Simulation-based Comparative Study of PROFIBUS and PROFINET Topologies

Nurtakin Guliyeva Shukurova[1][0009-0004-9593-2595]

Azerbaijan Technical University, Baku, Azerbaijan

Abstract. The study investigates the impact of various network topologies used in the PROFIBUS and PROFINET communication protocols, which are widely used in industrial automation systems, on performance and system resilience. The study aims to determine the possibilities for optimizing the topology selection in Industrial Control Systems (ICS) networks in terms of connection reliability and continuity.

In the initial phase of the study, the bus, star, tree, and ring topologies were modeled in the GNS3 simulation environment and tested under scenarios such as cable breaks, network load, and changes in traffic intensity. The results showed that in the line topology, a 100% link loss was observed during a cable break, whereas in the ring topology, link continuity was maintained thanks to the alternative transmission path.

In the next phase, to address the identified weaknesses, the implementation of redundant structures, network segmentation, optimization of the switch architecture, and the creation of alternative transmission paths have been proposed at the theoretical and simulation levels. It should be noted that the optimization measures have not been fully implemented in a real industrial environment; they have only been evaluated within the framework of modeling and analysis.

Based on the simulation results, the application of redundant and distributed structures has the potential to increase link continuity during failures and can enhance the overall reliability of the system. At the same time, the use of segmentation and alternative transmission paths can reduce network latency and minimize packet loss. The obtained results provide a methodological contribution to the scientific justification of topology selection during the design of industrial networks and to ensuring the continuity of production processes. Furthermore, the practical implementation and experimental verification of the proposed optimization mechanisms on real hardware is considered appropriate for future research.

Although evaluated solely through GNS3 simulations, which may not fully capture physical-layer effects in real ICS environments, the proposed optimizations show promise; future research should validate these on actual PROFIBUS/PROFINET hardware with PLCs.

Keywords: Industrial Control Systems network, PROFIBUS, PROFINET, GNS3, topology optimization.

1 Introduction

The Industry 4.0 concept has accelerated the digital transformation of manufacturing systems over the last decade and has become one of the main directions of scientific research. Extensive literature reviews show that this concept is not limited to merely increasing the level of automation, but also involves the integration of Cyber-Physical Systems, the Industrial Internet of Things, and communication infrastructure that ensures real-time data exchange [1]. In this regard, the performance, latency, and resilience of industrial networks are critical in an Industry 4.0 environment. Therefore, the architecture and topological structure of industrial networks directly impact the effectiveness of manufacturing systems.

Reliable and continuous data transmission in industrial automation systems is one of the key conditions for the stable and safe management of production processes. The PROFIBUS and PROFINET protocols, which are widely used in modern industrial networks, offer high-speed and deterministic communication capabilities [2], [3]. However, improper selection of the network topology can lead to connection loss, increased delays, and reduced system resilience [4]. In particular, in bus-type topologies, a single point of failure can cause the entire system to stop [5].

PROFIBUS is a traditional fieldbus that primarily operates over serial communication, while PROFINET is a modern, Ethernet-based industrial network technology. The correct and optimal application of these technologies is directly related to the structure of the chosen topology. Although performance analysis of industrial networks has been conducted in existing studies, the optimization of various topologies in a simulation environment and their evaluation under fault scenarios have been investigated to a limited extent.

In this paper, industrial network topologies are modeled in the GNS3 simulation environment, tested under failure and traffic load scenarios, and the impact of optimization mechanisms is analyzed.

Research Questions:

RQ1: Which topology minimizes packet loss under cable break scenarios?
RQ2: How does redundancy reduce latency in network topologies?

2. PROFIBUS and PROFINET

PROFIBUS (Process Field Bus) is a fieldbus technology that provides communication between PLC (Programmable Logic Controller) devices, sensors, drives, and other systems in industrial control systems. This technology, which complies with the IEC61158 standard, also has DP (Decentralized Peripherals) and PA (Process Automation) variants. The DP variant is used for systems such as machine automation. PA, on the other hand, creates a safe physical layer for use in areas with an explosion hazard. Although it has similarities to fiber optic and infrared cables, this technology, which primarily uses cables based on the RS-485 standard, ensures the operation of industrial control systems and provides compatibility between devices from different manufacturers [7].

