Normalized Routing Load (NRL) into one comprehensive analytical framework. This combined method allows for a broader depiction of routing stability in dynamic MANET settings.

Simulation experiments carried out with NS-2 assessed routing stability across different node densities, mobility rates, and mobility models. The findings show that routing stability diminishes as node density and mobility rise, leading to greater link breakage rates and elevated routing overhead. The study also indicated that mobility trends greatly affect routing behavior, with the Gauss-Markov mobility model offering more stable routing conditions than the Random Waypoint and Random Direction models. Moreover, the identified positive correlation between CSI and packet delivery ratio verifies that the suggested metric accurately represents overall network effectiveness.

The heat map and surface analyses further underscore the interplay between node density and mobility, showing that routing stability is influenced by the collective effect of various network parameters. These results suggest that the suggested CSI framework can offer important insights into routing patterns and facilitate a more thorough performance assessment of MANET routing protocols.

Future efforts might enhance the suggested framework by adding more performance metrics like energy usage, throughput, and delay variability. The CSI concept can also be utilized in assessing new MANET routing approaches, such as machine learning-based routing protocols and adaptive mechanisms intended for very dynamic network situations

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