e-ISSN 2549-7472
Edumatic: Jurnal Pendidikan Informatika
Volume 10, Issue 10, **240-249.**
https://e-journal.hamzanwadi.ac.id/index.php/edumatic
DOI: 10.29408/edumatic.v10i1.34243

Evaluation of PCC Load Balancing for Dual ISP Networks: Enhancing Throughput and Traffic Stability

Bustomi [1,*] , Muhlis Tahir [1]

[1] Universitas Trunodjoyo Madura, Indonesia
[*] Corresponding author: Bustomi, Universitas Trunodjoyo Madura, Indonesia
✉ 220631100112@student.trunojoyo.ac.id

Received: 3 March 2026 | Revised: 16 March 2026 | Accepted: 23 April 2023 | Published: 27 April 2026

Abstract

Multi-ISP network management frequently encounters uneven traffic distribution and reduced connection stability, even when bandwidth capacity is sufficient. Prior studies show that load balancing techniques such as Per Connection Classifier (PCC) can effectively distribute traffic; however, most remain focused on implementation, with limited evaluation of network processing efficiency and inconsistent findings across testing scenarios. This study empirically examines the effectiveness of PCC integrated with failover in enhancing dual-ISP network performance through a controlled experimental design comparing conditions before and after implementation in a real network environment. Key parameters include throughput, traffic distribution, connection stability, and packet rate, analyzed using a quantitative comparative approach. The results demonstrate a substantial improvement in download throughput from 15–18 Mbps to 36–41 Mbps (±130–150%) and upload throughput from 14–17 Mbps to 36–40 Mbps (±120–140%), accompanied by more balanced traffic distribution and a notable reduction in packet rate, indicating increased processing efficiency. The integration of failover further ensures uninterrupted service continuity. Overall, the findings provide empirical evidence that connection-based load balancing not only optimizes traffic distribution but also improves processing efficiency, extending prior research and offering practical relevance for multi-ISP environments with dynamic traffic conditions.

Keywords: dual isp; load balancing; mikrotik; network traffic management; per connection classifier

To cite this article: Bustomi, B., & Tahir, M. (2026). Evaluation of PCC Load Balancing for Dual ISP Networks: Enhancing Throughput and Traffic Stability. *Edumatic: Jurnal Pendidikan Informatika*, *10*(1), 240–249. https://doi.org/10.29408/edumatic.v10i1.34243

INTRODUCTION

Inefficient multi-ISP network management remains a common issue across various modern network environments, including educational institutions, enterprises, and campuses with high and dynamic traffic characteristics (Abuhamdah & Al-Shabi, 2022). Globally, the demand for stable and scalable connectivity necessitates the implementation of effective network traffic engineering and resource optimization. However, the availability of more than one internet connectivity path does not automatically result in efficient load distribution. Without proper management mechanisms, bandwidth utilization tends to be uneven. This condition leads to traffic congestion, increased latency, and degradation of connection stability (Jasim & Al-raweshidyg, 2024). This highlights that network performance is determined not only by bandwidth capacity but also by the effectiveness of traffic management mechanisms based on load balancing and network optimization principles (Oikonomou & Rouskas, 2024).

Load balancing is part of the network optimization paradigm aimed at efficiently distributing traffic loads to maximize resource utilization (Al Reshan et al., 2023) and maintain Quality of Service (QoS) (Zhou et al., 2023). The main challenge in multi-ISP networks lies in the complexity of session-based traffic distribution and dynamic network conditions. Each communication connection requires path consistency (session persistence) to maintain data integrity. Improper distribution mechanisms can lead to packet out-of-order issues, increased packet loss, and disruptions in session-based services (Tawfeeg et al., 2022). Additionally, changes in network conditions, such as the failure of one ISP path, require mechanisms capable of automatically maintaining service continuity (Trung & Kim, 2025). This complexity makes traffic management in multi-ISP networks a non-trivial problem that requires a more adaptive approach.

Previous studies have examined the implementation of load balancing methods such as Nth, Equal Cost Multi Path (ECMP), and Per Connection Classifier (PCC) in multi-ISP networks. Research by (Amalia et al., 2022) shows that PCC performs better than Nth in maintaining connection stability, while (Fathurrohim & Basuki, 2025) found that PCC excels in preserving session consistency compared to ECMP. However, most of these studies focus primarily on technical implementation aspects without conducting in-depth comparative analyses of QoS parameters. Furthermore, other research such as (Nugroho et al., 2023) indicates that PCC improves traffic distribution but does not systematically examine its impact on network processing efficiency, such as packet rate and router load.

