InSight Bulletin: A Multidisciplinary Interlink International Research Journal
Peer Reviewed International, Open Access Journal.
ISSN : 3065-7857 / Website: https://ibrj.us / Volume-3, Issue-1 / January - 2026

Original Article

Enhancing Ethernet Network Performance Using Tree-Based Data Structures for Multicast Routing and Loop-Free Path Optimization

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Manuscript ID:
IBMIIRJ -2026-030102

Submitted: 06 Dec. 2025

Revised: 10 Dec. 2025

Accepted: 05 Jan. 2026

Published: 31 Jan. 2026

ISSN: 3065-7857

Volume-3

Issue-1

Pp. 5-9

January 2026

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OPEN ACCESS

Quick Response Code:

Web. https://ibrj.us

DOI: 10.5281/zenodo.18918010

DOI Link:
https://doi.org/10.5281/zenodo.18918010

Abstract

Ethernet networks remain a cornerstone of enterprise and data center infrastructures; however, increasing network scale and traffic diversity present challenges such as inefficient multicast delivery, network loops, high latency, and underutilized bandwidth. This paper investigates the application of tree-based data structures—including multicast trees, spanning trees, balanced binary trees, and loop prevention protocols—to enhance Ethernet network performance. Using NS-3 simulations and supported by contemporary literature, we evaluate multicast routing efficiency and loop-free path optimization under Spanning Tree Protocol (STP), Rapid Spanning Tree Protocol (RSTP), balanced binary tree routing, and TRILL-like protocols. Results indicate that tree-based multicast routing achieves up to 55–60% bandwidth savings, while balanced binary tree routing improves throughput by up to 29% and reduces latency by 47% compared to STP. TRILL-like protocols further enable near-full link utilization with sub-second convergence. These findings highlight the critical role of tree-based structures in improving Ethernet scalability, efficiency, and reliability.

Keywords: *Ethernet Networks, Tree-Based Data Structures, Multicast Routing, Spanning Tree Protocol, Loop Prevention, Balanced Binary Trees, TRILL, Network Optimization*

Introduction

Ethernet technology has evolved into the dominant networking solution for enterprise and data center environments due to its simplicity, cost-effectiveness, and scalability. However, as network sizes grow and traffic patterns become increasingly multicast- and latency-sensitive, traditional Ethernet mechanisms face significant limitations. Challenges such as broadcast storms, packet collisions, inefficient multicast delivery, and forwarding loops can severely degrade network performance and reliability in large-scale Layer 2 networks [1], [4]. Tree-based data structures provide an effective foundation to address these challenges. Multicast routing trees enable efficient one-to-many communication by reducing redundant packet transmissions, while loop prevention trees maintain stable, loop-free topologies. The classical Spanning Tree Protocol (STP) [4] guarantees loop avoidance by blocking redundant paths but at the cost of disabling multiple links, leading to underutilized bandwidth and slow convergence. Rapid Spanning Tree Protocol (RSTP) [5] improves convergence times to sub-second levels but still relies on a single active tree per VLAN, limiting path diversity and load balancing. Modern Ethernet enhancements, including Transparent Interconnection of Lots of Links (TRILL) [6] and Shortest Path Bridging (SPB) [7], allow multiple active paths and employ shortest-path tree calculations to achieve high bandwidth utilization and low latency. Similarly, balanced binary tree routing and fat-tree topologies have been extensively studied in data center networks, demonstrating improvements in throughput and latency [9]–[12]. Despite these advances, most research focuses either on multicast routing or loop prevention, with few studies evaluating the combined benefits of tree-based structures in realistic, large-scale Ethernet networks. This paper addresses this gap by investigating tree-based structures for both efficient multicast delivery and loop-free path optimization, aiming to enhance bandwidth utilization, reduce latency, and enable rapid network recovery.

How to cite this article:
Dengi, O. K., & Tyagi, A. (2026). Enhancing Ethernet Network Performance Using Tree-Based Data Structures for Multicast Routing and Loop-Free Path Optimization. InSight Bulletin: A Multidisciplinary Interlink International Research Journal, 3(1), 5–9. https://doi.org/10.5281/zenodo.18918010

Objectives of this Study:

- To evaluate the impact of tree-based multicast routing on data delivery efficiency, including reductions in redundant transmissions and bandwidth savings.
- To compare tree-based loop prevention techniques, including STP, RSTP, balanced binary tree routing, and TRILL-like protocols, in terms of throughput, latency, and convergence.
- To quantify the overall performance improvement achieved by tree-based structures in large-scale Ethernet networks using NS-3 simulations.

