Economic Evaluation for 5G Planning of a Distribution Network Considering Network Coupling and Important Node Identification

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***Abstract*—The rapid development of communication services in the power distribution network poses challenges for existing wireless communications, and the deployment of a fiber optic network is costly and difficult. The emerging 5G technology has been piloted in power distribution networks, though the cost-effectiveness of its large-scale deployment remains unclear. This paper proposes an economic evaluation method for 5G planning in power distribution networks, considering the coupling relationship between power distribution and communication networks and the identification of important network nodes. First, the objective function to solve the planned number of 5G base stations is established. This is solved using the adaptive particle swarm algorithm and K-means algorithm. Second, the coupling relationship between the distribution and communication networks is discussed and quantified. The node importance of the coupling network is analyzed to identify the important nodes, and micro base stations or optical fibers are added to improve the reliability of the distribution network at the communication level. Finally, an economic evaluation index of 5G planning of the distribution network is established. The paper compares the economic solutions of 5G and 4G communications in city and town scenarios using the IEEE 123-node network as an example, and concludes that the economics of 5G are better than those of 4G.**

***Index Terms*—5G, coupling relationship, node importance, economic evaluation, adaptive particle swarm, K-means.**

I. INTRODUCTION

As an important component of distribution network operations, the distribution communication network plays a key role in acquiring status information and transmitting operational control signals within the distribution network. With the rapid development of society, the progress of making the distribution network more intelligent is accelerating, and the amount of relevant information in the distribution network is increasing enormously. Therefore, higher requirements are placed on the transmission capacity and delay performance. Existing fiber optic communication can meet the needs for the rapid development of the networks, but it is challenging to deploy extensively in cities because of high costs and difficulties associated with laying fiber optic cables. On the other hand, the current 4G wireless communication cannot meet the communication needs of different distribution network businesses for transmission bandwidth and communication latency [1]. Therefore, there is an urgent need for a communication method with high bandwidth and low latency to meet the communication requirements of future networks.

As an emerging communication technology, 5G has been recognized for its superior communication capabilities [2], [3]. In China, 5G commercialization has been widely promoted in many industries. Several pilot projects have been tested in the power grid, such as the 5G smart grid jointly built by Shandong Qingdao Power Supply Company and China Telecom Qingdao Branch. However, 5G communication has yet to be widely adopted in power distribution networks and is only at the pilot stage. Therefor the economic feasibility of the comprehensive application of 5G in the power distribution networks requires urgent research. The deployment of communication networks is often associated with the structure of power distribution networks, a correlation called coupling [4]–[5]. Therefor it is necessary to consider the impact of coupling in the economic research on 5G planning for power distribution networks.

References [6], [7] take the minimum investment cost as the goal and consider operational loss, geographical factors, and other constraints to obtain optimal planning of the wireless network. Based on active antenna units (AAUs) in 5G, reference [8] establishes an objective function considering coverage area and cost, and uses a particle swarm algorithm to plan and analyze the configuration of AAUs. In [9], the objective function of

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minimizing the power consumption and maximizing the coverage area of a 5G base station is developed, and an improved real-valued genetic algorithm is used to obtain the optimal planning of the base station. References [10], [11] study the planning problem of heterogeneous networks to minimize the planning cost and energy consumption, and optimize the solution considering the constraints of base station power and bandwidth. Reference [12] proposes a new method for optimizing cell base station deployment. It treats the deployment of base stations as a multi-objective optimization problem with finite backhaul capacity and terminal probability constraints, and uses Lagrangian relaxation and forbidden search algorithms to solve the problem. In [13], [14], a swarm intelligence algorithm is used to work out the optimal communication base station layout that satisfies the constraints of communication capacity, coverage and cost. It eliminates the redundant base stations by an iterative method. In [15], an approximation algorithm is used to optimize the objective function by minimizing the total cost of ownership (TCO) and the energy consumption constraint, and the base station planning for heterogeneous networks is obtained. In [16], a link addition strategy is proposed to improve the robustness of power grid and communication networks with a coupling relationship, while the number of links added is determined based on the node degree of the coupled network. Using K-means to process and mine the historical grid data, reference [17] uses Markov chains to predict the importance of grid nodes, and to obtain the important ones. Reference [18] proposes a GDF-ICN architecture for identifying the critical nodes of the grid while also introducing the concept of group information to improve the performance of critical node identification. Reference [19] proposes a method for identifying complex grid nodes by combining the application of renewable energy sources, system topology and transmission currents. Based on stochastic currents, reference [20] adopts power node degree, power node betweenness and aggregation coefficients to identify vulnerable nodes of the grid, and use entropy and ideal solutions to obtain grid critical nodes. In [21], a heterogeneous interdependent network model is proposed to study the evolution of cascading faults for the coupling relationship between grid and communication networks, while fault evolution feature selection is used to obtain the critical nodes. Reference [22] proposes seven centrality metrics, which are combined with the correlation coefficient of integrated entropy and inter-attribute correlation of Spearman. A multi-metric decision method is provided for identifying important nodes in a grid.

The main problems of existing methods can be summarized as:

1) Only considering the initial construction cost.

When evaluating the economics of the distributed communication networks, existing papers typically only consider the initial construction costs. They often neglect the potential changes in costs brought about by overlooking late revenue and the increase in service demand over time. For 5G communication, the investment in planning involves not only the initial expenditure, but also the benefits brought by the 5G base station itself. Therefore, if the benefits are ignored, the final results of the planning may be incorrect.

2) Ignoring the influence of important nodes in the coupled network when communicating.

