Hybrid Hierarchical Communication Network Optimal Placement for Transmission Line Online Monitoring in Smart Grid

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Abstract —To conquer problems of bandwidth bottleneck and high latency in chain-type wireless communication network for transmission line online monitoring, an optimal model and multi-object-based decision for hybrid hierarchical communication network planning are proposed. A theoretical placement planning model of optical fiber separated towers is formulated with object of cost and end-to-end latency optimization, while satisfying constraints of graph-based path connectivity and bandwidth. Particle swarm optimization algorithm is used to solve the model to acquire the set of Pareto-optimal solutions along with the decision matrix. The most satisfactory communication network planning scheme is selected by the multi-attribute decision-making method based on fuzzy entropy weight of Vague set. Finally, the effectiveness of the proposed model and algorithm is validated by results of the case study. Our analysis shows that an optimal placement can be obtained to configure network for delivering information to the dispatching center efficiently and cost-effectively.

Index Terms—Online monitoring, smart grid, WSN, optical fiber separation, network planning

I. Introduction

Currently, the widespread overhead transmission lines are vulnerable against various forms of natural disasters and malicious physical events, which adversely affects the overall performance and stability of the grid. Different sensors are expected to be placed for the dispatching center to master the status of the power system. As an important part of the smart grid development strategy, transmission line online monitoring system has the advanced characteristics of information, network and automation. It achieves the intelligent operations [1], security early warning [2] and health status evaluation [3], [4] of transmission lines based on highly sharing and data mining of the multi-sourced heterogeneous monitoring information. Compared with the traditional status monitoring, online monitoring communication system transmits large amount of data in high real-time. Especially in response to the limited transmission capacity and declining safety under inclement weather for transmission lines, online monitoring information based short-term dynamic line rating [5] and operation risk assessment [6] has acquired extension and application. Thus there is an impending need to build a high-performance data communication network that supports future operational requirements like real-time monitoring and control necessary for smart grid integration.

The optical power loss of Ethernet Passive Optical Network (EPON) with high speed limits its coverage and it costs much to install optical devices by separating Optical Fiber Composite Overhead Ground Wire (OPGW). Wireless Sensor Network (WSN), which is a distributed network system with the functions of sensing and communicating, plays an important role in transmission line online monitoring communication for its low cost, self-organization, high reliability, etc. One of crucial problems to applicate WSN technology to engineering application is: how to combine WSN which is a kind of relatively low-speed, close, cheap communication technology with other technology of high-speed, low-latency and expensive communication, and to solve problems of bandwidth bottleneck of “the last mile” and high latency in chain-type wireless communication network with a cost effective, flexible and reasonable placement. So far, there have been many scholars making reviews and analyses about the issue.

The authors of [7] analyzed the technology bottleneck of chain-type wireless communication network. It concludes that packets far from the target node have high collision probability and nodes close to the target node get heavy transmission burden, as a result of information gathering of a large number of sensor nodes and channel competition. The idea of introducing telecommunication wireless public network with higher speed and large communication ranges is put forward. But the access cost of wireless public network can't be evaluated quantitatively and the optimization arrangement scheme of cellular towers is unable to be presented. To solve the problem, taking the minimum delay as objective function, the authors of [8] developed a quadratic equation based solution to find the optimal placement of cellular transceivers. But the equation requires symmetric

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distribution for wireless sensor nodes and cellular towers. What's more, there exists rounding error in the optimal number of cellular towers. In [9] a placement problem was formulated to optimize the number and placement of the cellular enabled towers, which treats the installation and maintenance cost as objective function and considers latency and bandwidth constraints. However, it cannot determine the transmission path of data flow. Besides, it cannot achieve the optimal real time by network planning when latency is only considered as a constraint.

For the sake of the above problems, based on the principle of making full use of WSN and OPGW to build electric power communication network, a theoretical planning model of optical fiber separation placement is formulated with objectives of cost and end-to-end latency optimization, while satisfying constraints of graph-based path connectivity and bandwidth. Then the Pareto optimal solution set of the model is obtained by the Particle Swarm Optimization (PSO) algorithm. Consider both preference factor of decision makers and objective information of the decision matrix, the most satisfactory communication network planning scheme is selected by the multi-attribute decision-making method based on fuzzy entropy weight of Vague set.