Methodologically, earlier investigations have generally been conducted in simulated environments or restricted scenarios involving a limited number of users, which do not adequately reflect real operational conditions. This constrains the generalizability of findings to real-world networks characterized by dynamic traffic patterns and intense bandwidth competition. The PCC approach also presents limitations due to its reliance on static hashing mechanisms that do not account for dynamic link quality parameters such as latency and packet loss (Lilhore et al., 2025). Empirically, inconsistencies in results across studies regarding bandwidth optimization further indicate that the effectiveness of PCC is highly dependent on implementation context and testing scenarios (Aldossary et al., 2025).

Most previous studies have not integrated load balancing mechanisms with failover within a single empirically tested system framework. From a network resilience perspective, integrating these mechanisms is crucial to ensure high availability in multi-ISP networks (Ali et al., 2025; Simone et al., 2023). The absence of this integrated approach highlights a research gap that is not only practical but also methodological, including weaknesses in theoretical framework development and a lack of empirical validation in real network environments.

Based on these gaps and issues, this study proposes the implementation of a PCC-based load balancing method integrated with an automatic failover mechanism within a unified system framework. Unlike previous studies, this research not only focuses on implementation but also conducts an empirical performance evaluation through comparative analysis before and after system deployment in a real operational network environment with multi-user scenarios. Furthermore, this study is positioned within a broader context as a representation of implementation in institutional-scale networks with characteristics similar to those of schools, campuses, or enterprises, thereby enhancing the relevance and generalizability of the findings.

This research is conducted on the network of SMK Negeri 3 Bangkalan as a case study representing a real operational environment with dynamic and multi-user traffic characteristics, where the utilization of two ISPs has not been accompanied by optimal traffic management mechanisms, resulting in imbalanced load distribution and inefficient bandwidth usage. The main contribution of this study lies in presenting an empirical evaluation of the PCC method in a real network environment, conducting comparative performance analysis before and after implementation based on QoS parameters, integrating load balancing and failover mechanisms, and testing performance under multi-user scenarios. Therefore, this research is expected to contribute theoretically to the development of connection-based traffic management strategies and practically to the optimization of multi-ISP networks in educational environments.

METHOD

This study employs a comparative experimental design to evaluate network performance before and after the implementation of the PCC load balancing method integrated with a failover mechanism. This approach aims to obtain an empirical analysis of network performance improvement based on QoS parameters. The independent variable is the traffic management method (without PCC and with PCC combined with failover), the dependent variables include throughput, connection stability, traffic distribution, and packet rate, while the control variables consist of the number of users, ISP bandwidth, and testing duration.

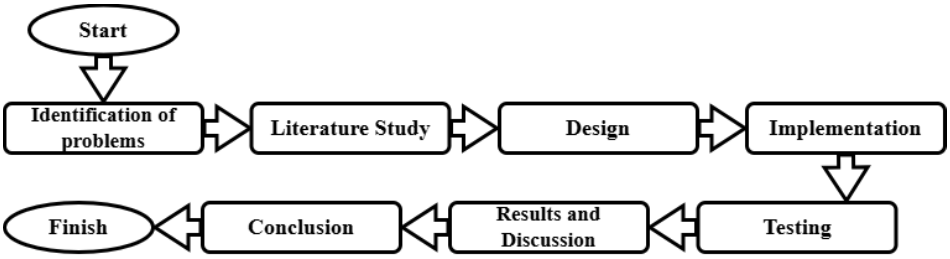


Figure 1. Research flow diagram

Figure 1 illustrates the research workflow, which includes problem identification, literature review, system design (topology, PCC, failover), implementation, QoS testing, results analysis, and conclusion. This workflow ensures that the study is conducted in a systematic and structured manner. The research was carried out on the operational network of SMK Negeri 3 Bangkalan, which utilizes a dual ISP architecture, each with a bandwidth of 50 Mbps. The network infrastructure employs a MikroTik router as the main gateway with a star topology. Testing involved approximately 20 active users to represent real network usage conditions.

The main device used in this study is a MikroTik router running the RouterOS operating system. Table 1 presents the software specifications, including the operating system, configuration tools, and network testing applications. Meanwhile, Table 2 provides the hardware specifications, covering the router, client devices, and supporting network components. Both tables are presented as references for system implementation.