Existing research often ignores the difference in the importance of objects when conducting communication planning. For example, in a distribution network scenario, each node has different importance because it is connected to different levels of loads. Thus, if such difference is ignored in planning, it is inconsistent with the actual situation.

This paper gives an economic evaluation method for the application of 5G base stations in distribution networks by:

1) Quantifying the coupling relationship between distribution and communication networks using complex network theory and Pearson correlation coefficients.

2) Considering the high communication performance requirements of the important nodes of the distribution network, while those nodes are determined by calculating the energy and information flows; improving the communication quality at the location of the important nodes by installing additional micro base stations at the important nodes.

3) Solving for the optimal number of base stations to be deployed in the distribution network by establishing a multi-objective function of coverage, deployment cost, and communication capacity.

4) Constructing 5G planning cost indicators for the distribution network, including investment costs, operational and maintenance costs, and benefits.

5) Establishing economic evaluation indices for distribution network 5G planning, including reliability, technical, and efficiency indices.

The main contributions of this paper thus are:

1) Using the improved Pearson correlation coefficient, combined with indicators of mutual similarity in node degree, node betweenness centrality, and clustering coefficient, the coupling relationship between the power distribution and communication networks is quantified and used as an indicator in the identification process of important nodes in the coupling network.

2) Important nodes are identified for the coupled network, and are increased by adding micro-base stations to improve their communication reliability. In particular, the important nodes are identified using a combination of energy and information flows, where the energy flow is determined by connectivity, topological entropy, load, and load importance.

3) The cost calculation and economic evaluation methods in the planning of a 5G application in a distribution network are derived. The cost calculation includes investment, operational and maintenance costs, and later benefit, while the economic evaluation index includes communication reliability, technical, and benefits indices.

This paper is planned to organize according to the following arrangement. Section II analyzes the research motivation of the article. In section III, firstly, the coupling relationship between the distribution network and the communication network is quantified and an evaluation index for the node importance of the coupling network based on the coupling relationship is provided; secondly, a comprehensive economic evaluation index is established that considers reliability, technicality, and efficiency. In section IV, the evaluation process of the article is provided. The case simulation is displayed in Section V and Section VI concludes this paper.

II. Motivation

The rapid growth of the distribution network and the huge amount of terminal data brought by the related power communication business make the communication transmission capacity of the distribution network extremely challenged. The existing distribution communication business mainly includes load control, distribution automation, intelligent inspection, distributed source storage scheduling, and power consumption information collection. Different communication services have different requirements for isolation and transmission performance, e.g., distribution automation services have the highest requirements for isolation and require a dedicated communication network to transmit the corresponding control signals. For intelligent inspection and electricity information collection, the isolation requirement of a communication network is low, so the public communication network can be used.

Figure 1 shows the differences in communication performance between 5G and 4G [23].

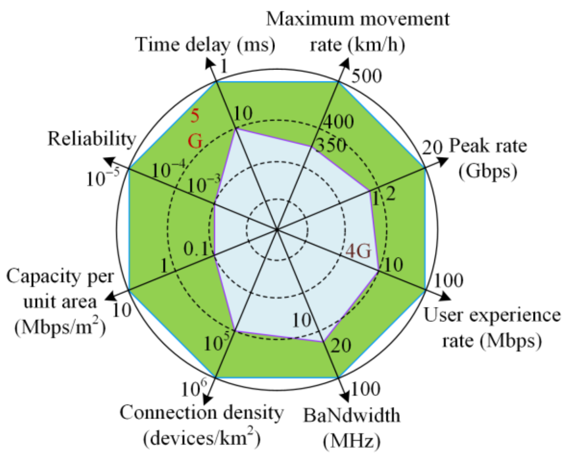

Fig. 1. The comparison of 5G and 4G communication performances.

The increase in data volume of power communication services makes it difficult for the existing 4G network to meet some of the power communication service demands, as shown in Table I. However, if optical fiber is used to replace 4G, there will be a significant increase in investment costs, as well as construction difficulties in some scenarios. The unique slicing function of 5G can be customized according to different communication needs, while the physical isolation between different slices is very good. Therefore, to meet the massive increase of service data in the distribution network and the requirements of different communication services for the isolation of the communication network, the planning of the 5G network can be carried out in the distribution network.

TABLE I
THE COMMUNICATION DEMAND OF POWER BUSINESS

Communication service	Bandwidth (M/s)	Time delay (ms)	Reliability (%)	5G	4G
Load control	0.05–2	<50	99.999	√	√
Distribution automation	2	<20	99.999	√	×
Intelligent patrol inspection	4–100	<200	99.9	√	×
User information collection	>2	<1000	99.9	√	×

III. Economic Evaluation Index for 5G Planning of Distribution Network

The communication planning and economic evaluation process of the network is shown in Fig. 2.

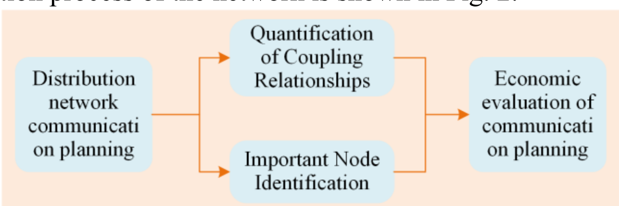

Fig. 2. Economic evaluation of communication planning.

A. Quantification of the Coupling Degree Between the Two Networks and Identification of Important Nodes

Distribution network: Because of the low grid voltage, the topology of the distribution network has the characteristics of closed-loop design and open-loop operation. The number of outgoing lines at each node of the distribution network is approximately equal, and the overall topological structure is evenly distributed.

