

An Optimization Method for Network Communication in Aluminium Smelter Reduction Shops

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Abstract

In recent years, aluminium producers have increasingly prioritized the development of smart factories, implementing advanced technologies such as real-time data acquisition and feedback systems for cell control, as well as intelligent unmanned cranes capable of multi-machine coordination. These innovations have significantly raised the bar for network communication, demanding higher levels of flexibility and stability. However, the unique structural layout, production processes, and strong magnetic fields in aluminium smelter reduction workshops pose challenges that simple network communication systems struggle to overcome. As a result, there is a pressing need for a communication solution that is both reliable and adaptable to these demanding environments.

To address this challenge, this paper proposes an optimization method for communication networks tailored to aluminium production workshops, focusing on network architecture and the characteristics of communication nodes. First, a Software-Defined Networking (SDN)-based approach is introduced to optimize the network architecture of electrolysis workshops. By segmenting the network into distinct functional areas and implementing customized communication solutions for each, the flexibility of the on-site communication network is significantly enhanced. Furthermore, an evaluation method is developed to assess the importance of communication nodes. This method analyses the impact of local node failures and the subsequent redistribution of network loads on production communication, enabling the identification of critical nodes for targeted protection. Research demonstrates that this approach not only ensures the stability of the communication network but also improves its flexibility, ultimately reducing communication costs in production.

Keywords: Electrolytic aluminium, Network architecture, Node importance, Communication solutions.

1. Introduction

Around 2005, aluminium smelters worldwide began transitioning from traditional bus architectures to Industrial Ethernet in order to reduce deployment costs and enhance the communication efficiency of control backbone networks [1]. However, inherent limitations such as complex device structures and poor interface compatibility have hindered Industrial Ethernet's performance in meeting multi-service demands under the complex working conditions of aluminium smelting [2]. Consequently, developing dedicated network optimization methods for aluminium electrolysis workshops is a significant engineering value.

To address this technical bottleneck, this paper proposes an innovative network communication optimization solution for aluminium electrolysis workshops. The solution implements a dual-dimensional optimization strategy: at the network architecture level, it achieves intelligent

configuration and flexible scheduling of hardware resources through subnet division and hierarchical modular design; at the data transmission level, it establishes a dynamic node criticality evaluation model to implement differentiated resource allocation strategies based on service priorities, thereby significantly improving system operational reliability while maintaining network flexibility.

2. Dedicated Network Architecture Design for Aluminium Electrolysis Production

With the continuous expansion of network node devices and growing demands for differentiated network transmission services in industrial environments, industrial communication technologies have evolved from fields systems to Industrial Ethernet. Currently, aluminium electrolysis plants in China are progressively upgrading their industrial Ethernet networks [3].

In typical aluminium smelting plants, two separate networks are typically deployed: an industrial intranet and an industrial extranet. The extranet primarily consists of office terminals, servers, and routers, handling routine office data transmission and internet connectivity. The intranet comprises sensors, controllers, and switches dedicated to transmitting production data and controlling equipment operations. The two networks are currently isolated to ensure the safety of production. However, with the increasing integration of AI-assisted operations, video image processing, and unified business management, data exchange between different networks has become essential, making the traditional dual-network model increasingly inadequate [4]. Therefore, optimizing the structure of field communication networks is critically important.

To address these challenges in production network systems, this paper proposes an efficient and flexible network architecture for aluminium electrolysis workshops based on Software-Defined Networking (SDN) principles, aiming to enhance transmission reliability and flexibility. SDN technology separates the data plane from the control plane, simplifying network management and control processes. This facilitates centralized network management and resolves compatibility issues caused by diverse protocols and hardware during cross-network data interconnection.

Figure 1 illustrates an SDN-optimized plant-wide network architecture for aluminium electrolysis plants, which is structured into three layers: the aggregation layer, access layer, and device layer. This design fully addresses the requirements for high real-time performance, reliability, and multi-service coordination in aluminium electrolysis production processes.

