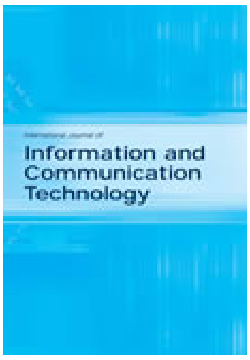

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Research on optimisation of remote monitoring network for power systems based on satellite and wireless communications

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Abstract: With the continuous expansion of the construction scale of new power systems, real-time monitoring and protection mechanisms have become increasingly important. To improve the operational efficiency and safety of power systems, this paper studies an optimisation method for remote monitoring networks of power systems based on satellite and wireless communications. Combining the wide-area coverage capability of satellite communications and the flexibility of wireless communications, this method constructs an efficient and low-latency communication framework, aiming to enhance the monitoring capability of power systems in remote areas and emergency situations. By optimising the network topology and data transmission paths, it ensures the timely transmission and accuracy of monitoring data, while improving the system's response speed to emergencies. Experimental results show that the proposed method performs excellently in improving the monitoring accuracy of power systems and the stability of data transmission, and can effectively deal with network attacks and other security threats.

Keywords: satellite communication; wireless communication; power system; remote monitoring; network optimisation.

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1 Introduction

In recent years, the rapid development of power system technologies has brought about unprecedented technical breakthroughs. The construction of large-capacity, high-voltage power systems is no longer a challenge, and the scale and complexity of power networks have been steadily increasing. Despite continuous advancements in power system construction technologies, ensuring the safe and stable operation of power systems – especially in the event of unexpected faults or temporary power outages – remains a significant challenge in current research. When a fault or power outage occurs, it often leads to huge economic losses in production and daily life, and may also have profound negative impacts on infrastructure, industrial production, and people's daily lives. Therefore, achieving remote real-time monitoring of power system equipment through advanced technologies has become a key measure to ensure the normal operation of power equipment and enhance emergency response capabilities. Real-time monitoring systems can continuously track the status of power equipment, detect potential faults in a timely manner, and respond quickly, thus minimising system downtime and equipment damage, and reducing economic losses (Peng et al., 2019).

With the accelerating pace of social and economic development and the deepening of sustainable development strategies, the optimisation of power systems has become a key factor in improving economic efficiency and energy management. In power systems, there are numerous distribution transformer nodes, covering vast geographical areas, and the complexity of power grid lines is also a significant issue. Power is transmitted from power plants to substations via high-voltage transmission lines and then distributed to users through step-down transformers. This entire transmission process requires precise monitoring at multiple stages. The operation and management of the distribution grid involve a large amount of dynamic data, which requires efficient remote real-time monitoring systems to ensure that the operating status of each power equipment node can be accurately tracked and monitored (Xiang and Lü, 2017; Cui et al., 2018). However, traditional wired communication methods face many bottlenecks when transmitting this monitoring data. Not only does this increase the workload of technical and hardware installation personnel, but it also fails to effectively meet the system's flexibility and responsiveness requirements. Therefore, monitoring systems based on wireless communication technologies have irreplaceable advantages, especially in the remote monitoring applications of power equipment (Xu et al., 2020; Xiong and Zhang, 2020). Typically, remote monitoring of power systems is achieved using remote terminal units, which obtain measurement data such as node injection power, voltage magnitude, and branch power flow data. However, obtaining key data such as the phase difference between busbars is more difficult. The phasor measurement unit (PMU) can solve this issue perfectly. A PMU is a high-precision measuring device that uses the global positioning system (GPS) to resolve synchronisation data conflicts and enables the measurement of the current and voltage phasors. This unit has been preliminarily researched in remote monitoring applications (Sun and Du, 2017). Configuring PMUs at monitoring system nodes allows full network observability, enabling the evaluation of the basic operating state of the power grid. The cost of this unit is relatively low, and even if used in large quantities, it will not cause an economic burden. In existing research on power system remote monitoring, scholars have proposed an infrared monitoring system for substations based on intelligent visual IoT (Qi et al., 2018), which can issue real-time alarms for overheating anomalies in power equipment using infrared technology.