Power communication network: The layout principles of its structure can be divided into three aspects. The power communication network feeder terminals are mainly located at switches of cables and overhead lines. The power communication network distribution transformer terminal is mainly used to monitor distribution transformers, whereas the power distribution terminals of the network are mainly located at the switching room and ring main unit [24].

As for the distribution network and distribution communication network, there is a coupling relationship between the two networks because of factors such as communication service collection and transmission, and the power supply of communication nodes [25], [26].

1) Quantification of the Coupling Degree

For the coupling relationship between the distribution and communication networks, reference [27] combines complex network theory and the Pearson correlation coefficient to reflect the coupling relationship between the two networks, but the method is only applicable to the one-to-one correspondence between nodes case [28], [29]. In actual situations, the coupling relationship between the two networks is shown in Fig. 3, where Fig. 3(a) is a simplified part of the communication network and Fig. 3(b) is a part of the distribution network. The dotted line between them is the power service transmission channel. The communication network and the distribution network have the following properties:

Property 1: The correspondence between communication network nodes and distribution network nodes is not unique. Specifically, a communication node corresponds to one or more distribution network nodes, or one distribution network node corresponds to multiple communication nodes.

Property 2: The number of communication network nodes and distribution network nodes are not necessarily equal. Communication network nodes are often fewer than the distribution network nodes, and there is also a one-to-many or many-to-one physical association between communication network nodes and distribution network nodes.

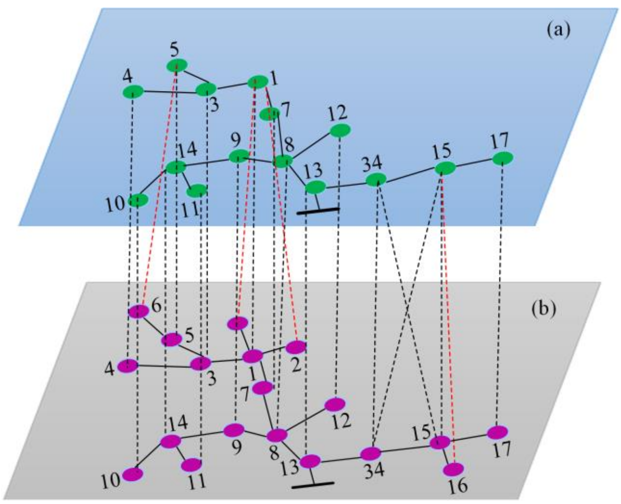

Fig. 3. Coupling relationship between distribution and communication network. (a) Communication network. (b) Distribution network.

Thus it is difficult to apply the method in [27], and also no specific formula for calculating the coupling quantization relationship is given.

In this paper, the Pearson correlation coefficient is modified by the relationship matrix of the coupling network to adapt to the one-to-many relationship, and the specific coupling quantitative relationship calculation method is given in combination with the weight. The process is as follows.

Step 1: Degree mutual similarity ρ_{D}, betweenness mutual similarity ρ_{B} and clustering mutual similarity ρ_{c}.

In calculating ρ_{D}, ρ_{B} and ρ_{c}, it is necessary to calculate the node degree *D*, node betweenness *B* and node clustering coefficient *C* in complex network theory. To characterize the sum of links directly associated with a node V_i in the network topology, the number of connections starting from node V_i is defined as the node out-degree $\deg^{+}(V_i)$, and the number of links ending at node V_i is the node in-degree $\deg^{-}(V_i)$, the calculation of node degree *D* is thus given as:

$$D=\frac{\deg^{+}(V_i)+\deg^{-}(V_i)}{2} \tag{1}$$

To characterize the degree of influence of node V_i in the network and the utilization of data flow or energy flow between node pairs (V_j, V_k) by node V_i, the calculations of node betweenness *B* is given as:

$$B_i=\left(\sum_{j\neq k}\delta_{jk}(i)\right)\Big/\delta_{jk} \tag{2}$$

where δ_{jk} is the number of paths from V_j to V_k under the shortest route policy; $\delta_{jk}(i)$ is the number of paths through node V_i in δ_{jk}; *i* represents the *i*th distribution network node; and *j* represents the *j*th communication network node.

To characterize the degree of aggregation of node V_i with other nodes in the network, the node clustering coefficient *C* is calculated as:

$$C_i=\left[2\deg(V_i)\right]\big/\left[n(n-1)\right] \tag{3}$$

From the coupling relationship between the distribution and communication networks, the two networks' association matrix ***K*** is established. k_{ij} is an element in the matrix ***K***, which represents the connection relationship between distribution network node V_i and communication network node V_j, given as:

$$k_{ij}=\begin{cases}1, & \text{Have coupling relationship between } i \text{ and } j\\ 0, & \text{No coupling between } i \text{ and } j\end{cases} \tag{4}$$

The Pearson correlation coefficient is corrected using the correlation matrix ***K***, and the corrected Pearson correlation coefficient ρ is given as:

$$\rho=\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(X_i-\bar{X})(Y_j-\bar{Y})k_{ij}}{\sqrt{\sum_{j=1}^{m}\sum_{i=1}^{n}(X_i-\bar{X})^2(Y_j-\bar{Y})^2k_{ij}}} \tag{5}$$

where X_i can be the D or B or C of node V_i in the distribution network topology; while $\bar{X}$ is the average value of the relevant parameters; Y_j is the D, B or C of node V_j in the communication network topology; $\bar{Y}$ is the average value of the relevant parameters; m is the number of communication network nodes; and n is the number of distribution network nodes.

The modified Pearson correlation coefficient is used to solve for ρ_{D}, ρ_{B} and ρ_{c}.