II. Communication Network Design and Planning Model

A. Communication Network Design

Transmitting monitoring data reliably and in real time under the premise of data acquisition cycle in SCADA system [10] is the main task of transmission line online monitoring communication network. On one hand, as an emerging communication technology, WSN has the advantages of high monitoring precision, remote telemetry and remote control, self-organization [11], which can be used in the early stages of information acquisition and close range transmission. On the other hand, with the widespread installation of OPGW, combining OPGW separation technology and EPON communication technology [12], data can be transmitted in high speed and reliably by making full use of free OPGW cable cores. This article mainly studies private power communication network that using OPGW in part of towers to make up EPON network and covering other towers by wireless communication.

Hybrid hierarchical communication network composed of WSN and EPON network (Fig. 1) is divided into three layers. The first layer which consists of WSN nodes installed near each tower is responsible for communication within the tower. These nodes can be used to collect information of tension, acceleration, temperature, video images, etc. The second layer is responsible for communication among towers, which transmits monitoring data to optical fiber separated tower in multi-hop manner through sink node. Because of information gathering of a large number of sensor nodes and channel competition, packets far from the target node have high collision probability and nodes close to the target node get heavy transmission burden. Optical fiber communication is necessary for sending monitoring data to the dispatching center. The third layer is therefore EPON communication, which is composed of optical fiber separated towers and is responsible for importing data into optical fiber and sending to substations.

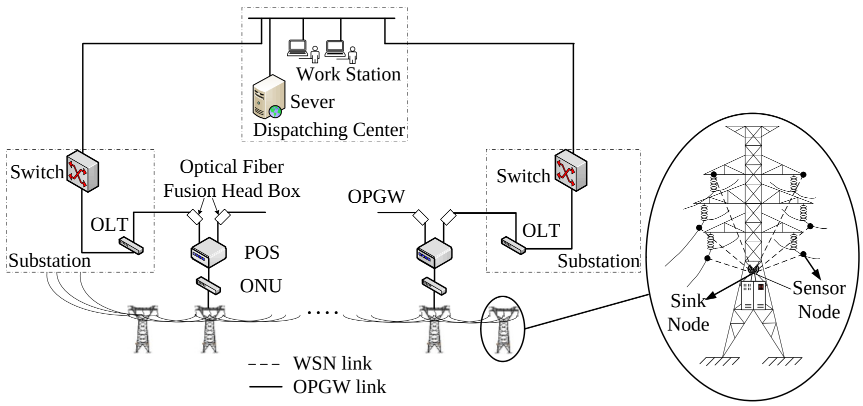

Fig. 1. Hybrid hierarchical communication network for transmission line online monitoring.

B. Planning Model for Communication Network

In order to ensure economy layout and real-time communication, the placement of optical fiber separated towers should be allocated reasonably so that the optimal cost and latency can be obtained. On the purpose of solving the cost of online monitoring communication network and the placement of optical fiber separated towers quantitatively, we formulate a placement problem to optimize the number and placement of the optical fiber separated towers to reduce the planning cost and end-to-end latency while respecting the graph-based path connectivity constraint and bandwidth constraint.

1) Model assumptions and graph-based network discription: To analyze above main issues of network planning convienientl, reasonable assumptions for our model are listed as follows.

- The same number and types of wireless sensor nodes are installed on each tower and data rate of each tower is the same.

- Monitoring data of non-optical-fiber separated towers is sent to the latest optical fiber separated tower through the adjacent node in multi-hop manner.
- Ignoring optical fiber transmission delay of from fiber separated tower to the transformer substation and from substation to dispatching.
- The end-to-end latency of data flow is the total time of each jump. The latency of one hop consists of transmission delay and channel collision detection delay [13].

The hybrid hierarchical communication network for transmission line online monitoring can be described as directed graph, G=(V, E) as shown in Fig. 2. V represents the set of vertices, V={DC} ∪ W1 ∪ W2: DC is the dispatching center; W1={SS1, SS2} is the set of two substations; W2 is the set of towers. E represents the set of feasible communication links among nodes, such as optical fiber links from optical fiber separated towers to SS1 and wireless communication links between adjacent towers. Whether the data flow produced by sensor nodes of the tower k passes a certain link can be indicated by $Y_{\text{start,end},k}$: "start" is the start node of the link; "end" is the end node of the link. $Y_{\text{start,end},k}$ is 1 only if the link is used by the flow, or 0 otherwise.