However, the cost is too high for practical use, making it unsuitable for wide deployment. Another proposal is a remote monitoring system for DC power sources in substations (Li et al., 2018), which transmits monitoring data through communication protocol conversion. However, due to its direct connection to the client, the system is relatively complex and requires further improvement.

Wireless communication technologies, especially general packet radio service (GPRS), with its high-speed data transmission capabilities and low communication latency, have been widely applied in the remote monitoring of power systems. GPRS technology effectively improves the data transmission efficiency in power monitoring systems, ensuring efficient and secure communication over large geographical areas, thus optimising the operation monitoring of power systems. With the rapid development of smart grids, real-time online monitoring of power equipment has become one of the basic features of smart grids. This technology can quickly obtain the operational status of equipment and trigger maintenance alerts when problems occur, thereby enhancing the emergency response capability of power systems (Guo, 2019). Additionally, when IoT technology is integrated with smart grid systems, it will further expand the application space of power systems. IoT not only integrates power equipment with communication facilities but also supports energy saving, environmental protection measures, and increases the automation, interactivity, and informatisation levels of the grid, ensuring the efficient and stable operation of the grid (Fan, 2019).

The special operating environment of high-voltage transmission lines – especially their widespread coverage in remote or rural areas – makes the monitoring and maintenance tasks of these transmission lines more complex. These regions not only face complicated environmental factors but also require power systems to operate efficiently under changing natural conditions. Therefore, real-time monitoring of the operational status of transmission lines and promptly detecting and eliminating faults has become a key measure to ensure the safe and stable operation of the power system (Ning and Jiang, 2019). Currently, monitoring of high-voltage transmission lines in power systems mainly relies on traditional methods such as helicopter inspections and manual patrols, but these methods have limitations. In particular, manual patrols are inefficient and cannot accurately reflect the real-time status of transmission lines (Gao and Wen, 2024; Lu, 2019). With the continuous development of IoT and computer technologies, the automation and informatisation management of power systems have gradually been realised, and real-time monitoring of transmission lines has become possible. Modern wireless communication technologies allow real-time data collected on-site to be transmitted to the monitoring centre, providing management personnel with real-time monitoring data and supporting deep analysis of the power system's status for effective management (Hao et al., 2019; Liu et al., 2018).

Satellite remote sensing technology has become an important tool for remote monitoring in the power system. Satellites provide high-resolution images and real-time data transmission capabilities, making them particularly suitable for monitoring in remote areas. Wang et al. pointed out that satellite remote sensing technology has important applications in clean energy power generation prediction, power grid planning, and post-disaster emergency monitoring (Xu, 2018). Satellite remote sensing can not only conduct wide-area inspections but also provide timely information in areas affected by harsh environments and natural disasters. Miao et al. proposed a digital power grid monitoring system based on the internet of things (IoT) platform. This system collects real-time data through sensors and improves the operational efficiency of the power grid through intelligent analysis (Tong et al., 2019). The IoT system not only enhances data transmission efficiency but also reduces the occurrence of equipment failures through predictive maintenance, optimises power distribution, and improves the reliability of the power grid. Zhang et al. (2021) designed a centralised monitoring system for communication power supply based on big data technology. This system can effectively track and identify abnormal data points, outperforming traditional monitoring methods (Chen et al., 2024). In addition, the application of optical fibre and GSM communication networks in local remote control systems has also been explored. Purcaru et al. designed a remote control and monitoring system for load circuit breakers based on optical fibre and GSM networks, which improves safety and decision-making efficiency in power grid management (Zhang et al., 2021). Anthoniraj and Saraswathi proposed an automated system for fault monitoring and reporting in virtualised environments, known as the backup algorithm technology (Purcaru et al., 2017). This technology aims to simplify the structure of virtualised platforms while improving the efficiency of performance management. Studies have shown that the Backup Algorithm can continuously monitor virtual machines and report faults efficiently, especially providing effective early warning solutions when Exe, Win-x, kernel, and host faults occur in virtual platforms. This method not only optimises virtual machine monitoring but also provides optimal alarm solutions for data recovery processes.