The device layer includes various field equipment such as robots, sensors, overhead cranes, pot controllers, electrolytic cell monitoring systems, and office terminals. These devices are widely distributed across key production areas, continuously collecting critical process parameters (temperature, current, voltage, material levels, etc.) and executing control tasks (anode adjustment, crane scheduling, fault detection, etc.). This layer generates massive industrial data, serving as the primary data source for the entire plant.

The access layer consists of data acquisition terminals, industrial switches, and network management devices. It handles network access for terminal equipment and is functionally divided into multiple domains (production, monitoring, security, office, etc.) to achieve logical isolation and resource management.

The aggregation layer primarily features core routers and SDN controllers that centrally manage resources from all access domains. It aggregates vast amounts of production data from various workshops and uploads them to cloud platforms for real-time monitoring and intelligent decision-making.

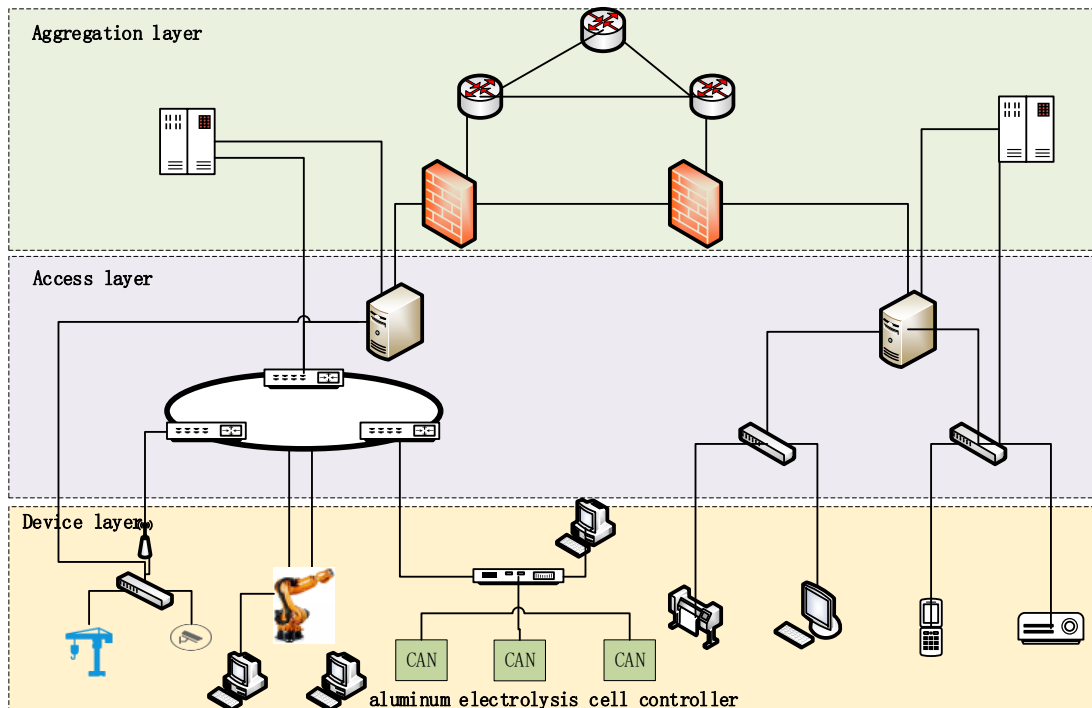


Figure 1. Network architecture diagram.

Leveraging the centralized scheduling capabilities of SDN controllers, this architecture enables dynamic network policy adjustments and optimal resource allocation, effectively ensuring stable network communication and uninterrupted business continuity throughout the aluminium electrolysis production process.