Step 2: Using ρ_{D}, ρ_{B} and ρ_{c}, the results of the degree of coupling between the two networks are weighted and summed to solve the result ρ_{sum}, as:

$$\rho_{\mathrm{sum}} = a\rho_{\mathrm{D}} + b\rho_{\mathrm{B}} + c\rho_{\mathrm{c}} \tag{6}$$

where a is the weight of ρ_{D}; b is the weight of ρ_{B}; and c is the weight of ρ_{c}. We define that when the coupling degree of two networks is $\rho_{\mathrm{sum}} > 0.7$, the two networks are strongly coupled. When $\rho_{\mathrm{sum}} < 0.7$, the coupling degree of the two networks is weak.

2) Quantification of Node Importance

When calculating the node importance of the coupled network, we consider the two factors of energy flow and information flow. The calculation process is as [27].

Step 1: From (1)–(3), the distribution and communication networks D, B and C are calculated, respectively. The node parameter matrix $\boldsymbol{\xi}_i = [\boldsymbol{D}_i, \boldsymbol{B}_i, \boldsymbol{C}_i] = [\xi_i^1, \xi_i^2, \xi_i^3]$ for the distribution network and the node parameter matrix $\boldsymbol{\xi}_j = [\boldsymbol{D}_j, \boldsymbol{B}_j, \boldsymbol{C}_j] = [\xi_i^1, \xi_i^2, \xi_i^3]$ for the communication network are then established.

Step 2: Using the correlation matrix $\boldsymbol{K}$ and Spearman's correlation coefficient, the node scalar value S_{r} of the coupled network of distribution and communication networks is determined, i.e.

$$\begin{cases} S_{\mathrm{r}} = \left| \sum_{i=1}^{N} k_{ij}\rho_{ij} \right|, & i \neq 1 \\ S_{\mathrm{r}} = 1, & i = 1 \end{cases} \tag{7}$$

where k_{ij} is the element in the ith row and the jth column of the correlation matrix $\boldsymbol{K}$; and ρ_{ij} is the Spearman correlation coefficient between the ith distribution and the jth communication network nodes. The Spearman correlation coefficient is calculated as:

$$\rho_{ij} = 1 - \frac{6 \times \sum_{l=1}^{R} (\xi_i^l - \xi_j^l)^2}{R(R^2 - 1)} \tag{8}$$

where R is the number of elements in the parameter matrix ξ.

Step 3: Calculate the information flow score of the coupled network nodes.

1) Determine the communication services of the distribution network, such as line protection and dispatching automation services, etc. Establish service evaluation indicators, such as business attributes, etc. For specific businesses, the service scores can be calculated according to the different business evaluation indicators in each distribution network communication service as in [28].

2) From the existence of different distribution network communication services in each node of the coupling network, each grid node's distribution communication service scores are summed to obtain the information flow score S_{inf} of each node, as:

$$S_{\mathrm{inf}}^{i} = \sum_{i_{\mathrm{inf}}}^{N_{\mathrm{inf}}} k_{i_{\mathrm{inf}}}^{i} S_{i_{\mathrm{inf}}}^{i} \tag{9}$$

where S_{inf}^{i} is the score of the i_{inf} communication service; i_{inf} represents the ith communication service; N_{inf} is the number of communication services in the coupled network; $k_{i_{\mathrm{inf}}}^{i}$ represents the status quantity of the i_{inf} type communication service at coupling node i, and its value is [0,1]; $k_{i_{\mathrm{inf}}}^{i} = 1$ indicates that there is i_{inf} type communication service at coupling node i, otherwise $k_{i_{\mathrm{inf}}}^{i} = 0$.

The distribution network business includes the following 5 types: load control, distribution automation, intelligent inspection, distributed energy resource storage, and power consumption information collection.

Step 4: Calculate the energy flow score of the coupled network

1) The energy flow evaluation metrics include connectivity, topological entropy, load and load importance.

Connectivity L: Reflects the average efficiency value of the remaining nodes after the failure of a node V_k in the coupled network topology, and is calculated as:

$$L = \frac{1}{n-1} \sum_{i=1}^{n-1} L_i \tag{10}$$

where n is the number of nodes in the coupling network and L_i is the average efficiency value of the remaining nodes after the node V_i fails.

Topological entropy E: Network topology entropy can be used to reflect the uniformity of complex networks, so it is applied in the distribution network topology to evaluate the balance degree of the distribution network structure.

The importance I_i calculation method of distribution network node i is shown as:

$$I_i = D_i / \sum_{i=1}^{N} D_i \tag{11}$$

where D_i is the degree of node i in the distribution network and N is the number of nodes in the distribution network. The importance i satisfies the condition of:

$$\sum_{i=1}^{N} I_i = 1 \quad (12)$$

The calculation of topological entropy E is given as:

$$E = -\sum_{i=1}^{N} (I_i \ln I_i) \quad (13)$$

Load H: Indicates the load of coupling network node V_i.

Load importance T: Used to evaluate the proportion of the 1-class load and 2-class load in the load of the coupled network node V_i, and is calculated as:

$$T = (\sum H^{1st} + \sum H^{2nd})/H \quad (14)$$

where H^{1st} is the 1-class load of the node V_i; H^{2nd} is the 2-class load of the node V_i; and H is the total load of the node V_i.

2) Calculate the connectivity, equalization degree, load and load importance of each node of the coupling network, and calculate the weight of each index. Finally, we perform a weighted summation to obtain the energy flow score S_{pow} of each node in the coupling network, as:

$$S_{pow} = w_1 L + w_2 E + w_3 H \quad (15)$$

where w_1, w_2 and w_3 are the weights of connectivity, topological entropy, and load importance, respectively.

