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TOPOLOGICAL STRUCTURE OPTIMIZATION AND COMMUNICATION RELIABILITY CONTROL OF WIRELESS MULTI-HOP COMMUNICATION NETWORK

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In order to ensure the real-time performance and reliability of multi-hop wireless network transmission, this paper firstly determines the optimal network topology structure through the network topology optimization algorithm, which is constrained by the limitation of communication delay on the network multi-hop number and the limitation of two non-crossing communication paths to ensure the transmission reliability. Then the power control algorithm based on model predictive control ensures the reliability of each wireless link in the optimized network topology. Finally, the algorithm is verified by simulation. The simulation results show that the proposed method can guarantee the real-time performance and reliability of data transmission of wireless multi-hop networks in the context of disturbed wireless communication.

Keywords: Wireless multi-hop network, Topology Optimization, Power Control

1. Introduction

There are higher requirements for status data communication of primary and secondary devices in smart substations. In the monitoring system of a substation, a non-centered mesh wireless multi-hop communication network can be adaptively constructed by multiple wireless communication nodes, each of which is responsible for data collection in the area where it is located, and sends the collected data to the sink node directly or through relay of other intermediate nodes [1]. Characterized by easy installation, rapid deployment, flexible structure, and strong scalability, the mesh wireless multi-hop communication network composed of the sensor nodes and the sink nodes remedies the flexibility weakness of wired communication and thus is very suitable for status monitoring

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of devices, data collection, mobile inspection, and other applications in the smart substation scenario [2].

In the context of multi-hop communication, the transmission delay from the sensor node to the sink node includes the single-hop delay between adjacent nodes along the path and the data buffering delay within the node [3]. Therefore, in a wireless multi-hop communication network with a structure of mesh, the transmission delay is approximately directly proportional to the number of relays [4]. Furthermore, because the communication path in the smart substation is also affected by noise signals generated by nearby power electronic equipment and communication equipment, as well as buildings and large-scale equipment, there exist problems such as wireless communication interference, reflection, scattering, diffraction, etc.[5-6], which have an negative effect on the reliability of the wireless link. When a node or a link fails, a backup communication path must remain working so as not to affect the reliability of data communication. Therefore, how to guarantee the real-time performance and reliability of data transmission in the wireless multi-hop communication network of the substation and satisfy the requirements of the power data communication criterion on delay and reliability has become the key to the applications of mesh wireless multi-hop communication network in the substation [7].

To this end, scientific researchers have done a lot of researches on this issue. [8] analyzed the major influencing factors of the network data transmission performance index in the power system. The Markov chain was employed to establish the data buffering queuing model for nodes in the distribution network, which was designed for real-time transmission analysis; based on the IEEE 802.15.4 standard Media Access Control (MAC) protocol and by introducing the Quality of Service (QoS)-MAC model, [9] gave high priority to guaranteeing the reliability of high-priority data transmission; In [10], the leading causes for the signal-to-noise ratio of wireless communication were analyzed, on the basis of which a model was built to optimize the transmission power of the nodes. Although the reliability and real-time performance of the wireless communication network is ensured, the methods above do not consider the influence of the network topology on the communication transmission. [11] designed a topological structure of wireless sensor network for fault detection in distribution network, and proposed a reliable WSNs routing method for fault detection in distribution network. However, this method does not take into account the effect of disturbance on wireless link, although the reliability and real-time performance of communication is safeguarded to a certain extent. Therefore, considering the network topology, performance optimization of the mesh wireless multi-hop communication network still requires further study.

To address the above-mentioned problems of wireless multi-hop communication network, this paper first establishes a graph-based model of the multi-hop network topology, and determines the optimal network topology structure through the optimized network topology algorithm, which is constrained by the limitation of communication delay on the network multi-hop number and the limitation that communication interrupt does not affect the transmission reliability. Then the power control algorithm based on model predictive control is proposed and the transmit power of nodes is adjusted to ensure the reliability of each wireless link in the optimized network topology. Finally, the algorithm proposed in this paper is verified by experiments in a substation.

