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Research on Low-Latency Communication Network Architecture for Power System Automation Driven by 5G Technology

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Abstract With the expansion of the scale of smart grid and the improvement of service real-time requirements, low-latency communication network becomes the key infrastructure to guarantee the automation and control of power system. This paper proposes an intelligent route optimization scheme based on multicast routing algorithm. The layered architecture and performance requirements of smart grid wide-area communication network are analyzed, and the shortest path tree algorithm is proposed. Combined with the multi-constraint QoS model, the improved multi-tree multi-constraint routing algorithm based on cost correction (MTMCR-CC) is designed. By dynamically adjusting the link cost function and constructing multicast tree candidate sets, network congestion prevention, load balancing and fault isolation are realized. Simulation results show that compared with the traditional SPRS and HCARS algorithms, MTMCR-CC always has a lower packet loss rate, the average bandwidth of the link reaches 69.72% of the maximum value, and the success rate of the node 25-position communication reaches 99%, and also performs significant optimization in the key indexes such as node load balancing. In the simulation scenario, the network traffic in all paths is lower than 2.5×107 bytes. It is proved that the proposed algorithm can meet the demand of millisecond response and high reliability of power system.

Index Terms smart grid, multicast routing algorithm, shortest path tree algorithm, MTMCR-CC algorithm, communication network

I. Introduction

With the continuous development of the smart grid, the types of grid services are gradually diversified, and the grid data information transmitted by networks at all levels in different services will also differ [1]. At the same time, the communication network at each level of the smart grid has different communication characteristics as well as service requirements, and the routing design method is also characterized by diversity [2], [3]. Therefore, in order to improve the service quality of the smart grid communication network, it is necessary to design the routing algorithm according to the specific needs of each layer of the network, so as to enhance the real-time power information interaction, effectively ensure the timeliness of the dynamic balance of power supply and demand, and ultimately enhance the frequency stability of the power grid [4]-[7].

In China's early power system, due to the low demand for communication bandwidth and stability, the transmission method of power line carrier communication dominated [8], [9]. By carrying carrier signals through power lines, the business requirements at that time could be met and the communication tasks could be well accomplished [10]. With the development of the business model and the continuous improvement of the power system's communication needs, the disadvantages of this model of power line carrier are gradually exposed [11]. Due to the low transmission rate of power line carrier transmission compared with fiber optic transmission rate, and easy to be interfered by external noise, this method has been unable to meet the communication needs of the current power private network [12], [13]. In order to further improve the quality of demand-driven power communication, routing technology is gradually applied to smart grid business communication. Although the traditional routing algorithm can simply realize the interaction of electric power information in smart grid, it still cannot meet the real-time demand of gradually improving electric power information interaction [14]-[16]. Moreover, the traditional routing algorithms in smart grid communication networks are not highly pervasive, and when applied to smart grid communication, they can cause real-time and reliability problems due to service-specific communication requirements [17]-[19]. Therefore, in the smart grid communication network, the selection of suitable routing algorithms according to the specific communication service requirements is an inevitable choice to improve the quality of smart grid communication and enhance the frequency stability of the power grid [20], [21].

This paper firstly introduces the basic structure of smart grid wide area communication network and clarifies the communication performance requirements. The concept of multicast routing is elucidated, and a multitree-based multicast routing method for vector networks is proposed. The multi-constraint QoS model is constructed, and the shortest path tree algorithm is improved by introducing the cost correction function and multi-tree distance indicator. Verify the performance improvement of MTMCR-CC algorithm in five dimensions through simulation experiments. Build simulation scenarios to evaluate the design and application effects of MTMCR-CC algorithm.

II. Low-latency communication network for power system automation based on multicast routing algorithm

As the core carrier of energy transformation, smart grid realizes the deep integration of power, information and control flows by integrating distributed energy sources, advanced measurement systems and wide-area protection devices. However, its wide-area communication network needs to support cross-area real-time data interaction, which imposes stringent requirements on end-to-end delay, reliability and dynamic adaptability. Current mainstream routing algorithms have limitations in load balancing, congestion control, etc., and are difficult to cope with network topology changes and service priority conflicts. In this paper, we focus on the low latency optimization of smart grid communication networks and propose a dynamic cost correction method based on multicast routing.

II. A. Smart grid wide area communication network

II. A. 1) Basic structure

Smart grid includes several major fields such as power generation, transmission, and control, including energy supply system, distributed energy, energy management system, advanced measurement system, priority control and data acquisition system, wide-area measurement system, and user information system. The construction of a smart grid power communication network needs to have high-speed, self-healing, broadband, and bidirectional characteristics, and be able to realize access and transmission of a variety of. Smart grid wide area communication to be realized is the communication between different systems in different areas of the grid, so the wide area network is to realize the communication between power generation, transmission, distribution, etc. and distributed energy of the smart grid. Smart grid wide area communication network is shown in Figure 1.