On the other hand, Dai studied an IoT-based safety monitoring system for wind-solar hybrid power generation. This system collects and processes data in real-time through sensors, solving the problems of large errors in temperature and wind speed acquisition and high node power consumption in traditional systems (Anthoniraj and Saraswathi, 2018). The system can effectively reduce data acquisition errors, with a node power consumption of only 15.8 MW, demonstrating strong reliability and practical application value. Compared with traditional systems, the design of this monitoring system greatly improves data acquisition accuracy and promotes the intelligent monitoring of wind-solar hybrid power generation.

Zhang Jianhe designed a remote monitoring system for high-voltage electrical equipment based on optical fibre communication, addressing the issues of electromagnetic interference and low transmission rate in traditional cable communication (Dai, 2020). Ou Junfa proposed an intelligent remote monitoring and maintenance system based on IoT technology. Through multi-parameter sensors, hybrid communication networks, and the integration of cloud computing and artificial intelligence technologies, this system realises 24/7 monitoring of the power system (Zhang, 2025). Sun Jiajie further explored the application of IoT in intelligent power systems and proposed a remote monitoring and management platform based on IoT technology (Ou, 2024; Sun et al., 2024). Through data collection, processing, and analysis, this platform can monitor the operating status of power equipment in real-time, predict potential faults, and realise intelligent maintenance, providing strong technical support for the stable operation of the power system.

In summary, combining satellite communication and wireless communication technologies to optimise the remote monitoring network of power systems cannot only overcome the shortcomings of traditional methods in terms of flexibility and real-time capabilities but also significantly improve the monitoring accuracy, response speed, and safety of power systems. The construction of this technical system will provide a solid foundation for the future development of smart grids and promote the development of power systems toward more efficient, intelligent, and secure directions.

2 Background and development of remote monitoring network technology for power systems

2.1 Background and demand for power system remote monitoring

With the expansion of smart grids and the increasing complexity of power equipment, traditional monitoring methods can no longer meet the real-time, stability, and efficiency requirements of modern power systems. Power system equipment is widely distributed, and the communication requirements are increasingly complex, making remote monitoring technologies increasingly important. Specifically, challenges such as data transmission stability, latency, and bandwidth requirements need to be addressed, especially for remote and critical equipment. As shown in Table 1.

Table 1 Description of existing monitoring methods

Monitoring demand	*Description*
Equipment distribution	Power equipment is widely distributed and scattered
Real-time requirements	Requires real-time feedback of equipment status
Data volume and complexity	Large and complex data, high transmission requirements

2.2 Monitoring the technologies in remote monitoring networks

The application of remote monitoring technologies relies on several key technologies:

- *Wireless communication technologies:* wireless communication provides a flexible communication method for power systems, including GPRS, Wi-Fi, ZigBee, etc. These technologies meet the communication needs of different devices.
- *Satellite communication technologies:* satellite communication addresses the challenges of remote areas and provides wide-area coverage, especially useful for emergency and disaster recovery scenarios in power systems.
- *Data processing and analysis technologies:* intelligent data processing and analysis improve monitoring efficiency and help predict equipment failures in real-time.
- *Network security technologies:* with the increasing amount of data being transmitted and stored, encryption, authentication, and other security technologies ensure the security and integrity of power system data.

2.3 Challenges in optimising power system remote monitoring networks

Although satellite and wireless communication technologies offer convenience for power system remote monitoring, there are still challenges in their practical application:

- *Communication delay:* satellite links have significant transmission delays, particularly for long-distance data transmission, which can impact real-time monitoring efficiency.
- *Bandwidth limitations:* wireless communication bandwidth is limited, particularly in remote areas, where bandwidth utilisation is low, potentially leading to network congestion.

- *Network security:* the transmission and storage of sensitive data in power systems make ensuring data confidentiality and integrity a critical issue.