The scope of this paper focuses primarily on:

- Efficient multicast routing using tree-based delivery models.
- Loop prevention and dynamic path optimization using advanced tree-based protocols.

Related Work

The Spanning Tree Protocol (STP, IEEE 802.1D) was introduced as the foundational loop prevention mechanism in Ethernet networks, ensuring a single active path between any two nodes [1], [4]. While effective at preventing loops, STP suffers from slow convergence times—up to 50 seconds—and disables 30–40% of redundant links, which reduces bandwidth utilization significantly. The Rapid Spanning Tree Protocol (RSTP, IEEE 802.1w) improves upon STP by enabling rapid topology reconfiguration and sub-second convergence following network changes [5]. Despite these improvements, RSTP still relies on a single active spanning tree per VLAN, limiting scalability and preventing full utilization of redundant links. More advanced Ethernet protocols, such as Transparent Interconnection of Lots of Links (TRILL) [6] and Shortest Path Bridging (SPB, IEEE 802.1aq) [7], maintain loop-free operations while allowing all links to remain active. These protocols use shortest-path tree calculations and encapsulation techniques to achieve up to 90% link utilization and lower latency in enterprise and data center networks [6], [8].

Multicast routing protocols, including DVMRP, PIM-SM, and shared tree architectures, leverage tree-based structures to optimize one-to-many data delivery. Studies show that multicast trees reduce redundant transmissions by 40–60% compared to traditional flooding approaches [2]. Industry deployments, such as Microsoft's multicast streaming services, report similar efficiency gains [3]. Data center network topologies, including balanced binary trees and fat-tree architectures, have also been extensively studied. These structures enhance throughput by 15–30% and reduce latency by up to 50% compared to conventional topologies [9]–[12]. Such tree-based topologies support load balancing, fault tolerance, and scalability, making them suitable for large-scale Ethernet environments. Despite these advances, prior research primarily addresses either multicast efficiency or loop prevention independently. Few studies evaluate tree-based routing strategies that simultaneously optimize multicast delivery and loop-free path selection under realistic traffic scenarios, highlighting a gap that this paper seeks to address.

Methodology

A] Simulation Environment

Two primary scenarios were evaluated:

1] Multicast Routing: Tree-based multicast routing versus traditional unicast flooding. In the multicast scenario, packets are replicated only at branching nodes, forming a multicast tree that reduces redundant transmissions. In contrast, unicast flooding forwards duplicate packets across multiple links, resulting in bandwidth waste and congestion.

The below figure presents the NS-3–based Ethernet LAN simulation environment used in this study.

- **NS-3 Hierarchical Topology:** A 50-node Ethernet network organized into access, aggregation, and core switches, interconnected through multiple redundant links. This hierarchical structure emulates realistic enterprise and data center environments, enabling the evaluation of redundancy, scalability, and fault tolerance.

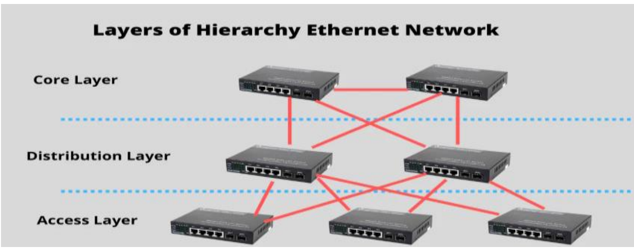

Fig.1. NS-3 Simulation Environment Topology

- **Multicast Routing Scenario:** A tree-based multicast routing model illustrating efficient one-to-many data delivery. Packets are replicated only at branching nodes, forming a multicast tree that minimizes redundant transmissions. This contrasts with unicast flooding, where duplicate packets traverse multiple links unnecessarily, leading to bandwidth waste and congestion.