In the network architecture proposed in this paper, the aggregation layer, which is the intelligent hub of the entire production network, assumes the core functions of global scheduling of network resources and data transmission optimization. The proposed centralized control model is significantly different from the traditional distributed network architecture. In traditional distributed architectures, the data transmission path is determined by each relay node based on local topology information. Although decentralized control is simple to implement, it is difficult to achieve optimal routing due to limited node resources and a lack of a global vision. In particular, under abnormal working conditions, such as node failure, a sudden drop in transmission efficiency can easily occur, and cascade failure can easily occur. In this architecture, the decision-making power of data transmission is shifted to the network equipment at the aggregation layer, which uniformly describes the transmission policy based on the global network state. In contrast, the equipment at the access layer is mainly responsible for the specific policy implementation. In addition, the network architecture also significantly reduces the dependence of the access layer devices on hardware resources such as computing and storage, thus simplifying the equipment configuration requirements and effectively reducing the overall construction and operation and maintenance costs of the aluminium electrolysis workshop in terms of network communication while guaranteeing communication efficiency.

3. Aluminium Electrolysis Shop Data Transfer Analysis

Regardless of the specific network architecture adopted, the essence of any communication network lies in its composition of intermediary devices – such as switches and routers – that possess storage and forwarding capabilities. Data transmission, in this context, refers to the process of routing, scheduling, and distributing massive volumes of data through an interconnected system. In complex industrial environments like aluminium electrolysis

workshops, ensuring data transmission efficiency and stability is a critical aspect of the optimization of communication systems.

Theoretically, there are two fundamental approaches to achieve efficient and stable data transmission. The first step is to establish dedicated point-to-point links through which each pair of communication devices is connected via an exclusive physical link. While this guarantees constant availability for direct communication between any two nodes, it becomes increasingly impractical as the number of devices grows due to high costs, poor scalability, and maintenance challenges. The second, and more commonly used approach involves sharing network resources, where switches and routers are responsible for relaying data across the network. This method offers greater flexibility and scalability; however, it can also lead to congestion, latency, or packet loss when data traffic surges or exceeds the processing capacity of intermediate devices. These risks are further amplified in harsh industrial environments characterized by high temperatures and strong electromagnetic interference.

To address these challenges, advanced network optimization techniques – such as bandwidth reservation and line scheduling – must be implemented. These mechanisms help improve resource utilization, maintain orderly data flows, and enhance the overall reliability and resilience of networks under demanding industrial conditions.

As shown in the Figure 2, the switch serves as a key intermediary device in communication networks and is typically composed of multiple ports interconnected via an internal switching module. Data packets enter through one port, are scheduled by the switching module, and exit through another port. In full-duplex mode, each port handles both data reception and transmission, thereby enabling efficient data flow paths. Switches are also equipped with buffer memory for temporary data storage; however, most on-chip cache capacities in switches are relatively limited, generally ranging from a few megabytes to several tens of megabytes. When distributed across all ports, each port may only have a few hundred kilobytes of buffer space, which can typically store only a few dozen packets during traffic bursts.

Although the bandwidth of switch ports has steadily increased in recent years, it still falls short of meeting the demands of the massive amounts of data generated in industrial environments. In industrial networks, the growing disparity between the explosive increase in data volume and the limited bandwidth of transmission equipment has become a major bottleneck restricting overall system performance. With the widespread deployment of sensors, smart terminals, and automated equipment in aluminium electrolysis workshops, these devices continuously generate large volumes of monitoring data while also requiring real-time transmission of critical control commands.

However, existing network infrastructures often struggle to handle such high data throughput, especially under conditions involving high-frequency data updates or the transmission of large data packets, where bottlenecks become more pronounced.

More critically, a failure at a key network node – such as a core switch or primary router – can rapidly lead to congestion and potentially paralyze the entire network, severely disrupting production continuity and compromising operational safety (Figure 3). Furthermore, the failure of a single critical node may trigger cascading effects across other interconnected subsystems, plunging the entire industrial network into disorder and resulting in significant economic losses and safety risks.