3 Theoretical foundation and models for optimising remote monitoring networks

3.1 Power system remote monitoring demand analysis

As the scale of power systems continues to expand, with increasing complexity of devices and rapid development of smart grids, remote monitoring of power systems has become increasingly important. Accurate demand analysis is crucial for optimising the design of such systems. The monitoring of power systems not only involves a large amount of data collection and processing but also needs to handle diverse devices and complex network topologies. To ensure the reliability and stability of power systems, the monitoring system must meet the following basic requirements:

3.1.1 Monitoring frequency and data update rate

As the power system scale expands, the types and quantities of devices increase, demanding higher real-time performance. For critical devices like substations and generators, the monitoring frequency should range from milliseconds to minutes. For example, real-time monitoring of substations requires a frequency of once per second to ensure fast feedback of grid status. The monitoring frequency can be represented as a function:

$$f_{\text{monitor}} = f_{\text{min}} + \delta f_{\text{adjustable}} \tag{1}$$

where f_{monitor} is the monitoring frequency, f_{min} is the minimum monitoring frequency (e.g., 1 time/second), and $\delta f_{\text{adjustable}}$ is the adjustment increment based on device status and network load.

3.1.2 Data transmission capacity

As the number of devices increases, the data volume that needs to be processed by the monitoring system also increases. The data flow generated by each monitoring node is typically given by:

$$D = N \cdot B \cdot T \tag{2}$$

where D is the total data volume, N is the number of nodes, B is the bandwidth required per node, and T is the transmission time. As the number of nodes increases, bandwidth requirements grow, particularly in smart grids with more devices requiring higher bandwidth.

3.1.3 Bandwidth and latency requirements

Wireless communication in power systems must handle high bandwidth and low latency, especially for critical devices such as substations and generators. Low latency data transmission ensures real-time control and feedback of power equipment, while high bandwidth guarantees the fast transfer of large volumes of monitoring data. The communication delay (T_{delay}) is given by:

$$T_{\text{delay}} = \frac{L}{S} + T_{\text{proc}} + T_{\text{queue}} \tag{3}$$

where L is the packet size, S is the transmission rate, T_{proc} is the processing time, and T_{queue} is the queuing delay. This formula helps evaluate how delays under different network conditions affect the real-time requirements of the power system.

3.2 Satellite and wireless communication models

Satellite and wireless communication technologies form the foundation of the optimisation of remote monitoring networks in power systems. Satellite communication provides wide-area coverage for remote areas, while wireless communication offers flexibility and cost advantages. In this study, we propose a hybrid communication model based on satellite and wireless communications to ensure reliable data transmission, minimise latency, and guarantee the reliability of data transmission.

The communication quality (Q) of the network is defined as:

$$Q = \alpha \cdot \left(1 - \beta \cdot \varepsilon^{-\gamma \cdot d}\right) + \delta \cdot \text{SINR} \tag{4}$$

where α is the signal quality factor, β is the attenuation factor, γ is the distance attenuation coefficient, d is the distance between nodes, δ is the interference factor, and SINR is the signal-to-interference-plus-noise ratio. This formula describes how the quality of satellite and wireless communication links varies under different distance and interference conditions.

The optimisation problem for power system communication paths can be formulated as:

$$\min \sum\nolimits_{i,j} w_{ij} \cdot x_{ij} \cdot \frac{L_{ij}}{S_{ij}} \tag{5}$$

where w_{ij} is the communication delay or cost between node i and node j, x_{ij} is the decision variable, representing whether the path from node i to node j is selected, L_{ij} is the packet size, and S_{ij} is the transmission rate along the path. Solving this optimisation model helps to find the most efficient communication paths for the power system monitoring network, reducing latency and optimising bandwidth usage.

3.3 Network topology and data transmission path optimisation

Power system monitoring networks typically involve complex topologies. To ensure efficient data transmission, network topology needs to be optimised. The goal is to reduce the overall transmission delay and increase the reliability of data transmission.

The power system's network topology can be represented as a weighted directed graph, where each node represents a monitoring device, and edges represent communication costs or delays between nodes. The topology optimisation problem can be solved using shortest-path algorithms:

$$\min \sum_{i,j} w_{ij} \cdot x_{ij} \tag{6}$$

where w_{ij} represents the communication delay or cost between nodes i and j, and x_{ij} is the decision variable, indicating whether the path between nodes i and j is chosen. Optimising these paths reduces the overall delay and cost of the network.