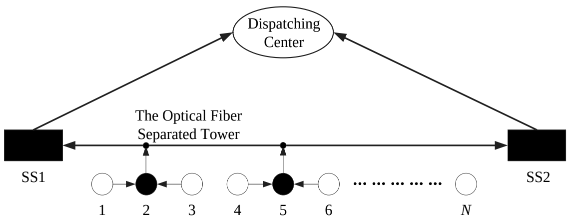

Fig. 2. Arrangement of hybrid hierarchical communication network.

2) Objective fuctions: The planning cost of the whole communication network is mainly composed of the layout cost of WSN devices along the transmission line consisting of N transmission towers and optical fiber separated towers, as shown below:

$$f_1 = N \cdot C_{\text{w}} + \sum_{i=1}^{N} C_{\text{f}} x_i \tag{1}$$

where C_{w} is the total layout cost of WSN devices of one tower, and C_{f} is the layout cost of one optical fiber separated tower. x_i is 1 if tower i is optical fiber separated tower, or 0 otherwise.

Assuming that there are s optical fiber separated towers in the network. d_1, d_2, …, d_{s+1} are the number of serial non-optical-fiber separated towers with the boundary of optical fiber separation towers. Every tower generates data at data rate of S_{d} and R is the transfer rate of wireless sensors. Reducing the maximum end-to-end latency of data flow is treated as the objective to ensure real time communication.

$$f_2 = t_{\text{MA}}(p+1) + \frac{S_{\text{d}}(p^2+3p)}{2R} \tag{2}$$

where t_{MA} is the average channel access latency of CSMA/CA, and $p=\lceil \max(d_i)/2 \rceil$ is the maximum number of towers went by data flow before reaching optical fiber separated towers. The first term in (2) is the channel access latency related to channel sense medium access/collision avoidance mechanism. The second term in (2) is the transmission latency related to the throughput of nodes.

To obtain the optimal cost and real-time communication, considering both the planning cost of communication network and the end-to-end latency of data flow (hereinafter referred to as cost and latency), the multi-objective function can be formulated as

$$\min F = [f_1,\ f_2] \tag{3}$$

3) Constraints: The data flow generated by each tower is transmitted to the latest optical fiber separated tower through WSN in multi-hop manner. Then it is uploaded to substations via optical fiber channel and reaches the dispatch center. In order to guarantee the connectivity and reachability of data transmission path, the following constraints are established according to the geometric relationship in the directed graph.

$$Y_{\text{SS1,DC},k} + Y_{\text{SS2,DC},k} = 1 \quad \forall k \in [1, N] \tag{4}$$

$$Y_{i,j,k} \le Y_{j,\text{DC},k} \quad \forall i \in W_2,\ j \in W_1, k \in [1, N] \tag{5}$$

$$\sum_{i=1}^{N} (\text{Y}_{i,\text{SS1},k} + Y_{i,\text{SS2},k}) = 1 \tag{6}$$

$$Y_{i,j,k} \le x_i \quad \forall i \in W_2,\ j \in W_1 \tag{7}$$

$$\begin{gathered} Y_{i,j,k} \le Y_{r,r+1,k} \\ \forall i \in W_2,\ j \in W_1, \min(i,k) \le r < \max(i,k) \end{gathered} \tag{8}$$

Equation (4) ensures that any data flow will reach the dispatching center via substations. Eq. (5) ensures that if a data flow arrives at substations, it will reach the dispatching center. Eq. (6) ensures that every data flow must reach one the two substations via one optical fiber separated tower. Eq. (7) explains that if tower i connects with substations directly, the tower is an optical fiber separated tower. Eq. (7) and (8) show that if the kth flow goes though tower i which is optical-fiber-separated, it will go through all links from tower k to tower i.