Table 1. Software requirements specifications

No	Software	Description
1	Winbox versi 3.43	Used to remotely access the MikroTik router via GUI
2	Microsoft Windows 10	Operating system for administration and MikroTik configuration

The system configuration was carried out in two main stages. First, load balancing was implemented using the PCC method with the *both-addresses* parameter to ensure session persistence. This process includes creating mangle rules for connection classification, assigning connection marking and routing marking, and configuring routing with a 1:1 load-sharing ratio between ISPs. Second, a failover mechanism was integrated using *check-gateway* and routing distance settings to detect link failures and automatically redirect traffic to the active ISP.

Table 2. Hardware requirements specifications

No	Hardware	Quantity	Specifications
1	Mikrotik Router RB951Ui-2HnD	1 Unit	CPU: AR9344 600 MHz CPU Memory: 128 MB Ethernet: 5 ports
2	Laptop Server/admin	1 Unit	Device name: HP ProBook 450 G5 Processor: Core i5-8250U Memory: 8.00 GB System type: 64-bit operating system
3	PC *Client*	20 Units	Intel Core i3 Memory RAM 4 GB System type: 64-bit operating system
4	ISP	2 Units	Bandwidht ISP1 50 Mbps Bandwidht ISP2 50 Mbps

Testing was carried out under two conditions: before PCC implementation and after PCC integrated with failover, with each scenario conducted for 15 minutes under identical conditions where all users accessed the internet simultaneously. Data were obtained from MikroTik monitoring (traffic, packet rate, active connections) and Speedtest measurements, focusing on throughput, traffic distribution, packet rate, and connection stability, while latency and jitter were indirectly observed. Failover was evaluated by simulating an ISP disconnection, assessing switching time, session continuity, and network stability. Data analysis applied a descriptive comparative approach using average values, with performance improvements expressed as percentages. Consistency in users, duration, servers, and activities was maintained to ensure valid and objective comparison.

RESULT AND DISCUSSION

Result

The load balancing implementation was carried out on the network at SMK Negeri 3 Bangkalan using two Internet Service Providers (ISPs), namely IndiHome and PT-ERKA Jaringan Utama, with a MikroTik router as the main gateway. The network topology applies a dual ISP architecture integrated with the PCC method and an automatic failover mechanism. As shown in Figure 2, both ISPs are connected through interface *ether1* (ISP1) and *ether2* (ISP2).

The main change after implementation lies in the traffic distribution mechanism. Before applying PCC, all traffic tended to be concentrated on a single primary path. After implementation, connection distribution is performed using the PCC method with the *both-address* parameter. This mechanism ensures that each connection is consistently assigned to one of the ISP paths, transforming the traffic pattern from a single-path approach into a multi-path, connection-based model. In addition, the system is equipped with an automatic failover mechanism based on recursive routing, which enhances network availability in the event of a link failure.

The evaluation of traffic distribution was conducted using a comparative approach between conditions before and after PCC implementation, based on throughput and packet rate parameters. The measurement results show that prior to implementation, there was an imbalance in bandwidth utilization, indicated by the dominance of traffic load on one ISP path and a high packet rate exceeding 2,300 packets per second, reflecting packet density and processing load. After PCC implementation, a significant change in traffic distribution patterns was observed, where both ISPs exhibited simultaneous activity with more balanced throughput, namely ISP1 at 349.4 kbps (Tx) and 636.0 kbps (Rx), and ISP2 at 543.9 kbps (Tx) and 444.4

kbps (Rx). In terms of packet rate, a drastic reduction occurred to approximately 120–140 packets per second per interface, as illustrated in Figure 3.