PROFINET is an industrial network standard that provides connectivity between IT and OT. It is an Ethernet-based protocol used in industrial automation that operates in real time, providing secure and higher-quality production. It facilitates data exchange between controllers, such as PLCs, and devices, and can use protocols like TCP/IP and UDP/IP[6].

PROFIBUS primarily operates over serial communication, while PROFINET is Ethernet-based. The performance of PROFIBUS and PROFINET networks can be compared using several key parameters. PROFIBUS DP is a serial network protocol with a maximum speed of 12 Mbit/s and supports a maximum of 32 nodes per segment, expandable to a total of up to 126 nodes. PROFINET, on the other hand, is an Ethernet-based protocol with speeds of 100 Mbps and higher, which ensures deterministic behavior with real-time (RT) and isochronous real-time (IRT) mechanisms. For this reason, PROFINET is suitable for larger and more flexible topologies, while PROFIBUS is practical for smaller and more stable systems[6], [7].

Table 1. Comparative Technical Analysis of PROFIBUS and PROFINET Communication Protocols.

Parameter	PROFIBUS DP	PROFIBUS PA	PROFINET RT	PROFINET IRT
Physical Layer	RS-485	MBP (IEC61158-2)	Industrial Ethernet	Industrial Ethernet
Max Data Rate	12 Mbit/s [3]	31.25 kbit/s [2]	100 Mbit/s [8]	100Mbit/s (isochronous) [8]
Topology	Line, Tree	Line	Star, Line, Ring	Star, Ring
Real-Time Capability	Deterministic	Deterministic	Soft Real-time [2]	Hard Real-time [2]
Max Nodes	126 devices[3]	32 per segment [2]	>100 devices [8]	>100 devices [8]
Redundancy	Limited	Limited	MRP Support [8]	Advanced Redundancy [8]
Security Features	Basic	Basic	Advanced Security Concepts [9]	Advanced Security Concepts [9]

Table 1 provides a comparative overview of PROFIBUS and PROFINET technologies based on official specifications and the latest scientific literature. PROFIBUS DP supports data transmission speeds of up to 12 Mbps, while PROFIBUS PA operates at a speed of 31.25 kbps using the MBP physical layer [3]. In contrast, PROFINET has an Ethernet-based architecture and provides speeds of up to 100 Mbit/s, as well as real-time (RT) and isochronous real-time (IRT) capabilities [8]. Furthermore, PROFINET offers advanced redundancy mechanisms, such as the Media Redundancy Protocol (MRP), and enhanced security concepts for industrial communication environments [9].

3. TOPOLOGIES FOR PROFINET AND PROFIBUS

3.1 PROFIBUS DP Topologies

PROFIBUS DP is a serial fieldbus technology that provides deterministic data transmission between distributed field devices and a central control system in industrial automation systems. According to the official system description, a line topology is primarily used at the RS-485 physical layer [2].

In a line topology, all devices are connected in series on the same cable, and it is mandatory to place terminators at both ends of the segment. Incorrect selection or placement of terminators can cause signal reflection and communication errors.

Real-time analyses conducted by Eduardo Tovar and Francisco Vasques have shown that although PROFIBUS DP provides deterministic time behaviour in a line topology, a single point of failure (cable break or device failure) can affect the operation of the entire segment. For this reason, tree-type extensions via a repeater are implemented in large systems. Thus, although the linear topology is considered a simple and economical solution for PROFIBUS DP, it has limitations in terms of fault tolerance.

3.2 PROFIBUS PA Topologies

PROFIBUS PA is primarily intended for the process industry (chemical, oil and gas, and energy sectors) and uses the IEC 61158-2 MBP physical layer [2].