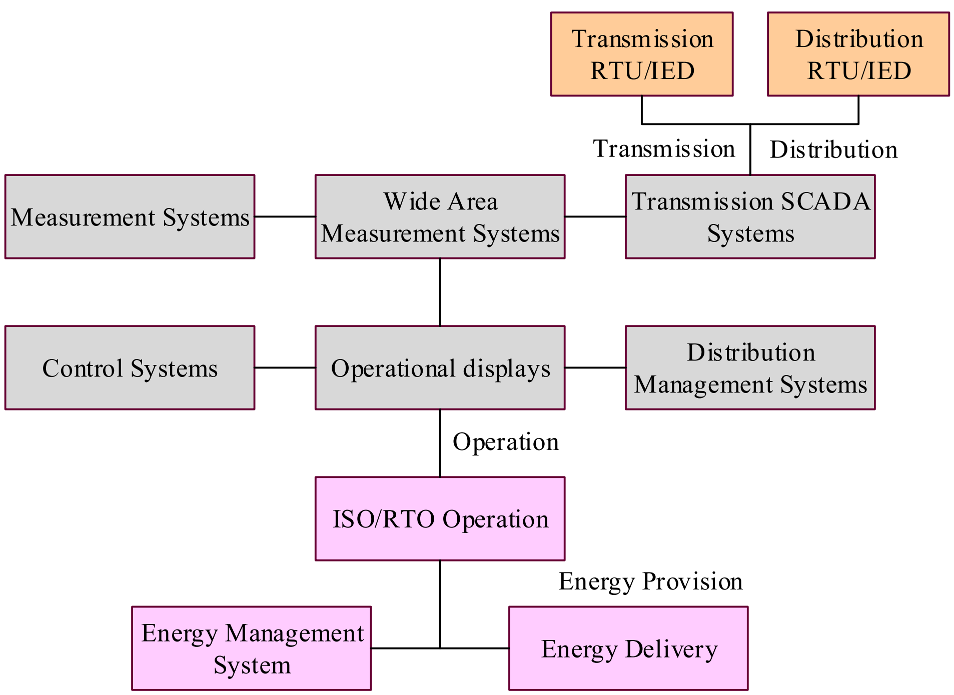


Figure 1: Wide Area Communication Network of Smart Grid

Wide-area communication network mainly carries out the communication between control and operation centers, intelligent substations, energy management and other systems, distributed energy sources, i.e., it is necessary to realize the communication between regional transmission organization/independent system operation running display, control system, transmission SCADA system, wide-area measurement system and distributed management system. At present, the wide-area protection communication system based on wide-area measurement generally adopts a combination of centralized and distributed structure system, and the centralized distributed structure is shown in Figure 2. The communication network adopts centralized structure in each sub-area, and a regional decision-making center is set up in the area to complete the decision-making function of protection and control, and at the same time, various IEDs are set up under it to collect information and complete communication. However, the network as a whole adopts a distributed structure, and the regional decision center is distributed in each region to complete its protection and control decisions. This structure can not only deal with powerful units and complex algorithms, the central processing unit of the station can also perform part of the wide-area protection function, share the computational pressure of the system processing unit, and reduce the time delay of data transmission; secondly, the division of the information exchange area can reduce the time delay of the exchange. This structural system integrates the advantages of both distributed and centralized structural systems, which is in line with the development trend of modern smart grid. Therefore, it is a more ideal structure.

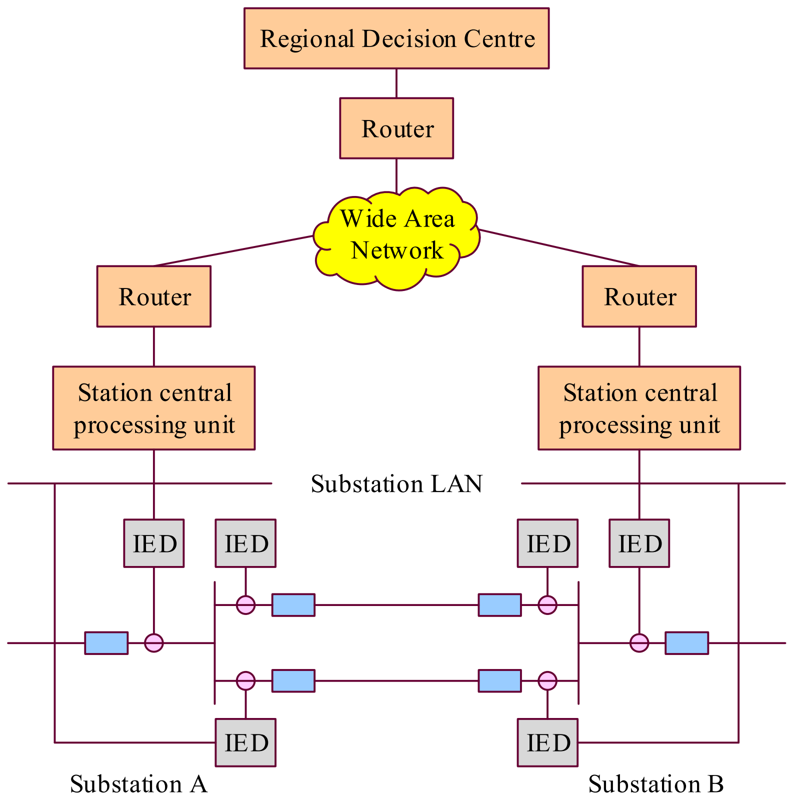


Figure 2: Centralized distributed structure

II. A. 2) Communication performance requirements

The smart grid is large in scale, complex in structure and wide in coverage, if we want to realize the comprehensive monitoring and control of the smart grid wide area communication system, we must complete the real-time exchange of data, so the ultra-remote real-time communication is the key to realize the smart grid wide area protection system. Therefore, information transmission delay is one of the important indexes to determine the performance of WAN communication. Delay is the time required for a message to be transmitted from the sending end of a communication network to the receiving end. The delay of the wide area communication system refers to the time interval between the information sent from the sending node and received by the receiving node including the working delay of all the devices in the transmission process and the network transmission delay, the specific composition is shown in Figure 3.