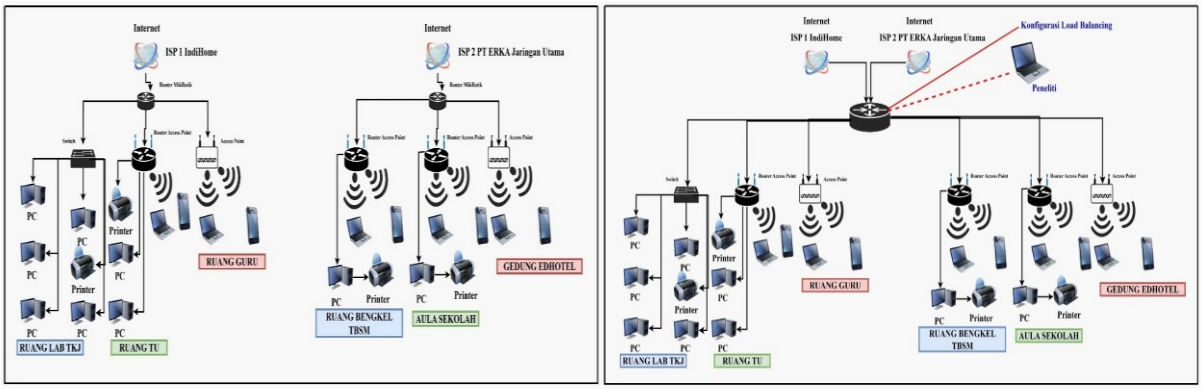
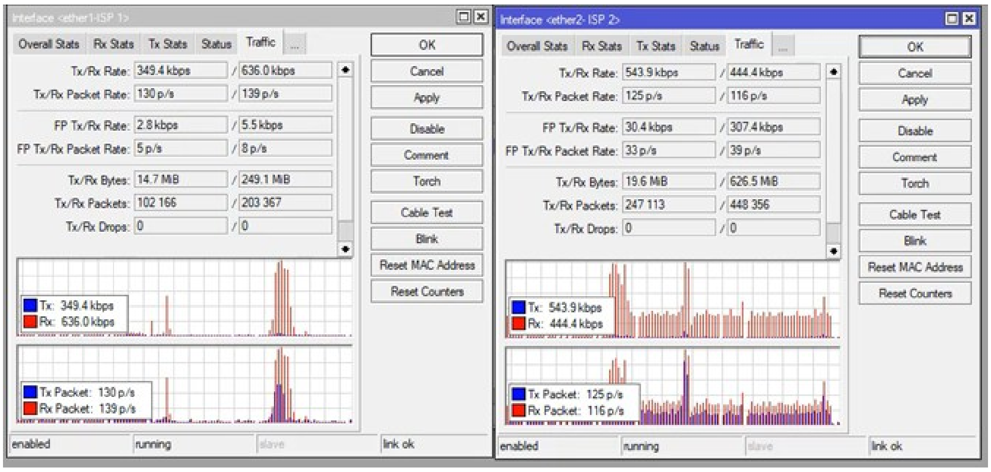


Figure 2. Network topology and pcc & failover scheme



Interface <ether1-ISP 1>

Tx/Rx Rate: 349.4 kbps / 636.0 kbps
Tx/Rx Packet Rate: 130 p/s / 139 p/s
FP Tx/Rx Rate: 2.8 kbps / 5.5 kbps
FP Tx/Rx Packet Rate: 5 p/s / 8 p/s
Tx/Rx Bytes: 14.7 MiB / 249.1 MiB
Tx/Rx Packets: 102 166 / 203 367
Tx/Rx Drops: 0 / 0
Tx: 349.4 kbps
Rx: 636.0 kbps
Tx Packet: 130 p/s
Rx Packet: 139 p/s
enabled running slave link ok

Interface <ether2- ISP 2>

Tx/Rx Rate: 543.9 kbps / 444.4 kbps
Tx/Rx Packet Rate: 125 p/s / 116 p/s
FP Tx/Rx Rate: 30.4 kbps / 307.4 kbps
FP Tx/Rx Packet Rate: 33 p/s / 39 p/s
Tx/Rx Bytes: 19.6 MiB / 626.5 MiB
Tx/Rx Packets: 247 113 / 448 356
Tx/Rx Drops: 0 / 0
Tx: 543.9 kbps
Rx: 444.4 kbps
Tx Packet: 125 p/s
Rx Packet: 116 p/s
enabled running slave link ok

Figure 3. Traffic monitoring graph after pcc load balancing implementation

The summary of changes in traffic distribution and packet rate is presented in Table 3 as a quantitative synthesis of the measurement results. It explicitly compares conditions before and after PCC implementation, including the level of load balancing across ISPs and the significant reduction in packet density as an indicator of improved network processing efficiency. This reduction consistently indicates decreased queue density and lower processing load on the router, demonstrating that a more balanced traffic distribution through PCC enhances system efficiency in managing network traffic.