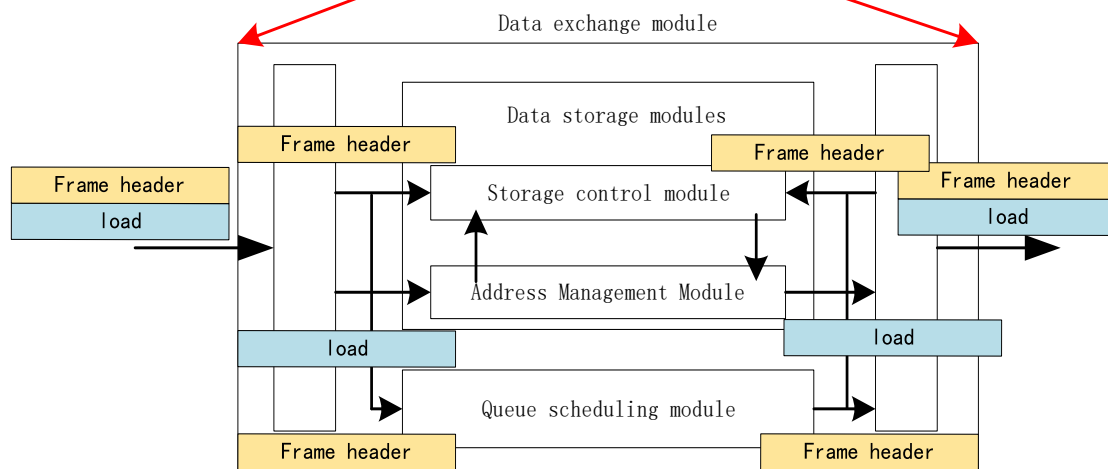


Figure 2. Schematic diagram of the device nodes.

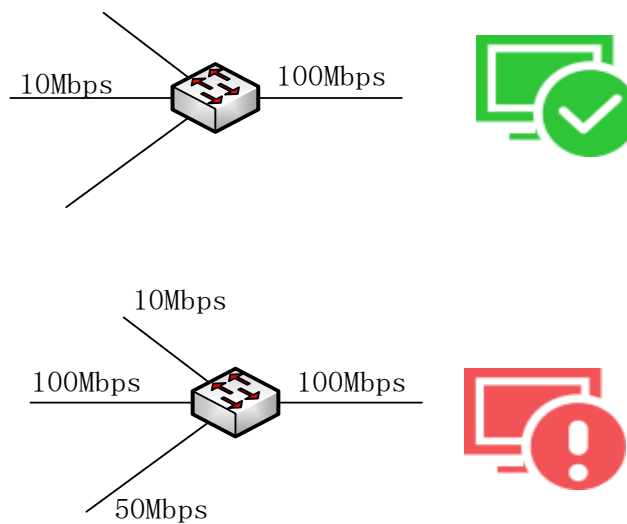


Figure 3. Network congestion diagram.

4. Transmission Optimization Method Based on Node Importance Ranking

For the aforementioned network architecture of the aluminium electrolysis workshop, this section proposes a method for evaluating the importance of communication network nodes and reserving bandwidth, aiming to address the challenges faced in data transmission. The network topology of the workshop is simplified and represented as a directed graph $G = (V, E)$, where V denotes the

set of nodes representing data processing and communication terminals, and E denotes the set of edges representing the connections between these terminals. It is assumed that all devices in the network are functioning properly.

Node importance is a fundamental concept in network science that is used to evaluate the relative influence and criticality of individual nodes within a network system—such as industrial networks, the Internet, or transportation systems [5]. A node’s importance is typically correlated with factors such as the number of its connections, the distribution of neighbouring nodes, and the volume of data it handles. In general, the more connections a node has and the greater its data traffic, the higher its importance. In communication networks, a node’s importance is also closely related to its load-handling capacity, such as buffer size and processing speed.

Methods for assessing node importance can be broadly classified into two categories. The first category evaluates a node’s centrality within the network topology while keeping the overall network structure intact. Common metrics include node degree, betweenness centrality, and traffic frequency. The second category assesses the impact on network performance when a node is removed, determining importance based on the extent to which the network’s functionality deteriorates as a result [6].