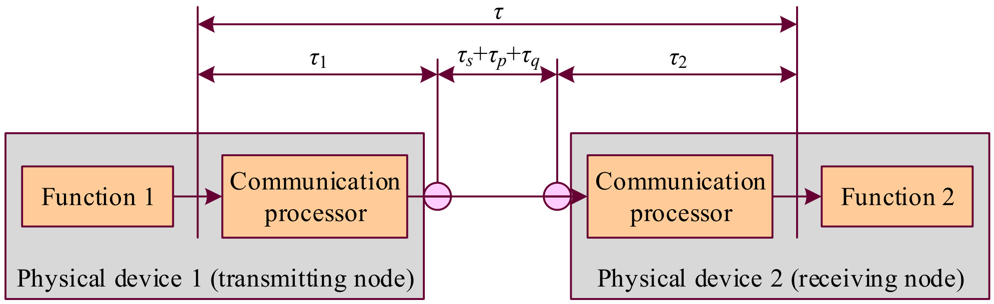


Figure 3: Composition of message transmission delay

The delay of the smart grid wide area communication system can be derived from equation (1)

$$\tau = \tau_1 + \tau_s + \tau_p + \tau_q + \tau_2 \tag{1}$$

Where, τ - total delay;

τ_1, τ_2 - processing delay, mainly including sending and receiving at the communication processor protocol for datagram compression, unpacking delay, and the communication processor operating system and performance related to the communication processor, generally a fixed value of no more than 10μs;

τ_s - send delay, it is the data from the node all the way into the transmission medium required time, the size of the delay depends on the data frame and link bandwidth;

τ_p - propagation delay, it is the time used to propagate the information between the sending site and the receiving site, by the communication channel medium and the length of the communication channel is related to the optical signal in the fiber propagation rate of about 2/3 of the speed of light (that is, $2\times10^8 m/s$), the propagation delay of the level of μs can be ignored;

τ_q - queuing delay, is the time required for information from entering the queuing queue to this information acquisition, mainly related to the communication routing protocol, queuing model, and the amount of services in the network and other factors.

In order to ensure that complete state information is obtained and security control measures are taken before destabilization or even collapse, the transmission, forwarding and processing of real-time information must be controlled to be completed in less than 30~50ms. Assuming that there is a provincial power grid with a scale of 50 nodes and sub-stations within a range of 1,000 kilometers from the central regulator, the transmission delay of the entire communication network needs to be less than 20ms in order to meet the communication performance requirements.

II. B. Multi-tree based multicast routing method for vector networks

II. B. 1) Multicast Routing Definitions

A common idea in multicast routing is to construct an extended distribution tree among the members of a multicast group. IP multicast traffic on a particular "sender-destination" pair is transmitted from the sender to the receiver through this spanning tree, which connects all hosts in the multicast group. Different IP multicast routing protocols use different techniques to construct these multicast spanning trees, and once the tree has been constructed, all multicast traffic will propagate through it.

Kompella is the multicast tree that minimizes the cost of solving delay constraints in multicast routing algorithms. The example solution procedure is shown in Fig. 4. For $G=(V,E)$ in Fig. 4, define the function $C(e)$ as a positive real cost function, $D(e)$ as a positive integer delay function, and e as an edge. The multicast source is s the set of multicast endpoints is S, and the integer □ is given as a delay constraint. Define the restricted minimum cost path between (U,V) as the minimum cost path between U and V that satisfies the delay constraint. Define a closed graph G' of the set of nodes N to be a complete graph of the set of nodes N with the same weights of the restricted minimum cost paths from nodes V to W.

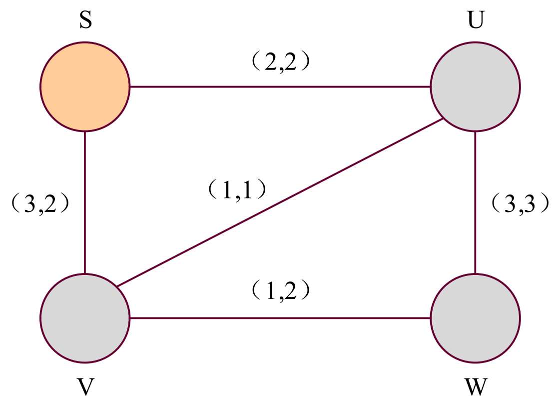


Figure 4: Sample solution process

First find the restricted cost paths of all pairs of nodes in the set $\{s\}\cup S$: then construct the closure G' of $\{s\}\cup S$. Define 2 more choice functions: one is the link cost function $f=\begin{cases} c(v,w), & If\ p(v)+D(v,w)<\Delta \\ \infty, & \text{Other} \end{cases}$, the other is a function that balances cost and delay $fdt(v,w)=\begin{cases} \dfrac{c(v,w)}{\Delta-(p(v)+D(v,w))}, & p(v)+D(v,w)<\Delta \\ \infty, & \end{cases}$. Then the minimum spanning tree is constructed using Primm's algorithm starting from s, and the edges in the minimum spanning tree are selected according to the following rules: do not violate the delay constraints and minimize the value of the selection function. Finally, the corresponding edges in the minimum spanning tree are replaced by constrained minimum cost paths and possible loops are eliminated, and finally a delay-constrained minimum cost multicast tree is obtained.