Step 5: From the information flow score S_{inf}, the energy flow score S_{pow}, and the scale value S_r, the node importance calculation of the coupled network is given as:

$$S = S_{inf} S_r + S_{pow} \quad (16)$$

B. The Optimization Indices for Base Station Number

Solving the initial communication macro base station planning problem establishes the objective of maximizing coverage area and minimizing initial construction cost. Relevant optimization indices are introduced, and include coverage, communication capacity and initial investment cost.

1) Coverage

When calculating the coverage of a base station, it is regarded as a circle with a radius of $r_{5G/4G}$, while considering the overlapping area of coverage between base stations. The calculation methods of the coverage area and the overlapping area of the signals between the base stations are:

$$S_{Station} = n_{5G/4G} \pi r_{5G/4G}^2 - S_{Repeat\_5G/4G} \quad (17)$$

$$S_{Repeat\_5G/4G} = (a_c n_{5G/4G} - b_c) \quad (18)$$

where $S_{Station}$ is the total coverage areas of the base stations; $r_{5G/4G}$ is the coverage radius of the 5G or 4G base stations; S_{Repeat_5G} are the signal overlap areas; $(a_c n_{5G/4G} - b_c)$ is the relationship between the number of fitted base stations and the signal overlap areas; while a_c and b_c are fitting coefficients, which are constants; and $n_{5G/4G}$ is the number of base stations installed.

2) Communication Capacity

In the communication planning of the distribution network, it is necessary to consider whether the capacity of the communication network can meet the distribution network business. At the same time, considering the development of the distribution network, the communication network capacity needs to have a certain redundancy. Therefore, bandwidth redundancy and terminal access redundancy are introduced, as:

$$\mu_{b\_5G/4G} = 1 - \frac{b_{Use}}{B_{5G/4G}} \quad (19)$$

$$\mu_{Device\_5G/4G} = 1 - \frac{n_{Device\_5G/4G}}{N_{5G/4G}} \quad (20)$$

where $\mu_{b\_5G/4G}$ is the bandwidth redundancy; b_{Use} is the used bandwidth; $B_{5G/4G}$ is the bandwidth of 5G or 4G; $\mu_{Device\_5G/4G}$ is the redundancy of terminal access; $n_{Device\_5G/4G}$ is the number of terminals connected to the communication network; and $N_{5G/4G}$ is the maximum number of access terminals that each of the two communication methods can accommodate.

3) Initial Investment Cost

When planning the macro base station of the distribution network, the initial investment cost is a constraint. The construction cost of the communication base station room, the cost of communication equipment, and the communication tower's construction are introduced, i.e.

$$C_{Struction} = c_{Wireless} n_{5G/4G} + c_{State} n_{State\_5G/4G} + c_{Tower} n_{Tower\_5G/4G} \quad (21)$$

where $C_{Struction}$ is the initial investment cost; $c_{Wireless}$ is the cost of a set of wireless equipment; c_{State} is the construction cost of a single computer room; $n_{State\_5G/4G}$ is the number of computer rooms; c_{Tower} is the cost of a single tower; and $n_{Tower\_5G/4G}$ is the number of communication towers required.

C. Calculation of the Final Planning Cost

In this section, the investment cost considers three parts: construction cost, later operation, maintenance cost and later benefit.

1) Initial Construction Cost

Considering the important nodes in a coupled network, in the 5G communication mode, micro base stations are added to important nodes. The investment cost of the micro base station is given as:

$$C_{\mu 5G} = \sum_{i=1}^{n} k_i c_{\mu} \quad (22)$$

where $C_{\mu 5G}$ is the cost of adding micro base stations to important nodes when considering the importance of nodes; k_i represents whether the ith node of the coupling network is important, and its value is [0, 1]; and c_μ is the cost of a single micro base station. In the 4G communication mode, optical fibers are added between important nodes, and the investment cost of optical fibers is:

$$C_{\text{Light}} = c_{\text{Light}} L_{\text{Light}} \tag{23}$$

where C_{Light} is the cost of optical fiber construction; c_{Light} is the cost per kilometer of optical fiber; and L_{Light} is the length of optical fiber being laid. In summary, the initial investment cost of distribution communication network planning is:

$$C_{\text{Invest}} = \begin{cases} C_{\text{Struction}} + C_{\mu 5\text{G}}, & 5\text{G} \\ C_{\text{Struction}} + C_{\text{Light}}, & 4\text{G} \end{cases} \tag{24}$$

2) Later Operation and Maintenance Costs

Considering the unique network slicing function of 5G communication [30]–[31], such as enhanced mobile broadband (eMBB), massive machine type of communication (mMTC), ultra-reliable & low-latency communication (uRLLC), it is possible to customize slices according to different distribution network services, while the network slicing customization can also reduce network construction costs.

The transmission of 5G power communication services can be realized by renting relevant slices, while 4G realizes service transmission by renting corresponding bandwidth. The costs of corresponding slice leasing and bandwidth leasing are part of the later operational and maintenance costs. In addition, the operation of the base station also needs to consider the cost of its power consumption. Finally, the maintenance cost of the relevant personnel and equipment needs to be considered. The calculations of each cost are:

$$c_{\text{Rent\_5G}} = (c_{\text{eMBB}} + c_{\text{mMTC}} + c_{\text{uRLLC}}) t_{\text{Rent\_5G}} \tag{25}$$

$$c_{\text{Inspection\_5G}} = C_{\text{Struction\_5G}} \lambda_{5\text{G}} \tag{26}$$

where $c_{\text{Rent\_5G}}$ is the cost of slice rental; c_{eMMB} is the slice rental of eMBB; c_{mMTC} is the slice rental of mMTC; c_{uRLLC} is the slice rental of uRLLC; $t_{\text{Rent\_5G}}$ is the rent time. $c_{\text{Inspection\_5G}}$ is the inspection cost for later maintenance, $C_{\text{Struction\_5G}}$ is the initial construction cost of 5G; and $\lambda_{5\text{G}}$ is the ratio coefficient between maintenance cost and initial construction cost.