Table 3. Traffic distribution and packet rate before and after pcc implementation

Parameter	ISP	Before PCC	After PCC	Change
Throughput Tx	ISP1	26,9 Mbps	349,4 kbps	Decreased (load distributed)
Throughput Tx	ISP2	19,8 Mbps	543,9 kbps	More balanced
Packet Rate (Tx)	ISP1	2.327pkt/s	130pkt/s	Significant decrease (~94%)
Packet Rate (Tx)	ISP2	1.650pkt/s	125pkt/s	Significant decrease (~92%)
Active Connections	ISP1 dominant	1.446 connection	Distributed	More balanced

Network performance testing was conducted through download and upload activities under active usage conditions, involving 20 concurrent users connected to the network. During the testing process, all users performed upload and download activities simultaneously within a 15-minute duration for each measurement session. The network utilized two Internet Service Providers (ISPs), namely IndiHome and PT ERKA Jaringan Utama, each with a bandwidth capacity of 50 Mbps. Network performance measurements were carried out using the Speedtest.net service to obtain data on access speed and connection stability.

The first test was conducted through simultaneous download activities using uniform file sizes across all clients. This test aimed to analyze changes in network performance, particularly in terms of download throughput, by comparing conditions before and after the implementation of load balancing. Based on Figure 4, testing on 20 active users shows that before PCC implementation, download speeds ranged from 10.56–24.31 Mbps with an average of approximately 15–18 Mbps. This variation indicates uneven traffic distribution and suboptimal bandwidth utilization. After implementing PCC with a 1:1 load-sharing ratio across two ISPs, each with 50 Mbps capacity, download throughput increased to a range of 32.73–45.56 Mbps, with an average of approximately 39–41 Mbps. Quantitatively, this represents an improvement of about ±130–150%. This increase indicates that both ISP links are operating simultaneously (bandwidth aggregation), allowing the total network capacity to be utilized more optimally compared to the pre-implementation condition.