Definition (1) represents a network by a directed graph $G=(V,E)$, where V is the set of network nodes, which can represent switches, routers, and hosts, as well as subnets, and E is the set of links, which represent communication links. The edge E has the attributes, BER er, $e\in E$.

Let $+R$ denote the set of positive real numbers and $R+$ denote the set of non-negative real numbers.

Definition (2) For any link $e\in E$, define 4 functions: delay function $delay(e):E\to +R$; The cost function $\cos t(e):E\to +R$; Bandwidth function $bandwidth(e):E\to +R$; Delay jitter function $delay\_litter(e):E\to R+$.

Definition (3) For any node $v\in V$, define 4 functions, the delay function $delay(v):V\to +R$; The cost function $\cos t(v):V\to +R$; Node's packet loss rate function $packet\_loss(v):V\to R+$; Node delay jitter function $delay\_jitter(v):V\to R+$.

Let $s\in S$ be a multicast source, $D\subseteq V-\{S\}$ be a multicast node set, $T(S,D)$ be a multicast tree consisting of S and D, and $\Pr(S,T)$ be a routing path from the source S to the end point T on the multicast tree $T(S,D)$ with $T\in D$, then, for a given source S, the the set of endpoints D has the following relation:

Delay: $delay(\Pr(s,t))=\sum_{e\in\Pr(s,t)} delay(e)+\sum_{e\in\Pr(s,t)} delay(v)$

Bandwidth: $bandwidth(\Pr(s,t))=\min\{bandwidth(e), e\in\Pr(s,t)\}$

Jitter: $delay\_jitter(\Pr(s,t))=\sum_{e\in\Pr(s,t)} delay\_jitter(e)+\sum_{e\in\Pr(s,t)} delay\_jitter(v)$

Loss rate: $packet\_loss(\Pr(s,t))=1-\sum_{e\in\Pr(s,l)}^{v\in\Pr(s,t)}\left(1-pac\det\_loss(v)\right)(1-er(e))$

Cost: $\cos t(T(s,D))=\sum_{r\in P(s,t)} \cos t(e)+\sum_{\in P(s,t)} \cos t(v)$

Since the delay jitter can be smoothed by buffering at the destination node, only the jitter limit at the destination node can be considered. Based on the above, the definition of QoS multicast routing problem is given:

Definition (4) QoS multicast routing problem

Given a network $G=(V,E)$, multicast source $S \in V$, multicast end set $D \subseteq V-\{S\}$, delay function $delay(\Pr(s,t)) \in +R$, delay jitter function $delay\_jitter(\Pr(s,t)) \in +R$, bandwidth function $bandwidth(\Pr(s,t)) \in +R$, packet loss function $packet\_loss(\Pr(s,t)) \in +R$, cost function $\cos t(\Pr(s,t)) \in +R$, and find a multicast tree $T(s,D)$ to satisfy:

Delay constraint: $delay(\Pr(s,t)) \le D_{out}$

bandwidth constraint: $bandwidth(\Pr(s,t)) \ge B_{out}$

Delay jitter constraint: $delay\_jitter(pr(s,t)) \le J_{out}$

Packet loss rate constraint: $packet\_loss(pr(s,t)) \le L_{out}$

Cost constraint: $\cos t(T(s,D))$ is minimized among all multicast trees satisfying conditions (1), (2), (3), and (4).

Where $T \in D$, $\Pr(s,t)$ is the routing path from the source S to the end point T on $T(s,D)$, and D out, B out, J out, and L out are the latency, bandwidth, jitter, and loss rate requests supplied by the user or application, respectively.

II. B. 2) Multi-Tree Multi-Constraint Routing Method Based on Cost Correction

From the perspective of network dynamics: although the multi-constrained optimal multicast tree generated by the shortest path tree algorithm can satisfy all the QoS constraints given by the specific application, once the following two situations occur during the operation of the algorithm:

(1) A change in the network state leads to a change in the link QoS parameters;

(2) The QoS constraints listed when analyzing the application requirements are unreasonable.

This will directly lead to difficulties in the processing of the shortest path tree algorithm, that is, the final multicast tree will no longer meet all the QoS constraints, and some of the conditions will not be satisfied. Therefore, it is necessary to make certain improvements on the basis of the shortest path tree algorithm, and give a perfect solution.

From the perspective of stability and reliability: the shortest path tree algorithm builds only one multicast tree, which cannot meet the requirements of real-time services for low-latency recovery and high application throughput, this paper considers the following two points:

(1) Consumption and failures on network links are uncorrelated with each other;

(2) The possibility of multiple different multicast trees failing at the same time is extremely low.