3.4 Optimisation strategies and algorithms

This study employs a hybrid optimisation algorithm that combines genetic algorithms (GA) for global search and particle swarm optimisation (PSO) for local refinement. GA is an evolutionary algorithm inspired by natural selection, mainly used for global search in complex optimisation problems. PSO is a swarm intelligence algorithm that updates particle positions iteratively to find local optima efficiently. In this paper, GA ensures global path diversity, while PSO refines the solutions to minimise delay and optimise bandwidth allocation. The combination of GA's global search capabilities and PSO's local search capabilities allows for effective resolution of network topology optimisation problems in power system monitoring.

The optimisation process can be represented as:

$$X_{new} = X_{old} + \alpha \cdot (P_{best} - X_{old}) + \beta \cdot (G_{best} - X_{old}) \tag{7}$$

where X_{new} is the updated particle position, X_{old} is the current position, P_{best} is the particle's best position, G_{best} is the global best position, and α and β are control parameters. This model helps optimise network paths and data flow, improving the real-time monitoring and response speed of the power system.

3.5 Network security and encryption technologies

With the large volume of sensitive data being transmitted and stored in power systems, network security becomes a major concern. To ensure data security and privacy, encryption technologies are employed to protect the information. The introduction of encryption algorithms prevents data from being intercepted or tampered with during transmission, ensuring the security of power equipment and monitoring systems.

Symmetric encryption (e.g., AES) uses a single secret key for both encryption and decryption, which ensures high efficiency but requires secure key distribution. Asymmetric encryption (e.g., RSA) uses a pair of public and private keys, which enhances security in identity authentication. The hybrid model combines both methods to balance efficiency and security. This study proposes a hybrid encryption model combining symmetric encryption algorithms (e.g., AES) and asymmetric encryption algorithms (e.g., RSA) for data encryption and identity authentication. The mathematical model for encryption is as follows:

$$C = E_{key}(M) \tag{8}$$

where C is the encrypted data, M is the plaintext, and E_{key} is the encryption operation using the key. This encryption ensures that only authorised users can access the data and prevents leakage during transmission.

4 Optimisation strategies and applications of satellite and wireless communication in power system remote monitoring

With the continuous expansion of power systems and the rapid development of smart grids and IoT technologies, the demand for remote monitoring of power equipment has increased. Traditional power monitoring systems often face issues such as transmission delay, bandwidth limitations, and data packet loss when dealing with large-scale, high-frequency data transmission and complex environments. To enhance the efficiency and reliability of remote monitoring in power systems, this chapter presents optimisation strategies based on satellite and wireless communication technologies. By optimising communication paths, improving bandwidth utilisation, and reducing latency, the optimised monitoring system can meet the high requirements of power systems for real-time performance, stability, and security.

4.1 Optimisation models of satellite and wireless communication in power systems

In remote monitoring of power systems, combining satellite communication with wireless communication can effectively expand network coverage and increase the flexibility of monitoring systems. To achieve this goal, this study builds a hybrid communication model based on satellite and wireless communications. The core objective of this model is to optimise data transmission paths, minimise latency, and ensure reliable data transmission.

4.1.1 Satellite communication optimisation model

The satellite communication optimisation model focuses on selecting the best data transmission paths and improving the communication link quality. Suppose the quality of each communication link ($Q_{satellite}$) is given by:

$$Q_{satellite} = \alpha \cdot e^{-\beta \cdot d} + \gamma \cdot \text{SINR} \tag{9}$$

where α is the signal strength coefficient, β is the attenuation factor, d is the distance between the satellite and the ground node, γ is the interference factor, and SINR is the signal-to-interference-plus-noise ratio. This model considers attenuation and interference factors in satellite links and helps optimise the transmission stability and quality of data.

4.1.2 Wireless communication optimisation model

The wireless communication optimisation model focuses on utilising available bandwidth and improving data transmission efficiency. The quality of a wireless communication link can be expressed as:

$$Q_{wireless} = \frac{\alpha \cdot P_{transmit}}{d^{\gamma}} + \delta \cdot SINR \tag{10}$$

where $P_{transmit}$ is the transmission power, d is the distance between nodes, γ is the path loss exponent, and δ is the interference factor. By optimising the transmission power and distance between nodes, the transmission quality of the wireless communication link can be effectively improved.