In this study, we adopted the second approach, using a node’s load capacity as the primary indicator of its importance. By analysing how each node affects the overall network performance, we establish a priority ranking of nodes in the workshop communication network, which serves as a foundation for subsequent resource optimization and bandwidth allocation strategies.

4.1 Remaining Load of the Node

The Intrinsic remaining load capacity R of a node represents its ability to accommodate additional transferred load. This capacity is determined by two main factors: first, the node's own remaining load-handling capacity; and second, the remaining load-handling capacity of its neighbouring nodes.

Assuming that the real-time load of node i is Q_i , and its total capacity is C_i , the remaining load capacity R_i of the node can be expressed as:

$$R_i = \begin{cases} C_i - Q_i, & C_i > Q_i \\ 0, & C_i \leq Q_i \end{cases} \quad (1)$$

To more accurately assess a node's remaining load-handling capacity, an improved method is proposed that comprehensively considers the remaining load capacity of neighbouring nodes. This approach integrates the node’s own remaining load capacity with that of its adjacent nodes, thereby providing a more realistic representation of the node’s actual load-handling capability within the network. As shown in the following equation:

$$Z_i = \begin{cases} [\min(R_i, \sum_{\alpha \in \Phi_i} R_\alpha)], & \Phi_i \neq \emptyset \\ R_i & \Phi_i = \emptyset \end{cases} \quad (2)$$

where:

- Z_i Global remaining load capacity of the node i
- R_i Intrinsic remaining load capacity of the node i
- Φ_i set of neighbouring nodes of the node i

The Equation (2) reflects the node’s ability to accommodate additional load, which is defined as the minimum value between its own remaining load-handling capacity and the total remaining load-handling capacity of its neighbouring nodes. If the node has no neighbours, its remaining load-handling capacity is solely determined by its own capacity.

4.2 Load Redistribution

The load redistribution mechanism defines the rule by which a failed node's load is transferred to other nodes in the network. As illustrated in Figure 4, when a node fails, the data flows originally passing through that node will reroute via alternative paths, and the associated load will be transferred to its adjacent nodes to ensure the effective operation of the overall network. This triggers a global update of the network's load distribution due to the node failure. Specifically, for all the still functioning communication nodes i , $Q_i' = Q_i + \Delta Q_i$, where Q_i is the load of node i before the update, Q_i' is the load after the update, ΔQ_i is the incremental load transferred to node i , and Φ_f denotes the set of all neighbouring nodes of the failed node f .