2. Modelling of wireless network and introduction to shortest path algorithm

2.1 Graph theory model of wireless multi-hop communication network in a substation

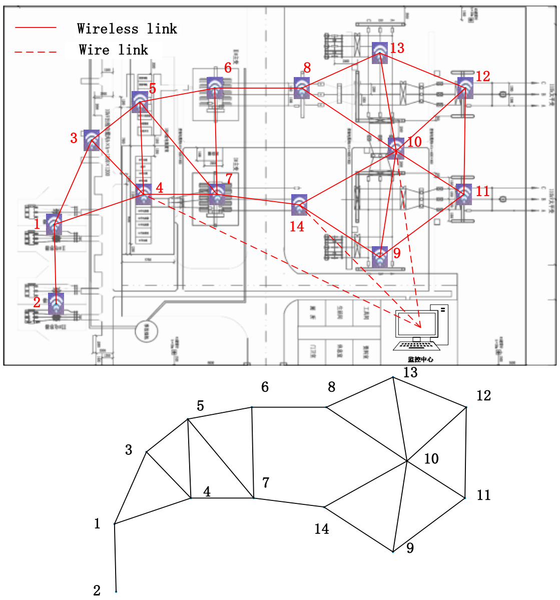

Fig.1 An example of multi-hop wireless network in a substation

Take the mesh wireless multi-hop communication network in a substation shown in Fig 1 as an example. The nodes mentioned in the Fig 1 can be divided into sink nodes (Node 4, 10, 14 in Fig 1) and device status sensor nodes (the rest in Fig 1), and the wireless communication link between nodes is regarded as an edge. Thus, the wireless multi-hop communication network can be indicated as $G = (V, E)$, in which V represents a finite set of nodes and E a finite set of wireless communication links. The wireless multi-hop communication network shown in Fig 1 can be expressed as:

$$V = \{v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, v_{11}, v_{12}, v_{13}, v_{14}\} \tag{1}$$

$$\begin{aligned} E = \{ & e_{1,2}, e_{1,3}, e_{1,4}, e_{3,4}, e_{3,5}, e_{4,5}, e_{4,7}, e_{5,6}, e_{5,7}, e_{6,7}, e_{6,8}, \\ & e_{7,14}, e_{8,10}, e_{8,13}, e_{9,10}, e_{9,11}, e_{9,14}, e_{10,11}, e_{10,12}, e_{10,13}, e_{10,14}\} \end{aligned} \tag{2}$$

Where, $v_i, i = 1, 2, \cdots, 14$ in (1) represents the i th node; $e_{i,j}, i, j \in [1,14], i \neq j$ in (2) represents the communication link formed between the i th and the j th nodes.

2.2 The shortest path algorithm

The ant colony algorithm [12] (ACA) is an intelligent algorithm that simulates the ants to find foods. The basic idea of the algorithm is that a large number of ants will release the pheromone along the foraging path and label the path they have travelled. The ants behind will tend to choose a path with a higher pheromone concentration. The state transition in the ant k can be expressed as:

$$P_{ij}^k = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}(t)]^{\beta}}{\sum\limits_{s \in J_k(i)} [\tau_{is}(t)]^{\alpha}[\eta_{is}(t)]^{\beta}}, & j \in J_k(i) \\ 0, others \end{cases} \tag{3}$$

Where τ_{ij} represents the pheromone along the path from node v_i to node v_j; η_{ij} is the inspiring factor defined as $1/d_{ij}$, where d_{ij} represents the distance between node v_i and node v_j; α, β represents the importance of the pheromone and the heuristic factor respectively, and $J_k(i)$ represents the set of nodes that the ant k is allowed to select in the next step.

The pheromone formula is updated as:

$$\tau_{ij}(t+n) = (1-\rho) \cdot \tau_{ij}(t) + \Delta\tau_{ij} \tag{4}$$

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}{}^{k} \tag{5}$$

$$\Delta\tau_{ij}^k = \begin{cases} \dfrac{Q}{L_k T}, \text{The kth ant goes from node } v_i \text{ to node } v_j \\ 0, \text{ others} \end{cases} \tag{6}$$

Where, ρ in formula (4) is the pheromone evaporation factor ($0 < \rho < 1$); $\Delta\tau_{ij}$ in formula (5) is the pheromone gain; $\Delta\tau_{ij}^k$ is the pheromone gain between node v_i and node v_j left by the ant K during the current path search; Q in formula (6) is a constant; L_k is the length of the path travelled by the ant k; T represents the total number of hops travelled by the ant k.

In the wireless multi-hop communication network shown in Fig 1, where the ants travel along the edge, the pheromone concentration along the shorter path from the sensor node to the sink node will get higher and higher, after a large number of ants search their paths. Finally, the shortest path will eventually be produced.

3. Network topology optimization algorithm

In the sample network, under the limitation of the real-time performance and reliability of transmission, the network topology should meet the following optimization requirements:

(1) In order to meet the real-time requirement of data transmission, the maximum number of hops for multi-hop communication should be minimized to the largest extent.

(2) In order to meet the reliability requirement of data transmission, there should be at least two paths leading to the sink node for each node at the same time. Besides, no intersection occurs between the two paths, so as to avoid existence of another transmission path in spite of path failure caused by node failure or link interrupt.

In order to meet the above requirements, this paper intends to optimize the topology algorithm of wireless multi hop communication network based on substation and develop a transmission power control algorithm. Because the application requires a higher data rate, couldn’t reduce the data rate to get a better bit error rate. Therefore, we plan to improve the reliability by controlling the transmit power. The wireless multi hop communication network topology algorithm is used to optimize the network topology required by the calculation process, and the power control algorithm realizes the above optimized network topology through transmission power control.