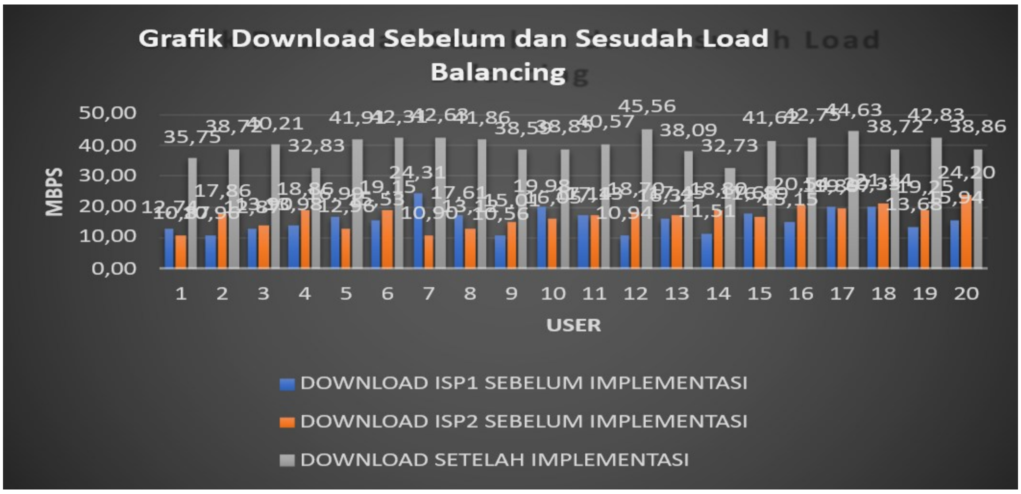


Figure 4. Download performance graph before and after load balancing

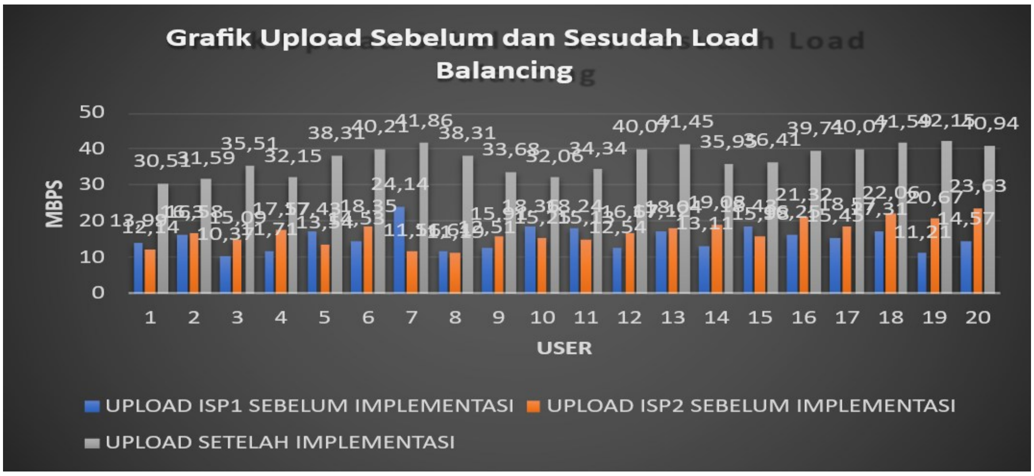


Figure 5. Upload performance graph before and after load balancing

The results of upload activity testing before and after the implementation of load balancing are shown in Figure 5. Prior to PCC implementation, upload speeds ranged from 10.37–24.14 Mbps, with an average of approximately 14–17 Mbps. This condition indicates the presence of a bottleneck caused by traffic centralization on a single gateway. After implementing PCC, upload throughput increased to a range of 30.51–42.15 Mbps, with an average of approximately 36–39 Mbps, representing an improvement of about ±120–140%. This increase occurs due to more balanced connection distribution, preventing traffic accumulation on a single path and allowing optimal utilization of available bandwidth.

Failover testing was conducted through a simulated disconnection scenario on one of the ISP links to evaluate the system's response to network failure conditions. Under normal conditions, clients were connected through one ISP path without connectivity issues, indicating stable system operation prior to testing. When the active link was disconnected, the system automatically redirected traffic to the alternative ISP path as a backup. The switching process occurred within a very short duration (less than 5 seconds based on observations), with minimal disruption to user connectivity and without interrupting active sessions during the transition.

The test results also indicate no significant packet loss during the failover process, and the connection remained stable. This demonstrates that the implemented *check-gateway* and recursive routing mechanisms effectively maintain service continuity (network resilience). A summary of the failover test results is presented in Table 4 as a quantitative synthesis, highlighting system response based on parameters such as failover time, packet loss, and connection stability. These findings indicate that the system is capable of adapting to link failures without significantly degrading service quality.

Table 4. Failover test results

Parameter	Result
Scenario	Disconnection of one ISP
System Response	Automatically switches to the active ISP
Downtime	Very short (< 5 seconds, observed)
Packet Loss	Not significant
Connection Status & Mechanism	Remains stable & uses recursive routing

Discussion

The results of this study indicate that the implementation of the PCC method integrated with failover effectively improves the performance of a dual ISP network. This improvement is observed not only in throughput but also in stability and traffic distribution efficiency. Mechanistically, this is attributed to the characteristics of PCC, which utilizes a hashing algorithm based on *both-addresses*, ensuring that each connection is deterministically mapped to a specific path while maintaining session persistence (Windarta et al., 2022). This mechanism prevents path changes during active sessions, thereby reducing the risk of packet out-of-order and retransmissions that can degrade network performance (Verma et al., 2022).

Traffic centralization on a single path indicates the presence of a bottleneck, characterized by increased packet density and queue buildup. This condition leads to high packet rates and a greater likelihood of bufferbloat (Komathi et al., 2024). After implementing PCC, traffic distribution becomes more balanced across both ISP links, resulting in distributed queue loads and a significant reduction in packet density. This decrease reflects reduced pressure on the queuing system and improved packet processing efficiency at the router level (Abuhamdah & Al-Shabi, 2022). Furthermore, the increase in throughput can be explained by the parallel utilization of both links (bandwidth aggregation) (Wiharti et al., 2023), although it remains influenced by TCP congestion control mechanisms and bandwidth competition among users (Maripini et al., 2025; Dong et al., 2022).

These findings are consistent with previous studies, such as (Amalia et al., 2022) which demonstrated that PCC is more effective than the Nth method in improving service quality, and (Fathurrohim & Basuki, 2025) which emphasized PCC's superiority in maintaining connection consistency compared to ECMP. However, this study provides additional contributions by demonstrating that improvements are not limited to connection stability but also extend to network processing efficiency, as evidenced by the significant reduction in packet rate. This complements the findings of (Nugroho et al., 2023) which primarily focused on traffic distribution without in-depth analysis of packet load. Variations in results across studies may be influenced by differences in testing environments, number of users, and traffic characteristics, indicating that PCC performance is highly contextual to its implementation (Aldossary et al., 2025).