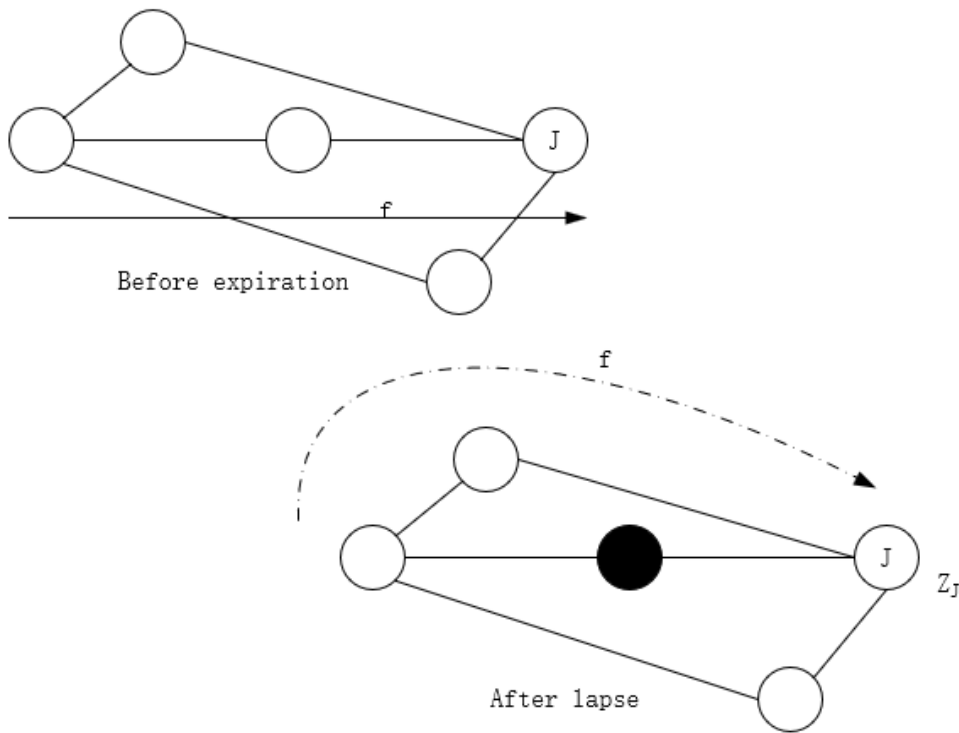


Figure 4. Reallocation schematic.

When reallocating the load, the load accommodation capacity of neighbouring nodes should be taken into account. Assuming the load of the failed node f is Q_f , and the remaining load capacity of its neighbouring nodes is Z_i , the redistributed load increment on the neighbouring nodes can be expressed by the following formula:

$$\Delta Q_i = Q_f \frac{Z_i}{\sum_{\alpha \in \Phi_f} Z_\alpha}, i \in \Phi_f \quad (3)$$

Based on the above load redistribution model, the ability of a node to trigger network cascading failures can be measured by the extent to which the failure of node f , due to the transfer of its own load to neighbouring nodes, causes those neighbours to also transition into a failed state. To

prevent further cascading failures, the redistributed load on node i is constrained by its remaining load capacity. The redistributed load on node i shall not exceed a fraction η of the remaining load capacity $(C_i - Q_{0,i})$. Here, the constant η represents the network's safety factor to prevent node i to operate too close from its capacity C_i , and $Q_{0,i}$ is the initial load of node i , before the failure of node f . This can be expressed by the following conditions:

$$\begin{aligned} \Delta Q_i < \eta \cdot (C_i - Q_{0,i}) \quad i \in \Phi_f \\ 0 < \eta < 1 \end{aligned} \quad (4)$$

where:

η Constant safety factor of network
 $Q_{0,i}$ Initial load of node i , before the failure of node f

To prevent a surge in the load of neighbouring nodes caused by a node failure, the node importance is defined by the following formula:

$$P_i = \frac{\sum_{a \in \Phi_i} \Delta Q_a}{Z_i} \quad (5)$$

Based on the above-described node importance metric, priorities can be assigned and ranked for any node in the network. A higher node importance indicates greater load fluctuations when neighbouring nodes fail, which reflects the node's sensitivity to fault propagation. When the node importance value exceeds 1, it indicates a potential temporary failure risk for that device. Therefore, device performance should be improved by increasing the cache capacity and bandwidth to enhance the network transmission efficiency. This method can save network resources and improve the stability of the network.

5. Experimental Results and Analysis

Simulation software was used to conduct experiments on the simplified network. Based on the assumption of failure of selected nodes, the relationship between node importance, bandwidth, and buffer size was observed to optimize transmission methods for key nodes adapting to the network. During the experiment, the number of switches in the network topology was kept below 10, and the initial network bandwidth was set to 1 Gbit/s. The initial data unit size was set to a maximum transmission unit (MTU) of 1500 bytes, with adjustments made in increments of 1500 bytes to ensure data transmission integrity. The experiments were run on a Windows device equipped with an Intel (R) Core (TM) i7-6700 processor and 16 GB of RAM.

5.1 Load Redistribution

The topology used in this experiment is the star topology and ring topology commonly used in industrial control networks, as shown in Figure 5. Both topologies allow for bidirectional data transmission.

In the two aforementioned topologies, the terminal devices located at the edge will transmit data periodically. The period of each data stream is randomly selected from the set of $\{2, 4, 8\}$ milliseconds, and the length of the smallest transmission unit (i.e., data frame) in the data stream is randomly chosen between 100 and 1500 bytes. Certainly, the shorter the packet transmission period, the more data streams need to be sent within a given time frame. Additionally, the larger the size of an individual data frame, the greater the overall data volume becomes, leading to an increase in network load.