3.1 The optimization of network topology

The wireless multi-hop communication network is represented as the graph $G=(V,E)$. The set of all nodes is indicated as V, and the set of wireless communication links E. The nodes can be divided into the preset sink nodes (m nodes, $2 \le m$) and the device status sensor nodes. In order to avoid abnormal operation of the entire network due to failure of a single sink node, two of the m preset sink nodes will be selected as the final sink nodes.

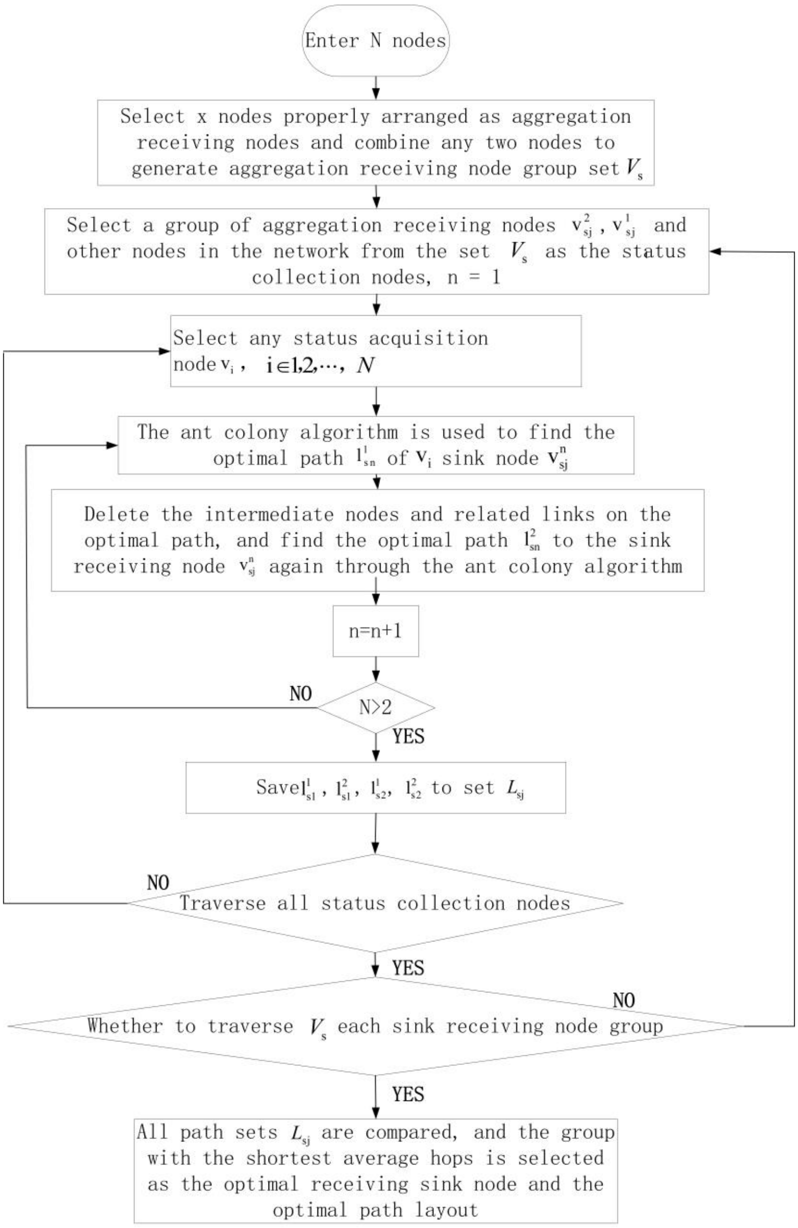

Fig.2 The algorithm of multi-hop wireless network reconstruction algorithm

The algorithm goes as follows:

(1) Make two preset sink nodes in pairs to generate a set of preset sink nodes $V_s = \{(v_{s1}, v_{s2}), (v_{s1}, v_{s3}), \cdots, (v_{s(m-1)}, v_{sm})\}$, $v_{s1}, \cdots, v_{sm} \in V$;

(2) Select a group of preset sink nodes from the set of preset sink nodes V_s. Define them as two sink nodes : v_{o1}^1 and v_{o1}^2. Set other nodes in the network as status

sensor nodes $v_i, i = 1, 2, \cdots, N-2$, N represents the total number of nodes in the $G = (V, E)$;

(3) Select the status sensor node v_i, and calculate the shortest path l_{i1}^1 from the node v_i to the sink node v_{o1}^1 by using the ant colony algorithm;

(4) Assuming that the above-mentioned shortest path fails, delete all intermediate nodes and paths on the above shortest path l_{i1}^1 from graph G. Repeat the ant colony algorithm to obtain a second shortest path l_{i1}^2 that has no intersection with l_{s1}^1. Include the path l_{i1}^1 and l_{i1}^2 into the set L_{s1};

(5) Repeat Step (3) and (4) to obtain two shortest paths l_{i2}^1 and l_{i2}^2 from the node v_i to the sensor node v_{o1}^2. Include them into the set L_{s1}.