As a result, “multi-tree” is proposed as the core idea of the subsequent research. In this section, we propose the Multi-Tree Multi-Constraint Routing based on Cost Correction (MTMCR-CC) method by utilizing a given correction function to adapt to the dynamic changes of the network, and utilizing the distances between the multicast trees to achieve fault isolation.

The basic idea of the MTMCR-CC method can be summarized into four main processes:

(1) Obtain the multi-constrained optimal multicast tree (MOT) in the current network state using the shortest path tree algorithm;

(2) Define the correction function according to the stress state and resource utilization of the links on the current MOT, obtain the correction coefficient from the calculation result of the correction function, and change the integrated cost of the links according to the correction coefficient;

(3) Run the shortest path tree algorithm to obtain new MOTs, and repeat the above process until a certain number of MOTs are stored in the multitree candidate set (MCS), and continue the subsequent process only if M multicast trees are stored in the MCS;

(4) Select the K MOTs with the smallest DC from the MSC using the multitree distance formula to be stored in the multitree routing set (MRS) so that they can be used as inputs in the subsequent execution of the priority-based multitree switching algorithm.

The MTMCR-CC algorithm flow is shown in Fig. 5.

The MTMCR-CC algorithm needs to take into account a special situation when executing: if a valid multicast tree is not found K for a period of time, it should take the initiative to throw an exception to end the search process of the multicast tree, to avoid falling into a dead loop. A more effective method is to set a timeout threshold (TOT) for timeout judgment, when the search time (ST) of the algorithm exceeds the TOT, it automatically triggers the “end program” and throws the exception of “the number of multicast trees is less than K”. The MTMCR-CC algorithm sets the TOT to be 3 times the average construction time (ACT) of the multicast tree. Since the ACT will be calculated and updated again after the construction of the new multicast tree, the value of the TOT changes dynamically with the changes of the network state.

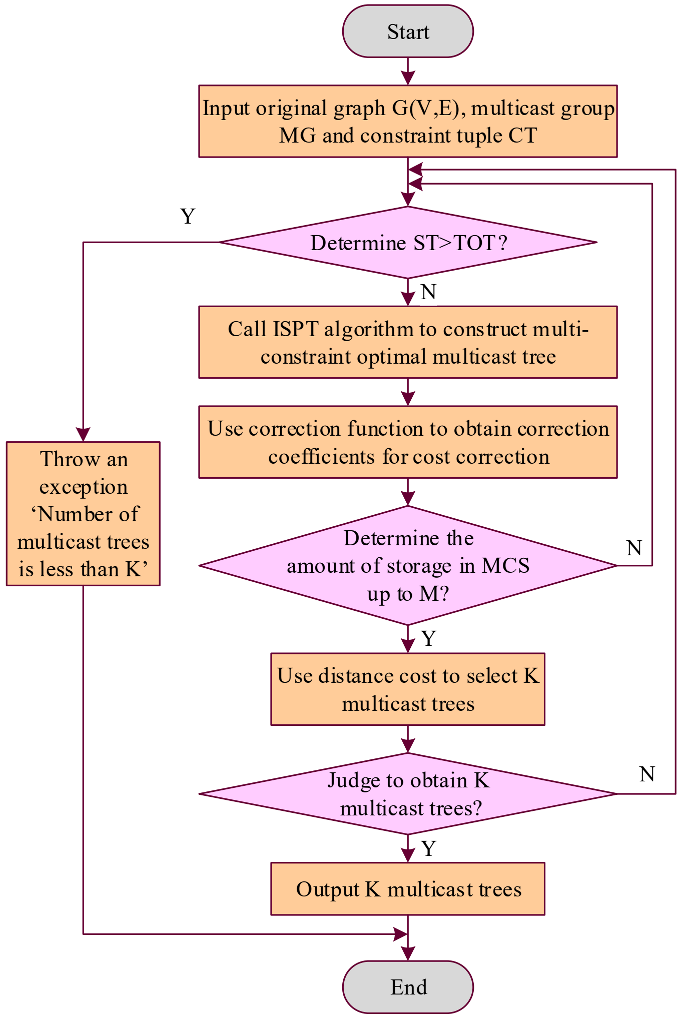


Figure 5: The process of the MTMCR-CC algorithm

III. Performance verification of power system communication network based on multicast routing algorithm

III. A. Comparative analysis of algorithm performance

In order to objectively evaluate the performance level of the proposed MTMCR-CC routing algorithm, two mainstream routing algorithms, SPRS and HCARS, are introduced for comparison: SPRS is a widely used routing algorithm, and the service is always transmitted by the shortest path from the destination node, with a large network load, and when the nodes have a certain data processing capacity, SPRS is prone to cause congested nodes to be even more congested or even network performance to deteriorate. HCARS dynamically adjusts the data transmission path according to the length of the node and neighbor nodes to the destination node and the node congestion, which can reduce the average waiting time of the packet in real time and improve the transmission efficiency, but HCARS is easy to be affected by the neighbor nodes to choose the local optimal path, which affects the network performance.