The base station equipment is mainly composed of two parts: AAU and building base band unit (BBU). The power consumption of the base station (macro base station) is mainly generated by the AAU, and mainly depends on the communication volume of business of the base station. It is assumed that the full-load power consumption of the macro base station is $P_{\max}$, where the full-load power consumption includes no-load power consumption P_0 and adjustable power consumption P_t. The traffic carried by the base station mainly affects the adjustable power consumption P_t, so the power consumption of the base station is established as:

$$P_i = P_0 + \beta P_t \tag{27}$$

where β is the coefficient of variation, and is calculated as:

$$\beta = \frac{\sum_{i=1}^{m} n_{\text{bs}}(i)}{N_{\max}} \tag{28}$$

where $n_{\text{bs}}(i)$ is the hourly traffic volume of grid node V_i covered by the base station and $N_{\max}$ is the maximum traffic volume that the base station transmission bandwidth can accommodate. Therefore, the power consumption W_i of a single base station i in unit time T is given as:

$$W_i = P_i T \tag{29}$$

Assuming that the electricity cost per unit time is C_0, the electricity cost of a single base station in time t is:

$$C_{\text{p}} = W_i \frac{t}{T} C_0 \tag{30}$$

The calculation method of 4G base station power consumption is similar to that of 5G shown in (30). From (25), (26) and (30), the later operational and maintenance cost of 5G communication in the distribution network can be obtained as:

$$C_{5\text{G}} = c_{\text{Rent\_5G}} + c_{\text{Inspection\_5G}} + C_{\text{p}} \tag{31}$$

The calculation method of 4G personnel and equipment maintenance cost is the same as in (31), while the communication bandwidth rental cost of 4G is：

$$c_{\text{Rent\_4G}} = C_{\text{Band\_4G}} t_{\text{Rent\_4G}} \tag{32}$$

The post-operation and maintenance cost of 4G communication planning in the distribution network is:

$$C_{4\text{G}} = c_{\text{Rent\_4G}} + c_{\text{Inspection\_4G}} + C_{\text{p}} \tag{33}$$

3) Later Benefit

From the characteristics of 5G, the later benefits of 5G mainly include: adjusting the base stations for business access according the real-time electricity price to reduce costs [32], [33], and the benefits of sharing communication towers, sharing network slices with other industries, and the benefits of 5G battery packs participating in demand response [34]. Here, we consider only the last three benefits: the rental fees for shared towers, the revenue from 5G base station energy storage participating in demand response, and the rental costs for network slices.

Shared tower rental income E_{Rent} is:

$$E_{\text{Rent}} = e_{\text{Share}} n_{\text{Share}} t_{\text{Share}} \tag{34}$$

where e_{Share} is the annual revenue of shared communication towers; n_{Share} is the number of communication towers that can participate in the sharing; and t_{Share} is the sharing period.

As a controllable resource, the energy storage device owned by the 5G base station can participate in the demand response of the power grid, to fully utilize its value and obtain benefits [35]. Combined with the energy storage of the 5G base station, one-day income can be calculated as:

$$E_{\mathrm{re\_day}}=\sum_{i=1}^{n}k_{pi}k_{si}k_{ci}\left[\frac{P_{\mathrm{ch}}^{2}(i)}{\Delta P_{\max}}C_{\mathrm{ch}}+\frac{P_{\mathrm{dis}}^{2}(i)}{\Delta P_{\max}}C_{\mathrm{dis}}\right] \quad (35)$$

where $E_{\mathrm{re\_day}}$ is the corresponding benefit obtained by the 5G base station energy storage participating in the grid demand response; k_{p_i} represents the mains supply status of the *i*th base station and its value is [0, 1], while at the normal mains supply k_{p_i} is 1; k_{s_i} represents the number of important grid nodes covered by the *i*th base station or the load status of the base station. Its value is [0, 1], while when overloading or covering more important grid nodes, its value is 0; k_{c_i} represents whether the *i*th base station energy storage charge/discharge conversion times exceeds the limit and takes the value of [0, 1] and k_{c_i} is 1 when the limit is not exceeded and is 0 when the limit is exceeded; $\Delta P_{\max}$ is the charging and discharging power of energy storage per unit time; $P_{\mathrm{ch}}(i)$ is the charging power required for the *i*th base station energy storage; while $P_{\mathrm{dis}}(i)$ is the discharging power required for the *i*th base station energy storage; C_{ch} is the time of use power price; C_{dis} is the unit discharging cost; and *n* is the number of base stations.

The income E_{resp} obtained by the 5G base station energy storage participating in the demand response within the time *T* (in days) is:

$$E_{\mathrm{resp}}=\sum_{i=1}^{T}E_{\mathrm{re\_day}}(i) \quad (36)$$

Power grid companies can share some power grid communication slices that do not require high communication isolation, such as eMBB network slices used to transmit surveillance video or drone inspection video. They can share these with other industries to make full use of bandwidth resources and gain benefits. We define this part of the income as E_{Band}, given as:

$$E_{\mathrm{Band}}=e_{\mathrm{Band}}t_{\mathrm{Rent}} \quad (37)$$

where E_{Band} is the benefit of renting slices; e_{Band} is the annual rental benefit of communication slices; and t_{Rent} is the lease term. From (34), (36) and (37), the later income E_{Earing} is:

$$E_{\mathrm{Earing}}=E_{\mathrm{Rent}}+E_{\mathrm{resp}}+E_{\mathrm{Band}} \quad (38)$$

Here, in the 4G communication mode, its benefits are mainly reflected in the sharing of communication towers, and its revenue is the same as (34).