(6) Select other status sensor nodes before repeating Step (3), (4) and (5). Run Step (7) until all status sensor nodes have been calculated;

(7) Select another group of nodes $(v_{si}, v_{sj}), i, j \in m$ from the set V_s mentioned in step (2), and denote them as the sink node; repeat steps (3), (4), and (5) to get the set L_{s2}. Repeat step (6) until all preset sink nodes in the set V_s are traversed.

(8) Compare the path sets derived from groups of the above-mentioned preset aggregation receiving nodes; select the group with the smallest average hops in the path set, $\min\{\bar{L}_{s1}, \bar{L}_{s2}, \cdots\}$, to get the optimal deployment of sink nodes and the corresponding shortest path (two paths for each node).

4. Link status space model of wireless propagation

Limited by reliability and real-time performance of transmission, the optimized wireless multi-hop communication network topology algorithm in a substation is used to determine its topological structure.

In a network with fixed topological structure, the transmit power of a device status sensor node should minimize its impact on other nodes, when satisfying the requirements for path link and reducing the bit error rate. Although a higher transmit power of the device status sensor node can realize higher signal-to-noise ratio and smaller bit error rate, normal operation of other nodes may be affected if the transmit power is too high. Therefore, after the wireless communication of the device state sensor nodes is modelled, the model predictive control is carried out in this section to get the optimal control feedback value and thus control the transmit power of the device status sensor node.

4.1 Link status space model

The requirement on reliability of data communication in a substation is usually expressed as the bit error rate. Take the O-QPSK model of the IEEE802.15.4[13] protocol for smart grids as an example, in which the relation between the bit error rate of communication P_{ber} and the signal-to-noise ratio P_{SNR} of the wireless link can be indicated as

$$P_l = (1 - P_{ber})^l \tag{7}$$

$$P_{ber} = Q\left(\sqrt{2\times 10^{\frac{P_{SNR}}{10}}\frac{B}{R}}\right) \tag{8}$$

$$P_{SNR}(k) = P_s(k) - P_x(k) \tag{9}$$

In (7), P_l is the reliability of packet, and P_l is constant, l is the bit length of packet, and the bit error rate is calculated according to formula (7). In (8), B is the noise bandwidth(kHz) of a node, R the data transmission speed (kbps), $Q(\cdot)$ the calculus function of the standard Gaussian distribution; in (9), $P_x(k)$ is the background noise of the receiving node at the moment k [14]; $P_s(k)$ the intensity of the signal received by the node at the moment k.

As buildings and various tall equipment are the main factors affecting the signal-to-noise ratio of the communication link in a substation, a logarithmic path loss model [15] suitable for high-density building areas is selected in this paper to explain the relationship between the received signal strength and the transmission path among nodes in the wireless multi-hop communication network. The above-mentioned logarithmic path loss model is expressed as:

$$P_s(k) = P_f(k) - P_l(d_0) - 10n(k)\log_{10}(d) + \chi_\delta(k) \tag{10}$$

Where $P_f(k)$ is the transmit power of the transmitting node at the moment k; $P_l(d_0)$ is the loss value (d_0=1 m) of reference path; $n(k)$ is the path loss index, namely the growth rate of the path loss with distance; d the actual distance between two nodes, in m; $\chi_\delta(k)$ the influence of multipath effect that obeys Gaussian distribution $\chi_\delta \sim (0,\sigma^2)$.

After subtracting $P_s(k+1)$ from $P_s(k)$ described in Eq(10), and selecting the system input $u(k)=\Delta P_f(k+1)=P_f(k+1)-P_f(k)$, system state variable $x(k)=[P_s(k)\ \ P_x(k)]^T$, system output $y(k)=P_{SNR}(k)$, system disturbance $w(k)=[\Delta Q(k+1)\ \ \Delta P_x(k+1)]^T$, the state space model is denoted as:

$$\begin{cases} x(k+1) = Ax(k) + B_1u(k) + B_2w(k) \\ y(k) = Cx(k) \end{cases} \tag{11}$$

Where $Q(k) = P_l(1) + 10n(k)\log_{10}(d) - \chi_\delta(k)$; $\Delta Q(k+1) = Q(k+1) - Q(k)$; $\Delta P_x(k+1) = P_x(k+1) - P_x(k)$.