In addition, the total bit rate of data flow in one link doesn't exceed the permitted bandwidth limit of the link.

$$\sum_{k=1}^{N} b_k Y_{i,j,k} \le BandC_{i,j} \quad \forall i,\ j \in V \tag{9}$$

where b_k is the data rate of tower k, and $BandC_{i,j}$ is the bandwidth limit of link (i, j).

III. The Solution and Decision-Making of Model

The planning problem of hybrid hierarchical communication network for transmission line online monitoring is a binary multi-objective optimization problem which is discontinuous, nonlinear and multi-variable. The two objectives relate to the same set of decision variables and have mutual restrictions. It is unlikely for them to achieve the optimal value at the same time. Pareto optimal solution set can be used to coordinate the relationship between two objectives [15]. We use multi-objective PSO which introduces adaptive inertia weight [16] and the global optimal position of random mutation [17] to solve the Pareto optimal solution set. Then the weak search ability and premature convergence phenomenon of traditional PSO can be conquered. What's more, the multi-attribute decision-making method based on fuzzy entropy weight of Vague set is adopted for the ordering of the optimal solution set and determines the best solution, which helps to avoid the blindness of the multi-objective linear weighting method.

A. PSO Based Multi-Objective Optimization

When we arrangement hybrid hierarchical communication network for transmission line online monitoring system, the placement of optical fiber separated towers is necessary to be optimized. So our particle is the coding sequence formed by x_i that indicates the placement of optical fiber separated towers, the encoding form is as follows:

$$X = [x_1, x_2, \cdots, x_N] \tag{10}$$

Each particle represents a kind of optical fiber separated towers placement. If a tower is an optical fiber separated tower, the corresponding element in the coding sequence is 1, otherwise 0.

The multi-objective PSO is applied to the multi-objective optimization of planning scheme for hybrid hierarchical communication network. Its solution steps are as listed below.

1) Inputting scene parameters of communication network. Aquiring communication network scale, packet size and channel access latency. Setting the bandwidth limit of links.

2) Initializing particle swarm and algorithm parameters (including the maximum number of iteration, the inertia weight, learning factor, etc.), randomly generating initial position and velocity, and randomly selecting one among non-dominated particle as the initial optimal particle of the swarm.

3) Calculating the cost and delay of particles as fitness value and deciding whether the constraints are satisfied.

4) The individual optimal particle is updated according to domination relationship between current new particles and individual optimal particle, and a new non inferior solution set is formed.

5) Merging the new inferior solution set and the old inferior solution set, updating the inferior solution set according to domination relationship.

6) Randomly selecting one particle from the inferior solution set as the optimal particle of the swarm.

7) Updating the inertia weight of each particle, and adjusting the speed and position of particles according to update formulas. It is worth noting that the placement variables should be integrated after updating.

8) Calculating swarm fitness variance and mutation probability, comparing a generating random number with the mutation probability and deciding whether the global optimal position mutates.

9) Checking whether the maximum number of iterations is reached, discontinuing optimization if it is true, otherwise, go to step (3).

B. Multi-Attribute Decision Making

After the Pareto optimal solution set is obtained by PSO, the most satisfactory solution will be selected by decision making between the cost attribute and the latency attribute of multi-objective optimization model according to the subjective preference and real requirements of communication network layout. Using the multi-attribute decision-making method based on fuzzy entropy weight of Vague set, the specific steps to decide the Pareto optimal solution set are as follows.

1) Triangular fuzzy number [19] is adopted to determine the fuzzy weight of attributes, which reflects the subjective emphasis of decision makers on cost and latency.

2) To obtain the objective weight by using information entropy method [20] to decide the difference of each attribute value in the Pareto optimal solution set.

3) Combining the fuzzy weight with the objective weight, the fuzzy entropy weight z_h of the hth attribute will be calculated by the weighted geometric mean method (h takes 1, 2).

4) Determining the membership degree vector of positive ideal scheme and negative ideal scheme, and then calculating comprehensive Vague value matrix V=([t_{kh}, f_{kh}]) of scheme set. t_{kh} and f_{kh} respectively represent true and false membership degree of the hth attribute value in the kth solution to the ideal solution.