The network topology used in the routing strategy simulation test contains 15 nodes and 23 bidirectional links. Since the service traffic in the power communication network changes dynamically in real time, if we want to find a transmission path with low delay and low bandwidth utilization for the power service, we have to obtain the status information of the links in real time, including the delay, length, and bandwidth utilization of the links. In order to quantitatively calculate the transmission delay of the link, assuming that the propagation speed of the signal in the fiber optic link is 2/3 times of the speed of light, the information propagation speed parameter $v_{data} = 2\times10^{8} m/s$ is set, and the delay of the link can be calculated by the ratio with the length of the link. The switching delay of the nodes is mainly caused by the coding and decoding of information and electrical switching, etc. The overall delay of the device sending and receiving signals is very small, about 1~100 us, and the node switching delay is set to

$T_{\text{switch}} = 0.1ms$ during the simulation. The queuing of data transmission will produce end-to-end delay, and packet transmission delay varies, usually the more stable the network, the smaller the network jitter delay, repeatedly use iperf tool ping test node to the destination node between the delay and take its average value, simulation set the network jitter delay $T_{\text{jitter}} = 0.1ms$; link can transmit the largest The maximum bandwidth that can be transmitted by a link is set to be $\max(B_j) = 100Mbit/s$. The impact of bandwidth on the transmission path of delay-sensitive services is often large.

III. A. 1) Packet Loss Rate

In testing the impact of different routing strategies on network performance, the values of each network parameter are set so that the network load (the average of the bandwidth occupancy rate of all links in the network) grows gradually by changing the average request bandwidth of the network power service, and then the changes in the packet loss rate of the three routing strategies are analyzed under different network loads, and the results of the test are shown in Fig. 6.

As can be seen from the figure, when the network load exceeds a certain threshold, the network performance will reach a critical state, either stabilizing or starting to deteriorate sharply. When the network load rate gradually increases from 10% to 90%, the packet loss rate of MTMCR-CC is always lower than that of SPRS and HCARS policies, and the difference of its value shows an obvious dispersion trend after the load rate exceeds 60%. When the network load gradually increases close to the maximum bandwidth of the link and congestion occurs, the SPRS policy is unable to adjust the forwarding path in a timely manner and thus the packet loss rate increases dramatically. HCARS policy is a dynamic routing policy but it does not take into account the future bandwidth utilization of the link and the priority of different services, which results in the data loss of sudden power services and some data streams with high service priority and low tolerable delay. . The MTMCR-CC strategy overcomes the shortcomings of HCARS and predicts the future link bandwidth occupancy rate, and the packet loss rate during the experiment is below the other two strategies, which reflects the superiority of the MTMCR-CC routing strategy. In addition, the packet loss rate of the three routing strategies increases when the network load increases, and even the packet loss rate is greater than 10% when the network load rate is 90%, and the network is already seriously congested and presents a paralyzed state, which is mainly affected by the routing strategies as well as the performance of the simulation platform. In the actual power communication network, in order to ensure the reliable transmission of power services, power communication services have strict packet loss rate limitations, and the use of bidirectional communication architecture, in order to ensure the long-term stability of economic production is rarely and not allowed to appear network paralysis.

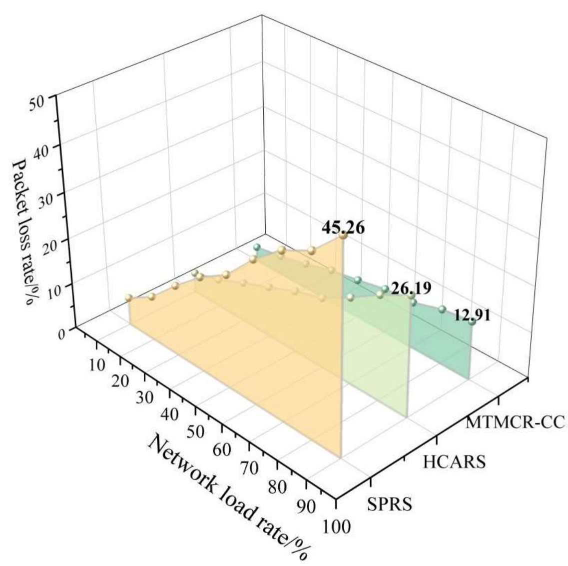


Figure 6: Comparison of packet loss rates

III. A. 2) Average link bandwidth utilization rate

In order to compare the average link bandwidth occupancy under the conditions of different routing policies, the average request bandwidth is gradually increased during the test, and the results of the comparison of the average link bandwidth occupancy between the MTMCR-CC routing policy and the SPRS and HCARS policies are shown in Fig. 7.

In Fig. 7, the average bandwidth occupancy rates of the network links of the three routing policies show different development trends, and when the average request bandwidth is small, the difference between the average bandwidth occupancy rates of the links of the three policies is small. The SPRS policy slows down the growth rate firstly, which is due to the fact that it purely allocates the data streams to the shortest paths in the corresponding paths in the path selection, which may lead to the situation of allocating multiple power services to the same paths, and easily lead to the link resource allocation. situation, which is prone to uneven allocation of link resources, increases the possibility of link congestion, and reduces the average link bandwidth occupancy rate of the whole network.The HCARS strategy only regulates the congestion after it occurs, and as the average request bandwidth gradually increases and reaches the upper limit of the processing capacity of its strategy, it is prone to link congestion, and the average bandwidth occupancy rate of the link decreases.The average bandwidth occupancy rate of the link of the MTMCR-CC strategy is always higher than the other two strategies, and its maximum value reaches 69.72%, which significantly exceeds 61.51% for HCARS and 54.60% for SPRS. This is because it predicts the future congestion of the link and performs congestion control in advance, which improves the congestion mitigation capability of the strategy, so it outperforms the other two strategies.