A, B_1, B_2, C is the corresponding coefficient matrix, where

$$A=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, B_1=\begin{bmatrix}1\\ 0\end{bmatrix}, B_2=\begin{bmatrix}-1 & 0\\ 0 & 1\end{bmatrix}, C=\begin{bmatrix}1 & -1\end{bmatrix}.$$

The incremental formula of formula (10) can be expressed into

$$\begin{cases}\Delta x(k+1)=\Delta Ax(k)+\Delta B_1u(k)+\Delta B_2w(k)\\ y(k)=C\Delta x(k)+y(k-1)\end{cases} \tag{12}$$

4.2 Model predictive control of the reliability

In the model predictive control presented in this paper, the dynamic nature of the wireless link is described by (11), and the control time domain c_t and prediction time domain p_t are set. We suppose that the system falls beyond the control time domain with unchanged control increment, which means that the node's transmit power increment $\Delta P_f(k)$ is constant; the disturbance variable $w(k)$ remains unchanged after the moment k, which means that ΔQ, ΔP_x keeps unchanged. Then the system's predictive model can be further established:

$$Y_p(k+1|k)=S_1\Delta x(k)+Iy(k)+S_2\Delta U(k)+S_3\Delta w(k) \tag{13}$$

Where $Y_p(k+1|k)$ represents $c_t\times 1$ dimensional output vector predicted for the future at the moment k; $\Delta U(k)$ represents $p_t\times 1$ dimensional control input increment vector predicted for the future at the moment k; S_1,S_2,S_3,I represents the corresponding coefficient matrix.

$$\begin{aligned}&Y_p(k+1|k)=[y(k+1|k)\ \ \cdots\ \ y(k+c_t\,|\,k)]^T_{c_t\times 1}\\ &\Delta U(k)=[\Delta \mathrm{u}(k)\ \ \cdots\ \ \Delta \mathrm{u}(k+p_t)]^T_{p_t\times 1}\end{aligned} \tag{14}$$

Where, $y(k+i\,|\,k)$,$i=1,2\cdots,c_t$ is the output of the system predicted at the moment k for the moment $k+i$; $\Delta \mathrm{u}(k+j)$,$j=0,1,\cdots,p_t$ is the system control input increment at $k+j$.

In the wireless multi-hop communication network of a substation, the transmit power of the device status sensor node should meet the path link and reduce the bit error rate while minimizing the impact of excessive node transmit power on other nodes to the largest extent. Then the optimal solution of the system can be expressed as:

$$\min_{\Delta U(k)} J(x(k),\Delta U(k),p_t,c_t)=\left\|\gamma_1\Delta U(k)\right\|^2+\left\|\gamma_2(Y_p(k+1|k)\right\|^2 \tag{15}$$

Where γ_1 is the weighting factor of the predictive control input increments. The smaller γ_1 is, the more greatly the expected control varies; γ_2

represents the predictive output error weighting factor; the larger γ_2 is, the more closer the expected output gets to the expected signal-to-noise ratio given by the system. Finally, after the above-mentioned model predictive control of the system is solved, the input increment vector ΔU^* of the optimal control can be obtained:

$$\Delta U^* = (S_2^T S_2 + 1)^{-1} S_2^T (S_1 \Delta x(k) - \mathrm{I} y(k) - S_3 \Delta w(k)) \tag{16}$$

The first element of the optimal control input increment vector ΔU^* is regarded as the unified control input increment $\Delta u(k)$.

5. Experimental results and analysis

In order to verify the method proposed in the paper, experiments are carried out in the wireless multi-hop communication network shown in Fig 1. The nodes are mainly placed around the primary and secondary devices to collect the device status parameters. Therefore, they are of Medium-speed message. According to on-site testing, the single-hop transmission delay between nodes is about 24ms, and of Medium-speed message type by means of telemetering according to the IEC61850 requirement (see Table 1), which is also valid for other communication protocols. The maximum delay is 100ms. Therefore, the maximum number of hops is limited to 4 in the experiments.

Table 1

IEC61850 P1 type (distribution type) communication real-time requirements

Type	***Object***	***Real-time requirements(ms)***
High-speed message	Interlock, remote tripping, logic recognition in the protection functions	≤ 100
	Close, reclose, start, stop, lock, release, etc.	
Medium-speed message	Normal status information, etc.	≤ 100
Low-speed message	Slow automatic control, records of transmission events, reading or changing setting values, system data display, etc.	≤ 500

The wireless multi-hop communication network topology that needs to be optimized is shown in Fig 1, and the linear distance between adjacent link nodes is shown in Table 2.