In PROFIBUS PA networks, line, star, tree, and, in some cases, ring topologies can be used. The tree topology is considered more practical in process industries due to the connection of widely distributed sensors and actuators.

J. P. M. D. P. Paiva et al. have shown that while PROFIBUS PA is more suitable for stable, low-speed applications compared to PROFINET PA, it has limitations in terms of scalability and flexibility.

Although the star topology allows for the isolation of local failures, the failure of the central point can cause a complete loss of communication.

3.3 PROFINET Topologies

PROFINET is an Ethernet-based industrial network technology and supports high speeds (100 Mbit/s and higher) and a combination of various topologies [2].

PROFINET supports star, line, tree, ring, and hybrid structures. In a star topology, all devices are connected through a central switch. This structure allows for the isolation of local failures, but a failure of the central switch causes a network outage.

The line topology has a simpler structure and can be built without a switch in some cases. However, a failure of one device can cause subsequent devices to lose connectivity. The ring topology, on the other hand, provides high fault tolerance through the Media Redundancy Protocol (MRP). Alexander Walz and his co-authors have shown that in PROFINET networks, redundancy mechanisms increase not only performance but also safety. Furthermore, the PROFINET RT and IRT modes directly influence the choice of topology. The IRT mode is optimized for applications requiring high-precision synchronization.

3.4 Comparative Analysis and Optimization Aspect

The choice of topology is not only a matter of physical configuration but also of optimizing network performance.

In PROFIBUS networks, a linear topology offers the advantage of low cable consumption and a simple structure, but it has a high risk of a single point of failure. PROFINET, on the other hand, allows for more flexible and redundant structures due to its Ethernet-based architecture.

Thus, as noted by Eduardo Tovar and Fernando Vasques, in serial fieldbus architectures, a deterministic transmission mechanism ensures predictable latency, but fault tolerance and structural redundancy remain limited in this type of network.

Andreas Walz and his co-authors, in turn, show that in Ethernet-based industrial networks, redundancy protocols, alternative routing mechanisms, and advanced security concepts significantly enhance system resilience and cybersecurity.

In addition, J. P. M. D. P. Paiva and colleagues emphasize that in the modern process industry, the choice of network topology should be based on the application's scale, the level of real-time requirements, and reliability metrics.

In this regard, the following technical parameters must be systematically evaluated during optimization: latency, packet loss, redundancy mechanism, recovery time in case of failure, as well as cable length and segment limits.

Thus, while standardized PROFIBUS networks with a linear architecture provide a cost-effective and technically efficient solution for small and medium-sized automation systems, in large-scale industrial environments requiring high reliability, PROFINET-based ring or hybrid topologies may be a more optimal choice. This choice is considered a strategic approach aimed at ensuring the network's resilience, continuity, and future scalability.

4. METHODOLOGY

The primary prerequisite for network optimization is the selection of an appropriate topology. For example, when selecting the topology for a Profibus network, the extent of the system's coverage area, the number of devices to be connected, cable distances, electromagnetic interference, and the system's reliability requirements must be taken into account. For example, while a bus topology is sufficient for small systems, tree or star topologies are more suitable for larger systems.

The optimization of the topology was evaluated within a simulation environment, not in a real industrial setting, through modeling. The selection criteria were determined based on theoretical literature and official technical specifications, but the practical implementation was only carried out on a virtual network model.

The GNS3 platform was used as the simulation environment. Although this platform allows for the emulation of the functional behavior of real network devices, it does not fully reflect physical environment factors (e.g., electromagnetic interference, the effect of actual cable length on signal attenuation, or industrial-grade hardware delays).

In this environment, routers, switches, and other network devices were configured, and traffic analysis and packet-level observations were conducted. The main reason for selecting this platform is that it allows for the analysis of the dynamic behavior of industrial Ethernet architectures, particularly PROFINET-based topologies.

In the simulation phase, line, star, tree, and ring topologies were implemented for PROFINET. The Media Redundancy Protocol (MRP) mechanism was implemented in the ring topology. For PROFIBUS, a bus topology was modeled. An objective comparison was ensured by applying the same number of virtual devices and a similar traffic load for each topology.