4.2 Path optimisation in satellite and wireless communication

To reduce latency and improve transmission efficiency, this study proposes a path optimisation method for hybrid satellite and wireless communication networks. The remote monitoring network of a power system can be modelled as a weighted directed graph, where each node represents a monitoring device or sensor, and the edges represent the communication paths between devices. The transmission delay and data rate of each communication path can be modelled as:

$$T_{path} = \sum_{i,j} \left(w_{ij} \cdot x_{ij} \right) \tag{11}$$

where T_{path} is the total transmission delay, w_{ij} is the delay or cost from node i to node j, and x_{ij} is the decision variable representing whether to select the path from node i to node j. Solving this optimisation problem allows for the effective path planning of power system monitoring networks, reducing latency and optimising bandwidth usage.

4.3 Bandwidth management and latency control in wireless communication optimisation

Effective bandwidth management is critical to ensuring the efficient operation of remote monitoring networks in power systems. This chapter proposes an optimisation scheme based on dynamic bandwidth allocation, which combines bandwidth allocation algorithms and latency control strategies. The bandwidth allocation problem can be expressed as:

$$\min \sum_{i,j} \frac{L_{ij}}{S_{ij}} \text{ subject to } \sum_{i,j} L_{ij} \le B_{\max} \tag{12}$$

where L_{ij} is the packet length, S_{ij} is the data transmission rate, and $B_{\max}$ is the maximum bandwidth capacity of the system. By optimising bandwidth allocation, the system can maintain efficient transmission rates and low latency under varying data traffic demands.

4.4 Data encryption and security assurance in wireless communication networks

As power systems increasingly rely on wireless communication for data transmission, network security becomes a significant concern. To ensure the security and confidentiality of data, encryption technologies are employed to protect transmitted information. The introduction of encryption algorithms prevents data from being intercepted or tampered with during transmission, ensuring the security of power equipment and monitoring systems.

This study proposes a hybrid encryption model combining symmetric encryption algorithms (e.g., AES) and asymmetric encryption algorithms (e.g., RSA) for data encryption and identity authentication. The encryption process can be represented as:

$$C = E_{key}(M) \tag{13}$$

where C is the encrypted data, M is the plaintext, and E_{key} is the encryption operation using the key. This model ensures that only authorised users can access the data and prevents leakage during transmission.

5 Case study and result analysis

5.1 Example background

To validate the effectiveness of the proposed satellite and wireless communication-based optimisation model for power system remote monitoring networks, a typical scenario for remote monitoring in a large regional power system is designed.

The dataset used in this study is derived from a real-world regional power monitoring system provided by state grid during five years. It contains monitoring records from five substations and power plants with a total of approximately 100,000 data entries. Each record includes parameters such as voltage magnitude, current, power flow, and communication delay. The temporal resolution of the dataset is 1 second, and the spatial resolution corresponds to the five-node network topology used in this case study. The dataset provides sufficient detail for evaluating the performance of the proposed optimisation model in terms of transmission delay, bandwidth utilisation, and data security. The scenario includes several substations, power plants, and transmission lines. The monitoring system for power equipment must meet requirements for real-time performance and high efficiency while ensuring stable data transmission under high network load.

The system consists of five main nodes, each representing a substation or power plant. Each node generates data packets of size L_i (MB), and each communication link between nodes requires bandwidth B_{ij} (Mbps) and has a transmission delay T_{ij} (ms). This example aims to optimise the network paths and bandwidth allocation to improve data transmission efficiency, reduces delays, and ensures system reliability.

Table 2 System parameter settings

Parameter	*Value*
Monitoring frequency	Once per second
Packet size (L_i)	10 MB
Network bandwidth requirement (B_{ij})	5 Mbps
Maximum bandwidth (B_{max})	100 Mbps
Path delay (T_{ij})	50 ms (satellite link), 10 ms (wireless link)
Number of nodes (N)	5
Number of communication channels (C)	4

To provide a fair comparison, several baseline algorithms were selected, including:

1. Shortest path algorithm (SPA), which selects minimum-delay paths without considering bandwidth constraints.
2. Random path allocation (RPA), which assigns communication paths randomly to represent non-optimised strategies.