5) Combining with the fuzzy entropy weight, comprehensive Vague value V_k=[t_k, f_k] of kth solution to the ideal scheme will be determined.

$$t_k = \sum_{h=1}^{2} z_h t_{kh} \quad f_k = \sum_{h=1}^{2} z_h f_{kh} \tag{11}$$

6) Calculating score function value $S1_k = t_k - f_k$ and $S2_k = 1 - f_k$. Then the adaptation degree of the *kth* scheme compared with ideal scheme is obtained. First of all, the scheme set is sorted according to $S1$. The greater, the better the scheme is. If S1 is the same, and then sorting according to $S2$ by the same judgement rule. Finally the optimal solution is selected.

Because the number of towers in specific schemes is not an integral multiple of the number of optical fiber separated towers, even if the cost and latency of schemes are the same, there are a lot of choices for the location of optical fiber separated towers. Arranging the location of optical fiber separated towers evenly can make the latency of all flows even. So we use the standard deviation of the number of serial non-optical-fiber-separated towers to measure the uniformity of arrangement. The standard deviation is calculated as:

$$\sigma = \sqrt{\frac{1}{s+1}\sum_{i=1}^{s+1}(d_i - \frac{N}{s})^2} \tag{12}$$

The solving flow chart of multi-objective planning problem based on PSO and multi-attribute decision making method is shown in Fig. 3.

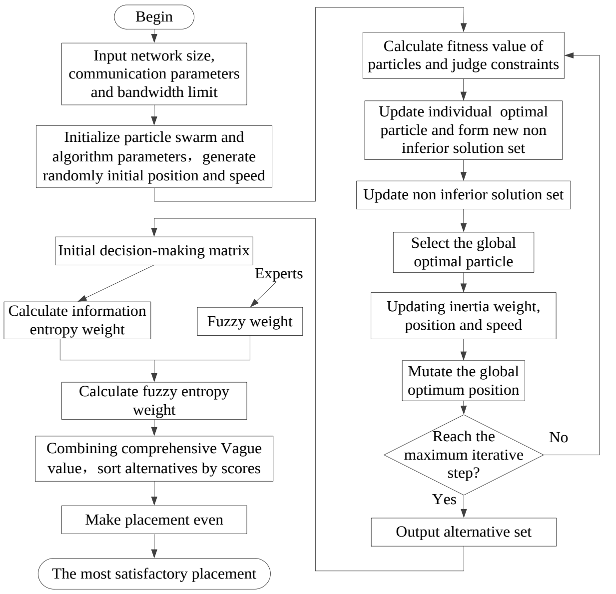

Fig. 3. Flow chart of multi-object optimization and decision method for hybrid hierarchical communication network arrangement.

IV. Optimal Placement Solution

In order to verify the effectiveness of the proposed optimal placement model and algorithm, we take the communication network structure as the case study. The network contains a dispatching center, two substations and 50 towers. The bandwidth limit R is 250 kbps [21]. The data rate of each tower is 32 kbps [7]. It takes 2000 yuan to arrange WSN devices on a tower. Considering the factors of construction, equipment purchase and power loss, an average of 120000 yuan is spent on an optical fiber separated tower. The average channel access time t_{MA} is 41 ms [22]. The swarm size of PSO takes 50; the largest number of iterations is 500; the learning factor takes 2.0; the initial value and end value of inertia weight are 0.9 and 0.4 respectively; the maximum mutation probability is 0.5 and the minimum value is 0. Fig. 4 shows Pareto non-dominated solution space of hybrid hierarchical communication network planning schemes after optimization of PSO.

As we can see from Fig. 4, Pareto optimal solutions distribute evenly in the target space, which provides broader choices for decision makers. What's more, there is none solution dominating another. Among the Pareto optimal solution set, the solution whose cost and latency are 6.1 million yuan and 0 s makes every tower optical-fiber-separated. It will take enormous cost and a lot of light attenuation which causes adverse effects on the original communication business of optical fiber. Therefore, we make subsequent analysis based on eliminating the solution. The fuzzy weight of the cost attribute and the latency attribute is given by the experience of three communication network planning experts. Then the fuzzy subjective preference weight vector is calculated as $[0.8211, 0.1789]^{\mathrm{T}}$. According to the decision matrix formed by the Pareto optimal solution set, the objective weight vector is calculated as $[0.1809, 0.8191]^{\mathrm{T}}$ by the information entropy method. It is obvious that the difference of latency is larger. The fuzzy entropy weight vector is calculated as $[0.5034, 0.4966]^{\mathrm{T}}$ by the weighted geometric mean method. Combining with the comprehensive Vague value matrix, all schemes of Pareto optimal solution set are scored as shown in Table I.