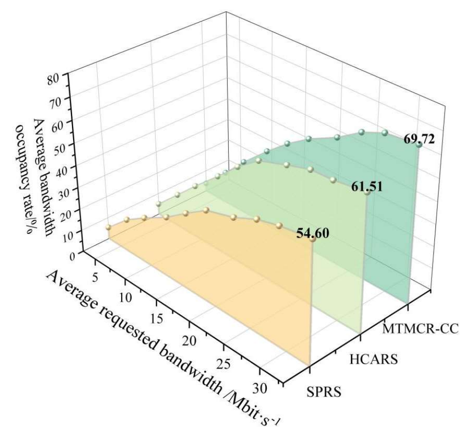


Figure 7: Comparison of average bandwidth occupancy rates of links

III. A. 3) Network node communication success rate

Communication test on the network nodes within the range of (300*300)m², set the effective communication distance as 100m, channel attenuation in (-5dB~-20dB) random values, set the effective life of the signal as 15s, when the information is sent, if the destination node still does not receive the information within 25s, it is considered that the node communication failure. In a certain time period, sending multiple commands continuously and repeating 100 times, the comparison result of node communication success rate is as shown in Fig. 8.

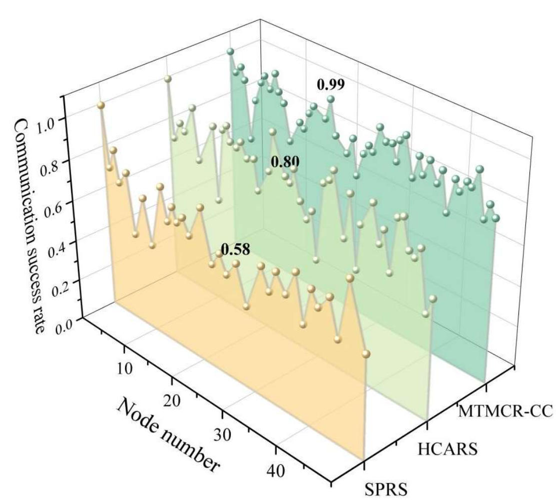


Figure 8: Comparison of node communication success rates

From Fig. 8, it can be seen that while the MTMCR-CC algorithm is not only able to better adapt to path changes and maximize the preservation of the optimal path, but also reduces the intervention of unnecessary nodes and improves the node communication success rate. In the test range of node numbers 10 to 40, the MTMCR-CC algorithm shows a significant advantage at node 25 position, and the communication success rate reaches 99%, which is 19% and 41% higher than that of the HCARS strategy (80%) and SPRS strategy (58%), respectively. It proves the strong adaptability of MTMCR-CC under non-uniform topology and meets the availability requirement of 99.99% for critical nodes in IEC 61850 standard.

III. A. 4) Node Load Balancing

Network load balancing is an important indicator of network performance, in this paper, the network node load amount is simulated to study the network load balancing situation comparison results are shown in Figure 9.

Figure 9 reveals the dynamic difference of load balancing, in the monitoring range of node number 0 to 50, the average load of nodes of MTMCR-CC algorithm is concentrated in the interval of 2-6, compared with HCARS and SPRS there is no difference of too much, which indicates that this strategy has a better load distribution balancing under non-uniform topology.

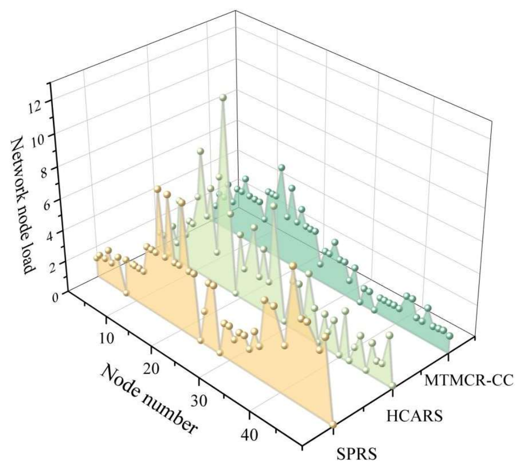


Figure 9: Comparison of network load balancing situations

III. A. 5) Algorithmic Route Optimization Capability

Setting up the source and destination nodes, path optimization is carried out by the ACS algorithm and DH-ACGA algorithm, respectively, and the logarithm of the number of hops of the nodes during the iterative optimization process is shown in Fig. 10.

From Fig. 10, it can be seen that the MTMCR-CC algorithm, on the other hand, only needs 15 iterations to converge to the current optimal path, which is much faster than the HCARS (19 iterations) and SPRS algorithms (20 iterations). It proves that the MTMCR-CC algorithm is able to converge at a faster speed and thus find the optimal path by utilizing its own local optimization and global search capabilities.