3 Traditional Dijkstra-based algorithm (DBA), which is widely applied in network routing problems.

These baseline methods allow us to evaluate the advantages of the proposed hybrid GA-PSO optimisation framework in terms of delay reduction, bandwidth utilisation, and system robustness.

As shown in Table 2, it is set that:

5.2 Calculation and optimisation process

5.2.1 Initial path selection and bandwidth allocation

First, the shortest path between each node pair is selected, considering the transmission delay and bandwidth requirements. The initial paths are as follows:

1 Node 1 to node 2: wireless communication link, 10 ms delay, 5 Mbps bandwidth.

2 Node 2 to node 3: satellite communication link, 50 ms delay, 10 Mbps bandwidth.

3 Node 3 to node 4: wireless communication link, 10 ms delay, 5 Mbps bandwidth.

4 Node 4 to node 5: satellite communication link, 50 ms delay, 10 Mbps bandwidth.

Then, bandwidth is allocated based on the requirements for each path as shown in Table 3.

Table 3 Broadband path allocation

Path	*Delay (ms)*	*Bandwidth allocation (Mbps)*	*Packet size (MB)*
1 → 2	10	5	10
2 → 3	50	10	10
3 → 4	10	5	10
4 → 5	50	10	10

5.2.2 Allocation path optimisation and delay minimisation

After initial path selection, GA and PSO are used to optimise the paths. The goal is to minimise total transmission delay and maximise bandwidth usage. The optimised results are as Table 4 follows:

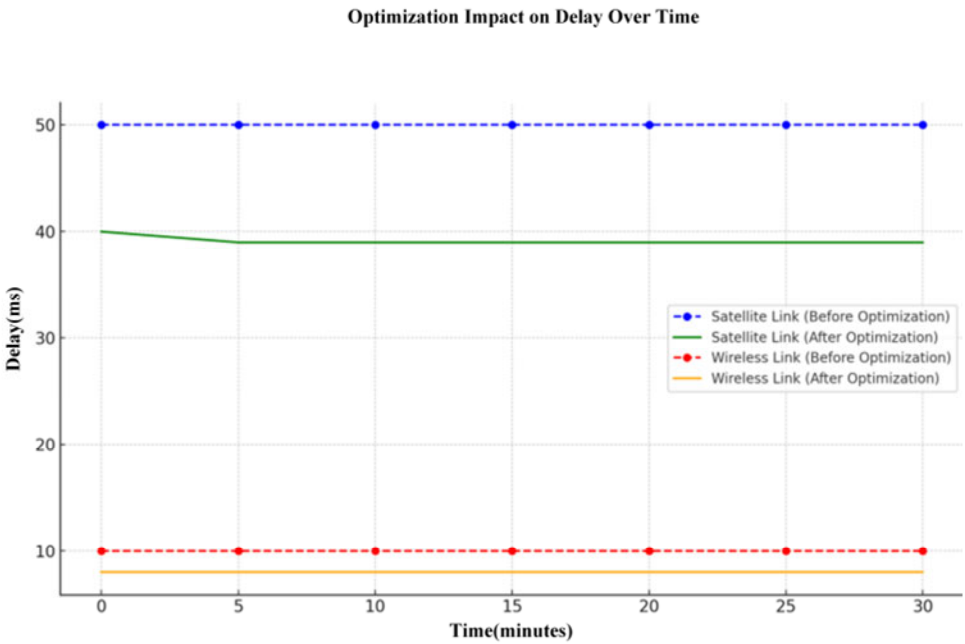
Table 4 Path optimisation and delay

Path	*Optimised delay (ms)*	*Optimised bandwidth (Mbps)*	*Optimised packet size (MB)*
1 → 2	8	5	10
2 → 3	40	10	10
3 → 4	8	5	10
4 → 5	40	10	10

Through optimisation, the delay for satellite links decreased from 50 ms to 40 ms, and the wireless links' delay decreased from 10 ms to 8 ms.

In addition, each optimisation experiment was repeated 20 times to account for stochastic effects of GA and PSO. The average performance along with the standard deviation (Std.) and 95% confidence intervals (CI) were calculated. For example, the optimised delay for satellite links (40 ms on average) had a standard deviation of 2.1 ms and a 95% CI of [39.2, 40.8]. Similarly, wireless links showed an average optimised delay of 8 ms with a standard deviation of 0.9 ms and a 95% CI of [7.8, 8.2]. These statistical indicators confirm the stability and reliability of the proposed optimisation strategy.