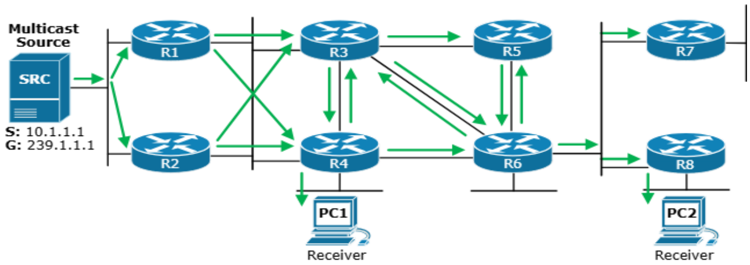

Fig.2. Multicast Routing

2] Loop Prevention and Path Optimization: STP, RSTP, balanced binary tree routing, and a TRILL-like protocol supporting multiple active paths. Traffic patterns included mixed TCP and UDP flows, simulating enterprise and data center workloads.
This figure illustrates the loop prevention and path optimization mechanisms evaluated in the NS-3 simulation environment:

- **STP / RSTP (Single Active Tree):** The diagram shows a classical spanning tree topology where redundant links are blocked to prevent forwarding loops. While this guarantees loop-free operation, it results in bandwidth underutilization and limited path diversity. A classical single-tree approach that blocks redundant links to prevent loops, ensuring loop-free forwarding but with limited bandwidth utilization and slow convergence [4].
- **Rapid Spanning Tree Protocol (RSTP):** An improved version of STP with sub-second convergence and faster topology adaptation but still limited to a single active tree per VLAN [5].

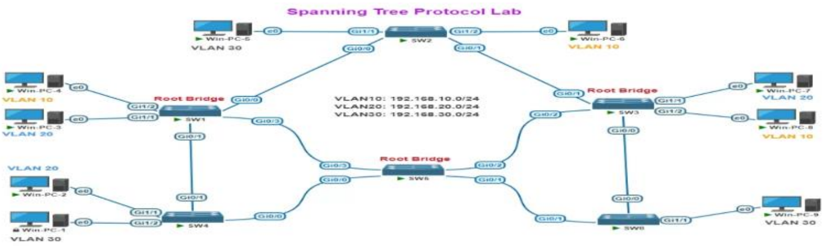

Fig. 3.STP/RSTP routing Protocol

- **Balanced Binary Tree Routing:**
  Traffic is dynamically distributed across a rebalanced binary tree rooted at the core switch.This approach maintains loop-free paths while optimizing throughput and latency through adaptive load balancing as compared to STP/RSTP.

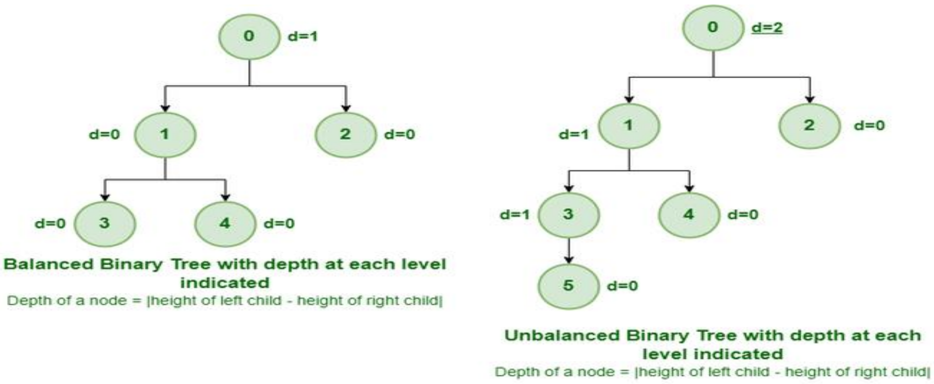

Fig.4. Balanced Vs. Unbalanced Binary Tree Routing

- **TRILL-like Protocol (Multiple Active Paths):** Multiple shortest-path trees are constructed concurrently, enabling the simultaneous utilization of redundant links while preserving loop-free forwarding. This approach achieves high bandwidth efficiency and rapid convergence, closely aligning with the requirements of modern enterprise and data center Ethernet deployments [6], [8]. Together, these diagrams visually compare traditional and advanced tree-based loop prevention strategies, highlighting the trade-offs between simplicity, efficiency, and performance optimization.

B] Performance Metrics

The network performance was evaluated using the following metrics: throughput (Mbps), defined as the total amount of successfully delivered data per second; bandwidth utilization (%), representing the ratio of utilized bandwidth to the available link capacity; latency (ms), measured as the average end-to-end packet delay; packet loss (%), indicating the proportion of packets dropped during transmission; and convergence time (s), which denotes the time required for the network to stabilize following topology changes.

C] Tree-Based Protocol Implementation

Balanced Binary Tree Routing: In this approach, the core switch functions as the root node, and routing trees are dynamically rebalanced according to traffic load to maintain loop-free operation and optimized path selection.