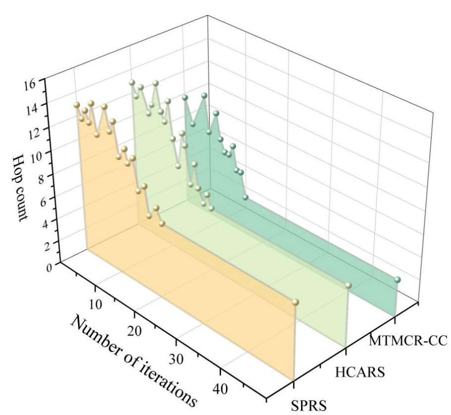


Figure 10: Comparison of the hop count of nodes

III. B. Simulation Scenario Performance Verification

The joint simulation scenario of power information physics is constructed, and the routing policies are sent through OpenFlow protocol to observe the dynamic performance of the two policies. The total joint simulation time is set to 32s, and the starting moment of each application packet sending is 2s. During the packet transmission with an effective simulation time of 30s, the network traffic is compared as shown in Fig. 11 after collecting network performance indicators and analyzing the relevant data with the help of the FlowMonitor component in NS3.

As can be seen from the figure, under the default policy, the paths reported in the measurement are more congested, such as path 1, path 4 and path 8 in the figure, and the network traffic is more than 3.5×107 bytes; while under the policy of this paper, the congestion of the branch paths that are directly connected to the control center is better than the default policy, and the network traffic is less than 2.5×107 bytes in all the paths.

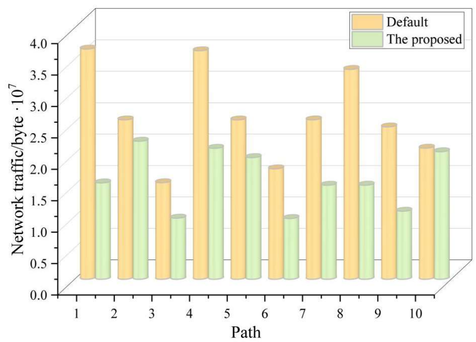
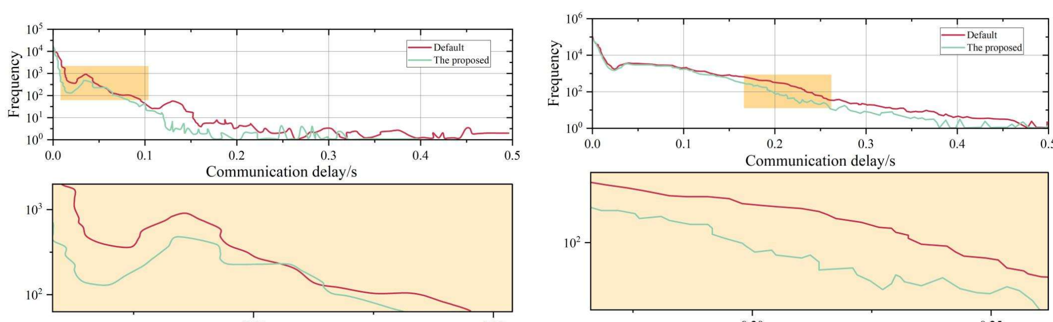


Figure 11: Comparison of Network traffic

To further compare the dynamic performance performance of the two strategies, the comparison of network delay between packets between each node of the measured transmission path and the unmeasured transmission path in the range of 2-32s duration is shown in Fig. 12(a~b). In order to facilitate the simultaneous plotting of statistical results with significant gaps, the y-axis in the figure adopts the logarithmic coordinate axis. In the measured transmission path and unmeasured transmission path scenarios, the delay frequency of the proposed strategy is always lower than that of the default strategy, which verifies the strong adaptability of the proposed strategy in dynamic network environments, and realizes the low-latency and reliable transmission in complex power communication scenarios.



(a)Measure the transmission path (b)Nonmeasured transmission path

Figure 12: Comparison of network latency

IV. Conclusion

In this paper, the MTMCR-CC algorithm based on cost correction is designed by improving the shortest path tree algorithm, and its performance level is verified through experiments.

In the simulation test, when the network load rate is gradually increased from 10% to 90%, the packet loss rate of MTMCR-CC is always lower than that of SPRS and HCARS strategies, and the average bandwidth maximum of the link reaches 69.72%, which is significantly more than that of HCARS (61.51%) and SPRS (54.60%). It shows a significant advantage at node 25 position, with a communication success rate of 99%.The average node load of the

MTMCR-CC algorithm is concentrated in the range of 2-6, and it takes only 15 iterations to converge to the optimal path, which is much faster than that of the HCARS (19 iterations) and SPRS algorithms (20 iterations).

In the simulation scenario, the default policy measures the reported paths to be more congested, and the network traffic of Path 1, Path 4, and Path 8 exceeds 3.5×107 bytes. In contrast, under the strategy of this paper, the network traffic in all paths is below 2.5 × 107 bytes. In both measured and unmeasured transmission path scenarios, the delay frequency of the proposed strategy is always lower than that of the default strategy, which verifies the strong adaptability of the proposed strategy in dynamic network environments, and realizes the low-latency and reliable transmission in complex power communication scenarios.

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