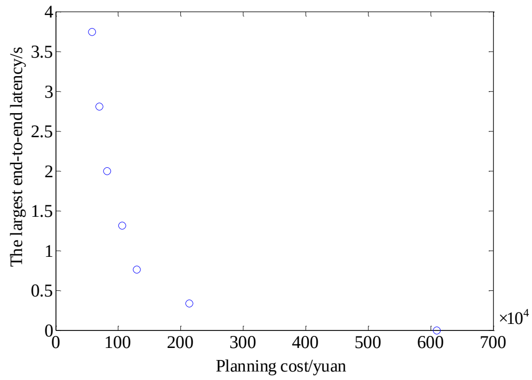

Fig. 4. Distribution of Pareto optimal solution set.

TABLE I: Scoring Results of Multi-object Optimization Schemes of Hybrid Hierarchical Communication Network Arrangement

Serial Number	Cost/yuan	Latency/s	Vague Score	Rank
1	214×10^4	0.338	(-0.007, 0.497)	2
2	130×10^4	0.763	(-0.373, 0.523)	5
3	106×10^4	1.316	(-0.437, 0.474)	6
4	82×10^4	1.997	(-0.311, 0.505)	4
5	70×10^4	2.806	(-0.197, 0.508)	3
6	58×10^4	3.743	(0.007, 0.503)	1

TABLE II: Arrangement Location of Fiber-Optic Towers of Every Scheme

Serial Number	The Placement of Optical Fiber Separated Towers
1	(2, 5, 8, 11, 14, 17, 20, 23, 26, 29, 32, 35, 38, 41, 44, 47, 49)
2	(3, 8, 13, 18, 23, 28, 33, 38, 43, 48)
3	(4, 11, 18, 25, 32, 38, 43, 48)
4	(5, 14, 23, 32, 40, 47)
5	(6, 17, 28, 37, 46)
6	(7, 20, 33, 45)

Six schemes of Pareto optimal solution set for communication network planning are listed in Table I. They don't dominate each other. The maximum latency among them is 3.743 s. When optical fiber separated towers are densely arranged, the end-to-end latency can be down to 0.338 s. Using (12) to make the layout location of each scheme even, a kind of placement corresponding to specific schemes can be obtained as shown in Table II.

From Table I, we can also see that scheme 6 is the best placement. Compared with other schemes, scheme 6 has the lowest cost and the largest latency, whose score is better than the other five kinds of schemes and is close to scheme 1. On one hand, the distance of six schemes from the positive ideal solution is similar. Scheme 1 and 6, both of which include the ideal value of cost and latency respectively are far away from the negative ideal solution. It causes $S1$ value of the two schemes to be better. On the other hand, the fuzzy entropy weight tends to cost less. As a result, scheme 6 is better than other schemes. It can be seen from the decision of scheme 6 that: the layout location of fiber separated towers distributed evenly; the bandwidth constraint is satisfied; the cost is low; the latency satisfies the requirement of SCADA system in second.

V. Conclusion

In this paper, we presented an optimal formulation for a cost and latency optimized hybrid hierarchical communication network capable of transmission of sensor data through the transmission line network in the presence of graph-based path connectivity and bandwidth constraints. The most satisfactory communication network planning scheme is obtained by combining multi-objective PSO and multi-attribute decision-making method based on fuzzy entropy weight of Vague set. Compared with the scheme determined only by humans, the communication network placement scheme optimized by our method can balance both subjective preference and objective information and make the placement suitable for the actual status of online monitoring communication system reasonably. Compared with the single pursuit of economic efficiency or real-time scheme, our method can choose the compromise by optimizing two objectives at the same time. The result of this paper helps electric power developer of future smart grid to balance efficiency and economy and formulate a scientific communication network planning scheme reasonably. As part of future work, we plan to study the affecting factors of decision-making.

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