Table 2

Distance between nodes

Link	***Distance(m)***	***Link***	***Distance(m)***	***Link***	***Distance(m)***
$\mathrm{e}_{1,2}$	30	$e_{1,3}$	30	$e_{1,4}$	35
$e_{3,4}$	25	$e_{3,5}$	20	$e_{4,5}$	30
$e_{4,7}$	25	$e_{5,6}$	20	$e_{5,7}$	40

$e_{6,7}$	45	$e_{6,8}$	30	$e_{7,14}$	35
$e_{8,10}$	45	$e_{8,13}$	30	$e_{9,10}$	40
$e_{9,11}$	35	$e_{9,14}$	35	$e_{10,11}$	30
$e_{10,12}$	30	$e_{10,13}$	35	$e_{10,14}$	40

In the wireless multi-hop communication network in Fig 1, v_4, v_{10}, v_{14} is the node that can be deployed as the preset sink node. Denote $V_s = \{(v_4, v_{10}), (v_4, v_{14}), (v_{10}, v_{14})\}$ as the preset sink node group set, where (v_4, v_{10}), (v_4, v_{14}) and (v_{10}, v_{14}) are set as groups of the preset sink nodes. By using the optimized wireless multi-hop communication network topology algorithm, the average number of hops along the path is the smallest when (v_4, v_{10}) is the group of the sink nodes, and the optimal network topology is obtained, as shown in Fig 3.

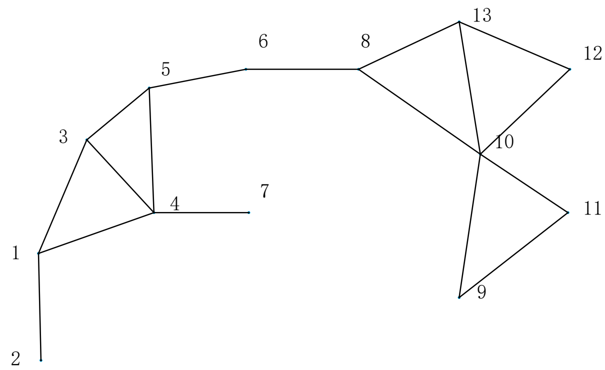

Fig.3 Optimal topology structure obtained by network topology optimization algorithm

Next, according to the optimal topological structure, the node power control algorithm is used to control the node's transmit power. Take the node v_1 as an example, which is connected to the node v_2, v_3, v_4 and not connected to other nodes. Therefore, it is necessary to reduce its bit error rate when the transmit power meets the condition of $\max(e_{1,2}, e_{1,3}, e_{1,4}) < l < \min(e_{1,5}, e_{1,7})$ at the communication distance l.

Table 3

Related initialization parameters

Parameter	***Initial value***	***Parameter***	***Initial value***
P_f	0	χ_δ	-4dBm
d	45	P_s	-60dBm
$P_l(1)$	23dBm	P_x	-99dBm
n	2.32	P_{SNR}	39dBm

See Table 3 for related initialization parameters of model predictive control of v_1's transmit power. According to the substation's communication reliability requirements, the reliability is set to be 99.99%. Thus, the corresponding bit error rate is obtained, and the corresponding signal-to-noise ratio $P_{SNR} = 39$dBm can be obtained using Eq (7). As it is impossible to carry out effective control if γ_1, γ_2 is too large or too small, set $\gamma_1 = 2, \gamma_2 = 2$; control time domain $c_t = 3$, prediction time domain. The above parameters are employed to carry out model predictive control against the nodes.

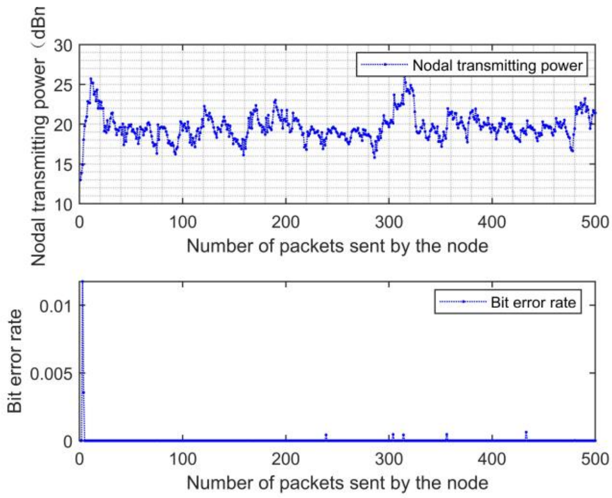

Fig.4 Model predictive control simulation results

Fig 4 shows the model predictive control simulation results obtained using the above parameters when the node v_1 is interfered by dynamic obstructions. It can be seen from the Fig that when the model predictive control is performed on the node, the bit error rate is relatively stable and approaches 0, and the interference effect of dynamic obstructions is slight.