The integration of PCC with a failover mechanism demonstrates the system's ability to maintain service continuity. This aligns with the concept of network resilience, where the system can adapt to link failures through automatic traffic redirection (Trung & Kim, 2025). The use of *check-gateway* and recursive routing enables rapid failure detection and seamless path switching without significant disruption to active connections, as also reported by (Wiharti et al., 2023).

Conceptually, this study provides insight that the effectiveness of PCC lies not only in balancing traffic distribution but also in reducing queue density and improving network processing efficiency. These findings reinforce that a connection-based approach is more stable than a packet-based approach in multi-user environments with dynamic traffic and has strong relevance for broader institutional network implementations. However, this study has several limitations. Methodologically, QoS measurements do not include parameters such as latency and jitter directly. Experimentally, testing was conducted using two ISPs with equal bandwidth, which does not fully represent heterogeneous conditions. In terms of generalization, the results are limited to an educational network environment and have not been tested on more complex network scales.

The implications of this study cover both theoretical and practical aspects. Theoretically, the findings strengthen the concept of connection-based load balancing as an effective approach for optimizing multi-ISP networks. Practically, this study provides a foundation for designing more efficient network systems through the integration of load balancing and failover mechanisms. Future research is recommended to develop adaptive methods that consider dynamic link quality, such as integration with QoS-based approaches or Software-Defined Networking (SDN), to further enhance performance in more complex network environments.

CONCLUSION

The results of this study indicate that the implementation of the PCC method in a dual ISP network at SMK Negeri 3 Bangkalan is empirically capable of resolving traffic imbalance and improving connection stability through balanced load distribution and integrated failover mechanisms that ensure service continuity. Scientifically, this study confirms that a connection-based load balancing approach is not only effective in traffic distribution but also enhances network processing efficiency by reducing packet density and queue pressure, while providing more comprehensive empirical evidence compared to previous studies. At the level of generalization, these findings can be applied as an approach for multi-ISP networks with dynamic traffic, including educational institutions, campuses, and enterprise environments. The implications of this study strengthen the concept of connection-based traffic engineering and provide a foundation for designing more adaptive, efficient, and reliable network systems. However, the limitations of this study include the absence of direct analysis of QoS parameters such as latency and jitter, as well as scenarios limited to homogeneous ISPs. Future research is recommended to develop adaptive approaches based on QoS or (SDN) and to test them in more complex network environments to improve the validity and generalizability of the results.

REFERENCES

Abuhamdah, A., & Al-Shabi, M. (2022). Hybrid load-balancing algorithm for fog computing environment. *International Journal Of Software Engineering & Computer Systems (IJSECS)*, *8*(1), 11–21. https://doi.org/10.15282/ijsecs.8.1.2022.2.0092

Al Reshan, M. S., Syed, D., Islam, N., Shaikh, A., Hamdi, M., Elmagzoub, M. A., ... & Talpur, K. H. (2023). A fast converging and globally optimized approach for load balancing in cloud computing. *IEEE Access*, *11*, 11390-11404. https://doi.org/10.1109/ACCESS.2023.3241279

Aldossary, D., Aldahasi, E., Balharith, T., & Helmy, T. (2025). A Systematic Literature Review on Load-Balancing Techniques in Fog Computing: Architectures, Strategies, and Emerging Trends. *Computers*, *14*(6), 217. https://doi.org/10.3390/computers14060217

Ali, H., Abouelatta, M. A., & Youssef, K. Y. (2025). Dynamic Connectivity Hub : Multiple ISPs Smart Aggregation for Optimized IoT Connectivity. *IEEE Access*, *13*, 18734–18748. https://doi.org/10.1109/ACCESS.2025.3529486

Amalia, E. R., Nurheki, Saputra, R., Ramadhana, C., & Yossy, E. H. (2022). Computer network design and implementation using load balancing technique with per connection classifier (PCC) method based on MikroTik router. *Procedia Computer Science*, *216*, 103–111. https://doi.org/10.1016/j.procs.2022.12.116

Dong, P., Shen, R., Li, Y., Nie, C., Xie, J., Gao, K., & Zhang, L. (2022). An Energy-Saving Scheduling Algorithm for Multipath TCP in. *Electronics*, 1–16. https://doi.org/10.3390/electronics11030490

Fathurrohim, M., & Basuki, A. (2025). Evaluation of traffic distribution performance of ECMP and PCC + CAKE for Multi-ISP load balancing on real networks using MikroTik. *KINETIK: Game Technology, Information System, Computer Network, Computing, Electronics, and Control*, *4*(4), 583-592. https://doi.org/10.22219/kinetik.v10i4.2374