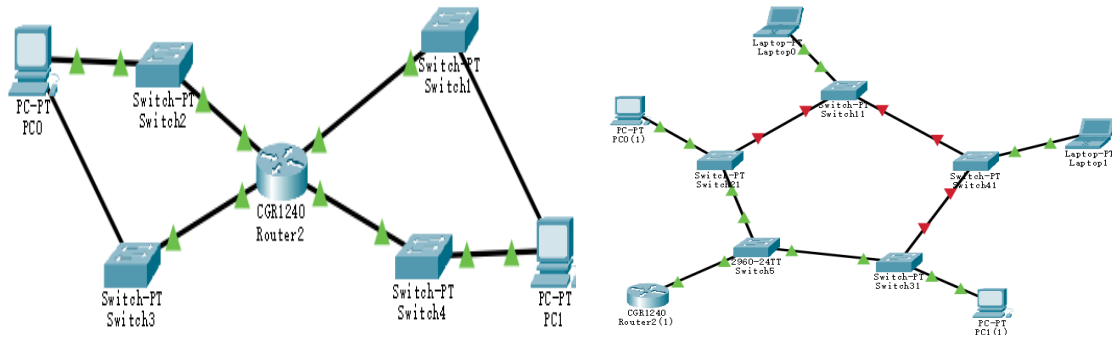


Figure 5. Network topology diagram.

The analysis of Figure 6 indicates that as the remaining load capacity of nodes increases (Node Status), the probability of node failures within the network significantly decreases. In particular, star topologies are more prone to network failures when node buffer capacities are generally limited, due to the cascading effects triggered by the failure of the central node. Therefore, in star networks, central node devices should be assigned higher priority and allocated more resources to effectively prevent potential network risks.

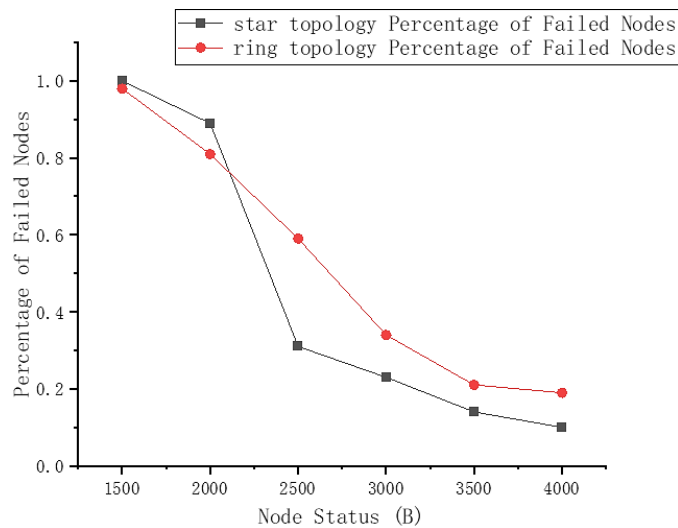


Figure 6. Topological experimental diagram.

5.2 Analysis of Remaining Load Testing of Nodes

The remaining load capacity of a node reflects the ability of neighbouring nodes to receive and accommodate transferred loads when a node fails. This capacity is generally influenced by the node's buffer size and the frequency of data transmission in the network. Typically, a larger buffer capacity and lower data generation frequency result in a stronger remaining load capacity, which reduces the likelihood of temporary node failure (Figure 7).

Analysis of Figure 7 shows that, when the devices have identical characteristics, the proportion of failed nodes in the network increases with the packet transmission frequency. This occurs because as the number of data packets rises, the remaining buffer capacity of nodes gradually decreases, thereby elevating the risk of temporary node failure. Furthermore, this risk worsens as the device buffer size diminishes.