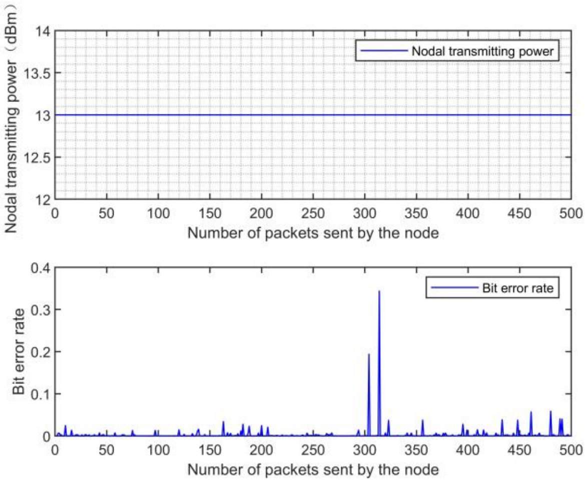

Fig.5 Simulation results under fixed transmit power

Fig 5 is the simulation results under fixed transmit power 13dBm when there is the interference from dynamic obstructions. It can be seen from the Fig 5 that the dynamic obstruction has a great influence on wireless communication interference, and the bit error rate is very unstable, which even exceeds 35% in some cases.

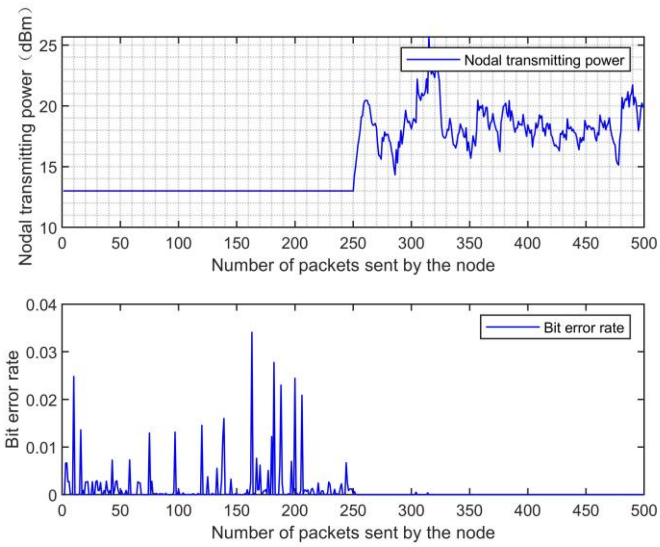

Fig.6 Control performance comparison

Fig 6 is the control performance comparison before and after model predictive control algorithm being active when there exists interference caused by dynamic obstructions. When the number of packets sent by the node is between 0 and 250, there is no control applied to the transmit power. It can be seen from the figure that the dynamic obstacles have a great impact on wireless communication, and the bit error rate is very unstable. Sometimes, the bit error rate is even greater than 35%. In this situation, communication reliably cannot be ensured. When the number of packets sent by the node is between 250 and 500, the model predictive control is activated. It is shown from Fig. 6 that the bit error rate is relatively stable and close to 0, and the interference effect of dynamic obstacles on the bit error rate becomes very small. The communication reliability is improved. The simulation results in Fig. 6 show that the model predictive control on the transmit power can effectively reduce the interference of dynamic obstacles on the bit error rate.

6. Algorithm Comparison

To compare the proposed control algorithm with other approaches, we simulated the control performance on bit error rate by the adaptive power control (ATPC) algorithm presented in [16]. The simulation result is shown in Fig. 7. It’s shown that the transmission power of the ATPC algorithm fluctuates greatly up and down. When the number of packets sent by the node is about 360, the transmission power and the bit error rate of the ATPC algorithm are suddenly increased. By comparing the simulation result shown in Fig. 4 and Fig. 7, we found out that the model predictive control is outperformed the APTC in terms of the bit error rate because the bit error rate in Fig.4 is more stable.

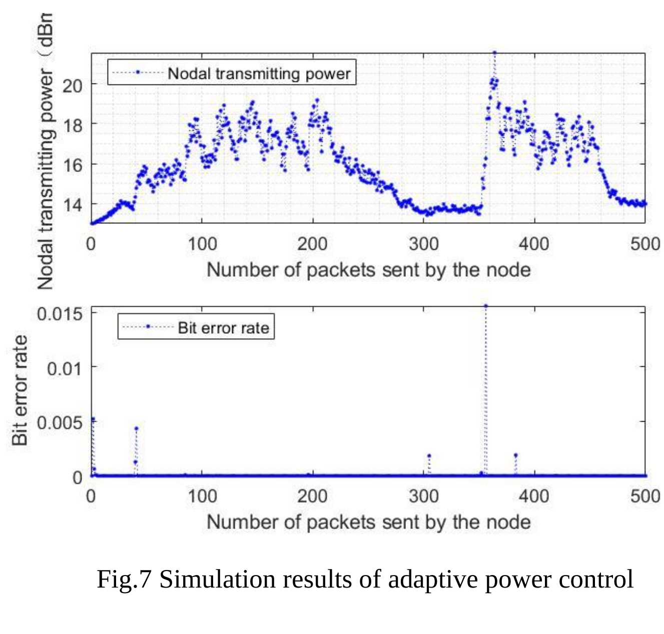

Fig.7 Simulation results of adaptive power control

Through the comparison of the two algorithms, it is obvious that the model predictive control is better.