The following test scenarios were executed as part of the study: physical cable cut (link failure), adding additional traffic load to the network, changing the transmission rate, and a comparison of the redundancy mechanism in active and disabled states. During the cable cut scenario, the network's recovery time was measured, while in the additional traffic scenario, latency and packet loss metrics were analyzed.

The following metrics were used for performance evaluation: end-to-end delay (ms), packet loss percentage, network recovery time (ms), traffic load, and connection duration. The total delay was evaluated as the sum of the following components: transmission delay, propagation delay, and processing delay. This approach allowed for an objective comparison between the topologies.

A comparative analysis of the simulation results showed that although the linear topology is superior in terms of minimal cable usage and simple structure, the failure of a single node can disrupt the operation of the entire segment. Star topology allows for the isolation of local failures, but the failure of the central switch leads to a complete loss of connectivity. The tree topology offers a balanced solution for larger areas. The ring topology, on the other hand, provides high fault tolerance through the MRP mechanism, allowing for the use of an alternative route during a failure and minimizing recovery time.

Thus, the simulation analysis conducted has shown that for small and medium-sized systems, simple linear structures may be sufficient, but in industrial environments where high reliability and durability are required, redundant ring or hybrid topologies are considered more optimal. The choice of topology is not just a matter of physical layout but also a strategic decision in terms of optimizing performance and reliability.

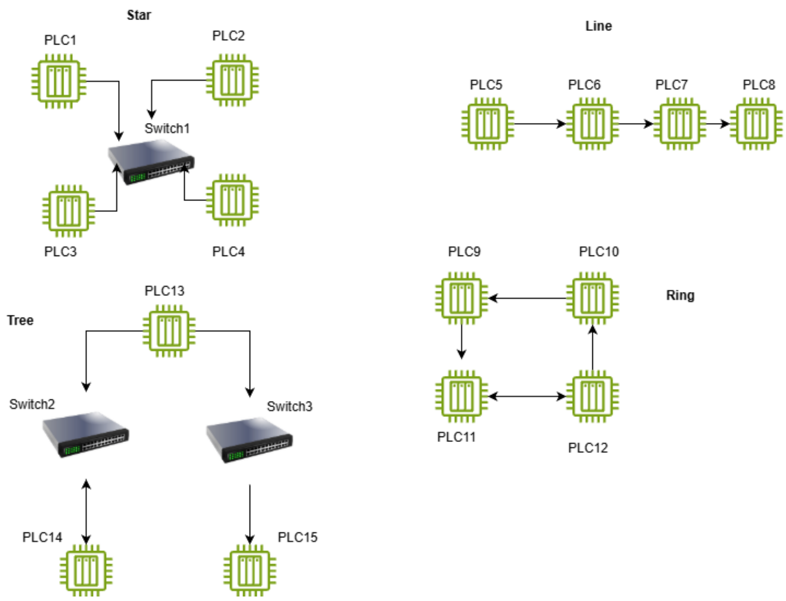

Figure 1. Star, ring, line, bus topologies

Various scenarios were tested during the simulation process: the physical cutting of the cable, adding an additional load to the network, and changing the transmission speed. As a result of these tests, metrics such as latency, packet loss, and link stability were observed.

Tests conducted on a star topology set up in the GNS3 simulation environment have shown that the network operates stably and with low latency under normal conditions. The average latency values for ICMP requests sent from PC1 to PC3 were in the 1–2 ms range.This result aligns with the performance characteristics of Layer 2-based Ethernet networks. However, during the testing process, in some cases, the latency values rose above 200 ms, and short-term packet loss was observed. This situation is not due to the network architecture but rather to resource shortages in the simulation environment (CPU load, virtual interface latency, etc.). Such high latency values are not typical for properly configured Ethernet-based PROFINET networks in a real industrial environment.