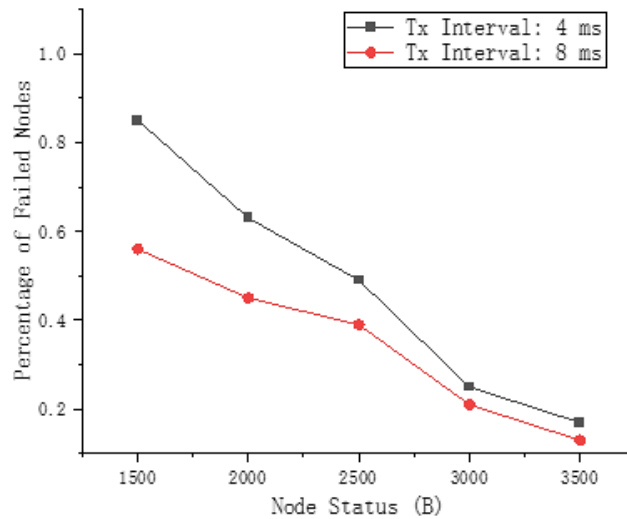


Figure 7. Node remaining load experimental chart.

5.3 Node Bandwidth Test Analysis

In addition, higher node bandwidths can effectively mitigate temporary failure risks. Adequate bandwidth expansion enables nodes to forward more cached data, thereby increasing their load headroom and improving network resilience against potential threats (Figure 8).

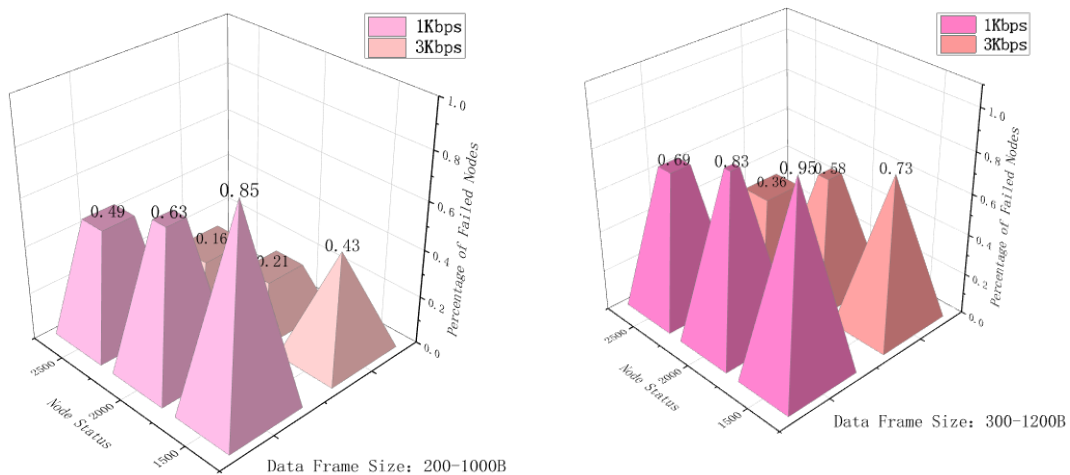


Figure 8. Node bandwidth test chart.

The analysis shows that increasing the node port bandwidth helps reduce failure risks in network devices. The proposed method is especially effective at low data volumes, where a higher bandwidth mitigates insufficient residual node load.

6. Conclusions

With the continuous increase in network node devices and the urgent demand for hybrid data transmission over a single network, aluminium electrolysis networks are facing challenges in terms of reliability, stability, and flexibility. At the same time, these challenges present opportunities for network innovation. However, network upgrades and optimization are not simply a matter of hardware upgrades. In response to the aforementioned requirements, this paper first designs a novel network architecture with the separation of control and transmission for

aluminium electrolysis workshops. This helps achieve centralized network control and improves interoperability among various types of network data, addressing issues caused by protocol and hardware incompatibilities, thereby enhancing networking flexibility. On this basis, a transmission optimization method based on node-importance ranking is proposed. This method uses the node residual load capacity to measure the importance of nodes in the network, thus reserving more bandwidth and buffer resources for critical nodes and reducing network instability caused by temporary node failures.

7. References

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