7. Conclusions

Aiming at the problems related to wireless multi-hop communication network in a substation, this paper proposes a network topology optimization algorithm and Link communication quality optimization algorithm. Firstly, the topology structure of substation wireless multi-hop communication network is determined by the network topology optimization algorithm with the transmission reliability and real-time as constraints. This allows two paths leading to the sink nodes to be established simultaneously for each node, when the real-time performance and reliability of data transmission are guaranteed. Then, after the optimal topological structure is obtained, model predictive control is performed on the transmit power of the nodes to realize the link between the nodes. based on the power control algorithm of model predictive control, the transmitted power of the status sensor node should not only satisfy the path link, but also reduce the influence on other nodes as much as possible, so as to ensure the reliability of each wireless link in the optimized network topology.

The simulation results show that the network topology optimization algorithm and link communication quality optimization algorithm proposed in this paper allow two paths leading to the sink nodes to be established simultaneously for each node, ensure the real-time performance of the wireless multi-hop network communication in the substation, and reduce mutual interference caused by excessive node transmission power.

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R E F E R E N C E S

[1] *Kocakulak M, Butun I*. An overview of Wireless Sensor Networks towards internet of things[C]//2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC). IEEE, 2017: 1-6.

[2] *He J, Yang Y, Chen Y, et al*. Wireless sensor monitoring network optimization research in smart substation[C]//2016 China International Conference on Electricity Distribution (CICED). IEEE, 2016: 1-6.

[3] *Sun Wei, Ding Zhen, Wang Jianping*. Research on delay optimization of smart grid based on multi-hop wireless sensor networks. Journal of electronic measurement and instrumentation, 2019, 33(08): 140-146.

[4] *Selvi M, Velvizhy P, Ganapathy S, et al*. A rule-based delay constrained energy efficient

routing technique for wireless sensor networks. Cluster Computing, 2019, 22(5): 10839-10848.

[5] *Yerra R V P, Bharathi A K, Rajalakshmi P, et al*. WSN based power monitoring in smart grids[C]//2011 Seventh International Conference on Intelligent Sensors, Sensor Networks and Information Processing. IEEE, 2011: 401-406.

[6] *Greer C, Wollman D A, Prochaska D E, et al*. Nist framework and roadmap for smart grid interoperability standards, release 3.0[R]. 2014.

[7] *Gungor V C, Lu B, Hancke G P.* Opportunities and challenges of wireless sensor networks in smart grid. IEEE transactions on industrial electronics, 2010, 57(10): 3557-3564.

[8] *Junhong W., Yuedong C., Mengyuan C.*, Research on fuzzy cognitive map based on Markov chain in Qo S optimization of smart distribution power grid WSN communication. Journal of Electronic Measurement and Instrumentation, 2016 (1): 12.

[9] *Jianping Wang, Ruju Fang, Wei Sun.* QoS Modeling of Wireless Sensor Networks in Smart Distribution Grid Communication. 2017, 95(4):4477-4495.

[10] *Sun W, Yu H, Yang Y, et al*. Confidence interval-based model predictive control of transmit power with reliability constraint. Wireless Networks, 2020, 26(5): 3245-3256.

[11] *Liu Yaoxian, SUN Yi, Wu Xin, Wei Lei, Duan Quansheng*. Reliable routing method for wireless sensor networks for fault detection of distribution networks. Power grid technology, 2015, 39(12):3609-3614.

[12] *Raghu Ramamoorthy, Menakadevi Thangavelu*. An improved distance-based ant colony optimization routing for vehicular ad hoc networks. 2020, 33(14):n/a-n/a.

[13] *Ma R, Meng W, Chen H H, et al*. Coexistence of smart utility networks and WLAN/ZigBee in smart grid[C]// IEEE Third International Conference on Smart Grid Communications. 2013

[14] *Teng H, Zhang K, Dong M, et al.* Adaptive transmission range-based topology control scheme for fast and reliable data collection. Wireless Communications and Mobile Computing, 2018, Article No. 4172049

[15] *Teng H, Zhang K, Dong M, et al*. Adaptive transmission range-based topology control scheme for fast and reliable data collection. Wireless Communications and Mobile Computing, 2018, Article No. 4172049

[16] *Lin, S., Miao, F., Zhang, J.,* et al. ATPC: Adaptive transmission power control for wireless sensor networks. ACM Transactions on Sensor Networks (TOSN), 2016, vol.12, no.1 Article No.6.