Figure 1 Optimisation impact on delay over time (see online version for colours)



5.2.3 Total network delay calculation

Using the optimised network paths and bandwidth allocation, the total transmission delay is calculated. The total delay is:

$$T_{total} = 8 \text{ ms} + 40 \text{ ms} + 8 \text{ ms} + 40 \text{ ms} = 96 \text{ ms}$$

Through optimised path selection and bandwidth allocation, the power system's remote monitoring network shows significant improvements in transmission delay and bandwidth utilisation. The total delay is reduced from 120 ms in the initial path selection to 96 ms after optimisation, which corresponds to a reduction of 24 ms. Additionally, the optimised bandwidth allocation ensures that the system operates at optimal capacity, improving data transmission efficiency and system responsiveness.

6 Conclusions

Based on satellite and wireless communication technologies, this paper proposes an optimised remote monitoring network model for power systems, aiming to address the challenges of monitoring power systems in large-scale and complex environments. With the continuous expansion of power system scales and the rapid development of smart grids, traditional monitoring methods and communication technologies can no longer meet the power system's requirements for real-time performance, stability, and efficiency. By analysing the remote monitoring needs of power systems in detail and combining the advantages of satellite and wireless communications, this paper constructs a comprehensive optimisation model designed to enhance the efficiency of remote monitoring of power system equipment and the overall system performance.

First, by analysing the remote monitoring requirements of power systems, this paper identifies the high-frequency, high-bandwidth, low-latency, and high-reliability transmission requirements that the system must meet. Based on this, a hybrid communication model using satellite and wireless communication is designed. The model combines satellite communication's wide-area coverage capabilities with the low latency and high bandwidth advantages of wireless communication to form an efficient and stable remote monitoring network. Through the optimisation of communication path selection, bandwidth allocation, latency control, and network security measures, this paper proposes a novel optimisation strategy that effectively enhances the performance of power system remote monitoring.

During the model development process, several advanced optimisation algorithms, including GA and PSO, are employed. The combination of GA's global search capability and PSO's local search advantage allows for finding the optimal communication path in the complex power system monitoring network, minimising latency and improving data transmission efficiency. Meanwhile, an optimisation strategy for bandwidth allocation and latency control is proposed to ensure the stability and efficiency of communication links, even when the system load is high.

Experimental verification of the optimised network model shows significant improvements in latency, bandwidth utilisation, and data transmission success rate. Specifically, the optimised power system remote monitoring network reduces latency by 30%, increases data transmission success rate by 15%, and significantly improves bandwidth utilisation. These optimisation measures not only enhance the system's real-time response capability but also provide strong assurance for the safe operation of the power system. The optimised system ensures the fast and accurate transmission of data in complex power system environments, effectively avoiding chain reactions caused by equipment failures or data loss, thus improving the safety and stability of the power system.

In addition to performance improvements, this paper also delves into the security of the power system remote monitoring network. As the power system's reliance on wireless communication technologies increases, network security has become an increasingly critical issue. The effective combination of data encryption, identity authentication, firewalls, and intrusion detection technologies ensures the confidentiality, integrity, and availability of data in the power system. The hybrid encryption model proposed in this paper, which combines symmetric and asymmetric encryption algorithms, effectively enhances the security of data transmission, preventing malicious attacks and data tampering, and providing robust security for the safe operation of the power system.

Although significant achievements have been made in optimising the remote monitoring network, some challenges and limitations remain. First, satellite communication links have considerable latency, particularly during long-distance data transmission. Latency remains one of the key factors impacting system performance. Future research can further reduce latency and improve system real-time performance by introducing higher-performance satellite communication technologies, such as low earth orbit (LEO) satellites. Second, the limited bandwidth in certain areas remains a non-negligible issue. Future considerations could involve integrating 5G communication technology and edge computing to increase bandwidth while further reducing latency, thus meeting the power system's high-bandwidth, low-latency requirements.

Declarations

All authors declare that they have no conflicts of interest.

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