D. Economic Evaluation of Distribution Communication Network Planning

For the economic evaluation of distribution communication network planning [36], the cost as well as the reliability and other properties of the communication planning must be considered. Thus, in this paper, the economic evaluation of distribution and communication networks is carried out for reliability, technology, and benefit.

1) Reliability Indices

The reliability index is mainly evaluated from the aspect of communication performance. The data loss rate and the network signal-to-noise ratio are introduced, combined with the coupling degree between the distribution and communication networks quantified in Section III-A, to calculate the reliability in 5G and 4G modes, i.e.

$$D_{\mathrm{Loss}}=\frac{d_{\mathrm{Loss}}}{N_{\mathrm{Data}}}\times 100\% \quad (39)$$

$$\eta_{\mathrm{p}}=\frac{P_{\mathrm{Noise}}}{P_{\mathrm{Data}}}\times 100\% \quad (40)$$

where D_{Loss} is the communication data loss rate; d_{Loss} is the amount of data lost or incorrectly transmitted during transmission; N_{Data} is the total amount of data transferred; η_{p} is the network signal-noise-ratio; P_{Noise} is the power of noise in data transmission; and P_{Data} is the power of data transmission. From (39), (40) and (6), the reliability index η_{Reliable} is:

$$\eta_{\mathrm{Reliable}}=\rho_{\mathrm{sum}}(D_{\mathrm{Loss}}+\eta_{\mathrm{p}}) \quad (41)$$

2) Technical Indices

For the planning of the distribution communication network, it is necessary to check the satisfaction rate of the communication mode for the distribution network business, and consider the adaptation of the communication mode to the development of the distribution network business. Therefore, technical evaluation indicators are proposed, including service bandwidth satisfaction rate, service delay satisfaction rate, terminal access redundancy, and bandwidth redundancy. The power service bandwidth satisfaction rate η_{Wide} and power service delay satisfaction rate η_{Relay} are:

$$\eta_{\mathrm{Wide}}=\frac{n_{\mathrm{Widemeet}}}{N_{\mathrm{Device}}}\times 100\% \quad (42)$$

$$\eta_{\mathrm{Relay}}=\frac{n_{\mathrm{Relay}}}{N_{\mathrm{Device}}}\times 100\% \quad (43)$$

where n_{Widemeet} is the number of terminals meeting relevant bandwidth requirements; N_{Device} is the total number of terminals connected to the distribution communication network; and n_{Relay} is the number of terminals that meet the requirements of related delay services, i.e.

$$\eta_{\text{Device}} = 1 - \frac{n_{\text{Device}}}{N} \tag{44}$$

where η_{Device} is the terminal access redundancy rate; n_{Device} is the number of terminals connected to the communication network; and N is the maximum number of terminals allowed to access the communication network.

The bandwidth redundancy ratio η_{b} is:

$$\eta_{\text{b}} = 1 - \frac{b_{\text{User}}}{B} \tag{45}$$

where b_{User} is the bandwidth used by the power business and B is the maximum allowable bandwidth of the communication method. From (42) to (45), the technical index η_{Tech} can be obtained as:

$$\eta_{\text{Tech}} = \eta_{\text{Wide}} + \eta_{\text{Relay}} + \eta_{\text{Device}} + \eta_{\text{b}} \tag{46}$$

3) Efficiency Indices

For communication planning, we establish a benefit index to measure the benefit of distribution communication network planning. Taking the benefit-cost ratio as the benefit index, as

$$\eta_{\text{Eff}} = \frac{E_{\text{Earing}}}{C_{\text{Cost}}} \times 100\% \tag{47}$$

where η_{Eff} is the benefit-cost ratio; E_{Earing} is the benefit obtained from the planning of the communication network; and C_{cost} is the investment cost of the communication planning.

E. Objective Function and Constraints

1) Objective Function 1

The optimal number of base stations for the communication planning of the distribution network is calculated, as:

$$f_1 = \omega_1 S_{\text{station}} + \omega_2(\mu_b + \mu_{\text{Device}}) + \omega_3 C_{\text{Struction}} \tag{48}$$

where ω_1 is the weight corresponding to the coverage index; ω_2 is the corresponding weight of the capacity index; and ω_3 is the corresponding weight of the initial construction index.

The constraints of objective function 1 are:

$$\text{s.t.}\begin{cases} S_{\text{station}} \geqslant S_{\text{N}}, \eta_{\text{b}} < 0.9 \\ \eta_{\text{Device}} < 1, C_{\text{Struction}} \leqslant C_{\text{N}} \end{cases} \tag{49}$$

where S_{N} is the actual area of the distribution network and C_{N} is the investment budget for the communication planning of the distribution network.

The adaptive particle swarm algorithm is used to solve (48), and to obtain the optimal number of base stations in the two communication modes.

Using the K-means clustering algorithm, the number of base stations is used as the number of clusters to cluster the distribution network nodes to obtain the installation location of base stations.

2) Objective Function 2

The cost of communication planning is calculated as:

$$f_2 = C_{\text{Invest}} + C_{\text{5G/4G}} - E_{\text{Benefit}} \tag{50}$$

By calculating (50), the investment costs of 5G and 4G communication planning are obtained.