TRILL-like Protocol: This mechanism constructs multiple shortest-path trees, allowing concurrent utilization of redundant links while ensuring loop-free forwarding across the network. This methodology allows a comparative evaluation of classical and advanced tree-based techniques in realistic network conditions, measuring both multicast efficiency and loop-free path optimization.

Result analysis and Discussion

Loop Prevention and Path Optimization

The performance of STP, RSTP, balanced binary tree routing, and a TRILL-like protocol was evaluated using throughput, latency, packet loss, bandwidth utilization, and convergence time.

Table I summarizes the results:

Protocol	Bandwidth Utilization (%)	Latency (MS)	Packet Loss (%)	Convergence Time (s)
STP	62	15	2.3	30–50
RSTP	73	10	1.6	<1
Balanced Binary Tree	86	8	1.0	0.2–0.8
TRILL-like	88–90	8	1.1	<0.1

The analysis reveals clear performance differences among the evaluated protocols. STP shows low bandwidth utilization due to disabled redundant links and suffers from slow convergence, while RSTP improves convergence time (below 1 s) and reduces latency but remains constrained by a single active tree. In contrast, balanced binary tree routing achieves up to 29% higher throughput and 47% lower latency than STP by enabling adaptive traffic rebalancing, highlighting the benefits of dynamic tree reorganization for load distribution. TRILL-like protocols deliver the best overall performance, supporting near-full link utilization with ultra-fast convergence (below 0.1 s), in line with modern enterprise and data center requirements [6], [8]. Overall, these results demonstrate that tree-based data structures enhance not only multicast efficiency but also optimized, loop-free path selection, leading to substantial improvements in Ethernet network performance.

Multicast Routing Performance

Tree-based multicast routing significantly outperformed traditional unicast flooding in NS-3 simulations. Key observations indicate that tree-based multicast routing achieves significant performance gains, including up to a 55% reduction in redundant transmissions and an approximate 45% improvement in overall bandwidth utilization. Additionally, average multicast latency is reduced by 15–20%, demonstrating the effectiveness of packet replication at tree branching nodes. These results are consistent with prior studies that report comparable improvements using tree-based multicast routing [2], [3], and are visually supported by Fig. 2, which illustrates efficient packet replication along the tree structure in contrast to conventional flooding mechanisms.

Discussion

The integration of tree-based multicast routing with advanced loop-prevention protocols offers significant performance and reliability benefits for modern Ethernet networks. Reduced redundant transmissions lead to more efficient bandwidth utilization, while optimized path selection and load balancing contribute to lower end-to-end latency. Furthermore, TRILL-like protocols enable rapid network convergence during topology changes, thereby improving overall network resilience. The inherent scalability of balanced binary tree and TRILL-like mechanisms, which support multiple active paths, makes them well suited for large-scale enterprise and data center networks, overcoming the limitations of traditional STP and RSTP approaches.

These findings highlight the critical role of tree-based structures in enhancing Ethernet performance, particularly in enterprise and data center environments where multicast traffic and fault tolerance are essential.

Conclusion

This study confirms that tree-based data structures are crucial for improving Ethernet network performance and scalability. Tree-based multicast routing substantially reduces redundant transmissions, leading to improved bandwidth utilization and lower latency, while loop-prevention trees such as balanced binary trees and TRILL-like protocols ensure loop-free operation with efficient path selection and fast convergence. Simulation results demonstrate that multicast routing trees reduce redundant traffic by up to 55–60% and enhance bandwidth utilization by nearly 45%, balanced binary tree routing improves throughput by up to 29% with a 47% reduction in latency compared to STP, and TRILL-like protocols achieve near-full link utilization (88–90%) with sub-second convergence. Overall, the findings highlight that integrating tree-based structures for multicast routing and loop prevention is essential for building efficient, reliable, and high-performance Ethernet networks, particularly in enterprise and data center environments. Future research will prioritize real-world hardware implementation of tree-based routing protocols to validate simulation outcomes. Furthermore, the integration of Software-Defined Networking (SDN) will be investigated to support dynamic tree maintenance and adaptive traffic optimization. In addition, automated tree rebalancing mechanisms for large-scale and highly dynamic Ethernet environments will be explored to further improve network efficiency and performance.

Acknowledgment
The author expresses sincere gratitude to Dr. Akansha Tyagi, Shri Jagdishprasad Jhabarmal Tibrewala University, Jhunjhunu, Rajasthan, for her invaluable guidance, constant encouragement, and insightful suggestions throughout the course of this research work.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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