The main advantage of a star topology is that the failure of one of the end devices does not affect the operation of the other devices. However, a failure of the central switch causes the entire network to fail. This characteristic is considered critical for reliability in industrial networks and necessitates the implementation of additional redundant mechanisms.

High availability and deterministic transmission are crucial in industrial Ethernet-based systems, especially in PROFINET architectures. Research shows that while centralized topologies are effective in terms of performance, they pose a risk for critical processes without redundant structures[8].

4.1 Recommendations for Optimization

To eliminate the weaknesses of the star topology and increase industrial-level reliability, the following optimization methods are recommended:

1. Adding a Redundant Switch

Adding a second switch as an alternative to the central switch increases network availability. This approach helps eliminate the single point of failure issue. In industrial networks, this method is one of the key elements of a high-availability strategy.

2. Transition to a Tree Structure

Load balancing can be achieved by creating a tree structure by combining several star topologies. This approach provides more effective traffic distribution in large-scale industrial facilities [11].

3. QoS and Traffic Prioritization

In a real industrial environment, it is possible to assign a priority for critical control traffic on PROFINET networks. This mechanism minimizes latency and ensures real-time transmission. In particular, the RT and IRT mechanisms play a crucial role in maintaining deterministic performance [10].

4. Ring and MRP Mechanism

Although the Media Redundancy Protocol (MRP) is primarily used in a ring topology, a similar level of reliability can be achieved with a redundant switch architecture. MRP ensures network resilience by activating an alternative route within milliseconds during a link failure.

5. RESULTS AND DISCUSSION

The simulation conducted in the GNS3 environment provided a comparative quantitative analysis of PROFIBUS and PROFINET topologies under identical conditions, including node count and traffic intensity. The performance was evaluated based on latency, packet loss, and recovery time across two primary states: normal operation and link failure scenarios.

Table 2. Performance Comparison Under Normal Conditions

Topology	Latency	Packet Loss	Throughput	Stability
Star	1-2 ms	0%	High	Very high
Bus	4-7 ms	5-10%	Medium	Medium
Ring	1-2 ms	0 -2 % (low load)	Low-Medium	Low
Tree	2-4ms	0-5%	High	High

5.1. Performance Under Normal Conditions

As summarized in Table 2, the Star and Ring topologies demonstrated the highest efficiency for PROFINET-based architectures. The Star topology yielded the lowest latency (1–2 ms) and 0% packet loss, confirming its high transmission stability for real-time industrial data. Conversely, the Bus (Line) topology exhibited higher latency (4–7 ms) and a packet loss rate of 5–10%, primarily due to increased propagation delays and the lack of a centralized switching mechanism.

Table 3.Performance Under Fault and Stress Scenarios

Topology	Scenario	Packet Loss	Recovery Time	Result
Star	Link Failure	20-40% (affected node only)	1–3s (Fast recovery)	Resilient

Bus	Traffic Increase	40-80%	N/A (Broadcast collisions)	Unstable
Ring	Congestion	15-30 %	N/A (Queue buildup)	Degraded
Tree	Link Failure	20-60%	N/A (Subtree isolation)	Partially Resilient

5.2. Resilience and Fault Tolerance Analysis

The study's most significant findings occurred during the link failure (cable cut) simulations, detailed in **Table 3**.

- Line Topology: A single cable break resulted in 100% link loss for all downstream nodes, confirming its vulnerability as a single point of failure in industrial environments.
- Ring Topology: Communication remained uninterrupted during a link failure. The implementation of the Media Redundancy Protocol (MRP) allowed the network to activate an alternative transmission path within milliseconds, ensuring near-constant link continuity.
- Star Topology: This structure allowed for the isolation of failures, where packet loss (20–40%) was restricted only to the affected node, while the rest of the network remained operational with a fast recovery time of 1–3 seconds.