Jasim, A. M., & Al-raweshidyg, H. (2024). An Adaptive SDN-Based Load Balancing Method for Edge/Fog-Based Real-Time Healthcare Systems. *IEEE Systems Journal*, *18*(2), 1139–1150. https://doi.org/10.1109/JSYST.2024.3402156

Komathi, A., Kishore, S. R., & Velmurugan, A. K. (2024). Network load balancing and data categorization in cloud computing. *Indonesian Journal of Electrical Engineering and Computer Science*, *35*(3), 1942–1951. https://doi.org/10.11591/ijeecs.v35.i3.pp1942-1951

Lilhore, U. K., Simaiya, S., Prajapati, Y. N., Rai, A. K., Ghith, E. S., Tlija, M., Lamoudan, T., & Abdelhamid, A. A. (2025). A multi-objective approach to load balancing in cloud environments integrating ACO and WWO techniques. *Scientific Reports*, *15*. https://doi.org/10.1038/s41598-025-96364-1

Maripini, H., Ghosh, T., & Vanajakshi, L. (2025). Queue Dissipation-Based Max Pressure Signal Control Using Vehicle Re-Identification Data. *IEEE Access*, *13*, 166530–166541. https://doi.org/10.1109/ACCESS.2025.3612125

Nugroho, K. T., Julianto, B., Tisna, D. R., & S, D. F. N. M. (2023). Quality Analysis of Service Load Balancing Using PCC, ECMP, and NTH Methods. *Jurnal Nasional Pendidikan Teknik Informatika: JANAPATI*, *12*(2021), 33–41. https://doi.org//10.23887/janapati.v12i1.55894

Oikonomou, E., & Rouskas, A. (2024). Efficient Schemes for Optimizing Load Balancing and Communication Cost in Edge Computing Networks. *Information*, *15*(11), 670. https://doi.org/10.3390/info15110670

Simone, L. De, Mauro, M. Di, Member, S., Longo, M., Natella, R., Member, S., & Postiglione,

F. (2023). Multi-Provider IMS Infrastructure With Controlled Redundancy : A Performability Evaluation. *IEEE Transactions on Network and Service Management*, *20*(4), 3984–3998. https://doi.org/10.1109/TNSM.2023.3282745

Tawfeeg, T. M., Yousif, A., Hassan, A., Alqhtani, S. M., Hamza, R., Bashir, M. B., & Ali, A. (2022). Cloud Dynamic Load Balancing and Reactive Fault Tolerance Techniques : A Systematic Literature Review (SLR). *IEEE Access*, *10*, 71853–71873. https://doi.org/10.1109/ACCESS.2022.3188645

Trung, K. N., & Kim, Y. (2025). Design and Implementation of a Cost-Effective Failover Mechanism for Containerized UPF. *Electronics*, *14*, 1–23. https://doi.org/10.3390/electronics14152991

Verma, L. P., Sharma, V. K., Kumar, M., Kanellopoulos, D., & Mahanti, A. (2022). DB - CMT : A New Concurrent Multi - path Stream Control. In *Journal of Network and Systems Management*. Springer US. https://doi.org/10.1007/s10922-022-09677-1

Wiharti, W., Lumasa, I., Rifka, S., Hidayatullah, I., & Febrian, A. (2023). Load Balancing and Fail Over MikroTik Implementation Using Per Connection Classifier (PCC) on Two Internet Providers Interconnection. *International Journal of Advanced Science Computing and Engineering*, *5*(2), 129–135.

Windarta, S., Suryadi, S., Ramli, K., Pranggono, & Surya, B. gunawan T. (2022). Lightweight Cryptographic Hash Functions: Design Trends, Comparative Study, and Future Directions. *IEEE Access*, *10*, 82272–82294. https://doi.org/10.1109/ACCESS.2022.3195572

Zhou, J., Lilhore, U. K., Poongodi, M., Hai, T., Simaiya, S., Norhayati, D., Jawawi, A., Alsekait, D. M., Ahuja, S., Biamba, C., & Hamdi, M. (2023). Comparative analysis of metaheuristic load balancing algorithms for efficient load balancing in cloud computing. *Journal of Cloud Computing: Advances, Systems and Applications*, *12*, 85. https://doi.org/10.1186/s13677-023-00453-3