5.3. PROFIBUS-Specific Observations

In the PROFIBUS DP and PA simulations, stable communication was found to be highly dependent on physical layer parameters. Specifically, the correct placement of terminators at both ends of a segment and strict adherence to standardized cable lengths were identified as critical factors in preventing signal reflection and ensuring deterministic behavior. While the line topology is cost-effective for small-scale PROFIBUS systems, it lacks the inherent fault tolerance observed in PROFINET-based redundant structures

6. CONCLUSION

This study shows that in industrial networks, not only the selection of the protocol but also the establishment of the correct topology is of great importance. While a properly configured bus topology with suitable parameters for PROFIBUS ensures stable communication, star and ring topologies stand out as a more flexible and secure solution for PROFINET.

Optimized topologies not only increase the reliability of industrial processes but also play a crucial role in preventing system failures.

6.1 Limitations

This study relies on GNS3 for modeling, which excels in network-layer simulation but lacks an accurate representation of PROFIBUS's RS-485 physical layer or PROFINET's real-time constraints on industrial hardware. Tests used synthetic traffic (e.g., ICMP/ping), not native cyclic I/O data from PLCs. No real-world factors like EMI or temperature were modeled.

7. FUTURE WORK

This study primarily examined the performance and reliability of different network topologies in a simulation environment. In future work, we plan to validate and extend these findings on real industrial hardware. This includes implementing the proposed architectures using Siemens S7 PLCs, capturing and analyzing actual PROFINET traffic, conducting evaluations based on IEC 61784 standards, and performing hardware-level fault injection tests to assess real-world behaviour under realistic failure conditions.

Additionally, exploring artificial intelligence and machine learning techniques offers a promising direction. ML models could dynamically monitor traffic patterns, latency, and packet loss to proactively detect anomalies and enable automatic rerouting, thereby improving resource management, real-time decision-making, and overall system resilience in large-scale industrial networks.

References

1. L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, “The expected contribution of Industry 4.0 technologies for industrial performance,” Technological Forecasting and Social Change, vol. 135, pp. 383–394, 2018.

2.PROFIBUS & PROFINET International, "PROFIBUS System Description – Technology and Application," PI White Paper, Karlsruhe, Germany, 2020..

3. PROFIBUS & PROFINET International, "PROFINET System Description – Technology and Application," PI White Paper, Karlsruhe, Germany, 2021.

4. J. Li, X. Li, and J. Gao, "Exploring Self-Organization and Self-Adaption for Smart Manufacturing Complex Networks," IEEE Access, vol. 8, pp. 132001-132014, 2020. doi: 10.1109/ACCESS.2020.3009575

5. X. Jiang, H. S. Lohne, and M. Gidlund, "Time-Sensitive Networking Technologies for Industrial Automation in Wireless Communication Systems," IEEE Industrial Electronics Magazine, vol. 17, no. 1, pp. 36-47, March 2023. doi: 10.1109/MIE.2022.3162381

6.S. P. Kumar and S. S. Shajin, "A Comparative Study to Evaluate the Performance of Communication Protocols for Process Industry," in Proc. 2023 7th Int. Conf. Computing Methodologies and Communication (ICCMC), Erode, India, 2023, pp. 1105–1110.

7. PROFIBUS Nutzerorganisation e.V., PROFIBUS Design Guideline, Order No. 8012_V129, 2020.

8.A. Walz et al., "Profinet Security: Selected Concepts for Secure Communication in the Automation Domain," in Proc. IEEE Int. Conf. Industrial Informatics (INDIN), 2023..

9. J. P. M. D. P. Paiva et al., "Use Case Comparison Between Profibus PA and Profinet PA Networks," in Proc. IEEE Latin American Symp. Circuits and Systems, 2025.

10. F. Depuydt and P. Saey, "Redundancy for PROFINET Networks," White Paper, KU Leuven, Dept. Electrical Engineering (ESAT), Ghent, Belgium, 2010.

11.M. Raţă, A. Gontean, and D. Moga, "Performance Evaluation of PROFIBUS Networks in Industrial Automation Systems," in Proc. IEEE Int. Conf. Industrial Informatics (INDIN), 2022, pp. 1–6.