3) Objective Function 3

Using (41), (46) and (47), the objective function 3 for the economic evaluation of communication planning is constructed as:

$$f_3 = \eta_{\text{Tech}} + \eta_{\text{Eff}} + \eta_{\text{Reliable}} \tag{51}$$

The constraint conditions of objective function 3 are:

$$\text{s.t.}\begin{cases} \eta_b < 0.9, \eta_{\text{Wide}} > 0.9 \\ \eta_{\text{Device}} < 1, D_{\text{Loss}} < 0.001 \\ \eta_{\text{Relay}} > 0.9 \end{cases} \tag{52}$$

In the scenarios of two communication modes, considering the constraints of (52), equation (51) is solved, and the economic evaluation results for 5G and 4G planning of the distribution network are obtained.

IV. Evaluation Process and Method

This paper uses the adaptive particle swarm optimization (APSO) and K-means clustering algorithms to obtain optimal solutions. The unified particle swarm algorithm can easily fall into a local optimum, but the APSO algorithm achieves the goal of global optimization through adaptive inertial weights. K-means is an iterative clustering algorithm that can set the clusters number. Our economic evaluation process of the planning for the distribution network is shown in Fig. 4.

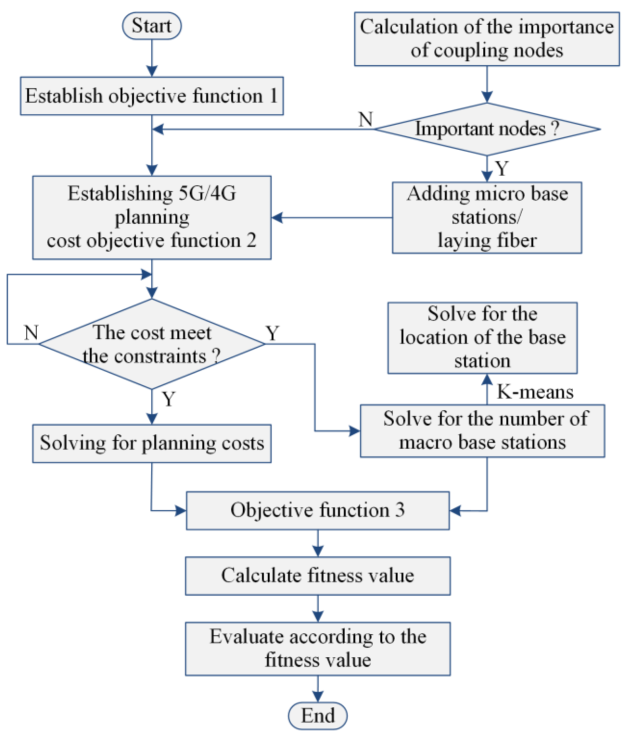

Fig. 4. Economic evaluation process for 5G planning.

V. Case Analysis

A. Simulation Parameter Setting

We use the IEEE 123-node distribution network as an example for simulation. The topological structure is shown in Fig. 5.

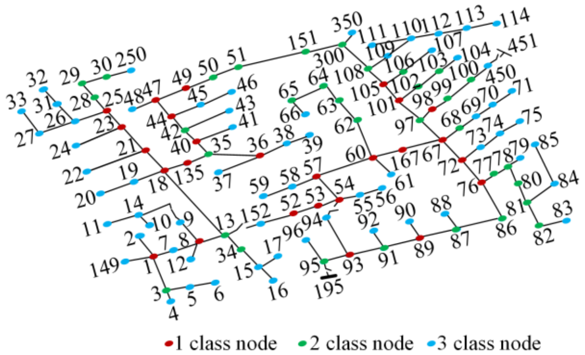

Fig. 5. The topological structure of the IEEE123-node network.

1 class nodes represent the first-level, 2 class nodes represent the second-level, and 3 class nodes represent the third-level loads in the distribution network.

The coverage radius of 5G and 4G base stations in city and town scenarios is shown in Table II.

TABLE II
The Coverage Radius of 5G and 4G Base Stations

Scenarios	Base stations	Covering radius (m)
City	5G	500
	4G	800
Town	5G	800
	4G	1200

For the installation of the base stations, the distributed installation method is adopted, and the AAU and BBU of 5G are installed separately. The BBU is concentrated in the computer room, while the AAU is installed on the communication tower. The way to install 4G equipment is the same as that for 5G. The cost parameter is shown in Table III (Notes: 10 k means 10 000 CNY).

TABLE III
The Cost Parameters of 5G and 4G Equipment

Project	Equipment (10k/piece)	C_p (10k)	Band lease (10k/year)	Lease time (year)	Tower (10k/piece)
5G	30	10	30	1–10	5
4G	12	8	10	1–10	5

Notes: Optical cable cost is 40 000 ¥/km, per optical line terminal is ¥ 200 000, per optical network unit is ¥ 2500. C_p is the computer room construction cost.

B. Simulation Results

1) Base Station Distribution Results

To establish the objective function, existing research primarily uses swarm intelligence optimization algorithms, such as particle swarm and genetic algorithms [37]. However, these traditional algorithms have the disadvantage of easily converging to local optima. Thus, this paper uses an adaptive particle swarm optimization algorithm with adaptive adjustment of iterative weights to improve global optimization capabilities and to obtain the optimal solution.

From the coverage radius of 5G and 4G in the 2 scenarios, Fig. 6 compares the convergence performance of a genetic algorithm (GA), traditional particle swarm optimization (PSO) and adaptive particle swarm algorithm (APSO) on the computation of objective function 1. The performance of the three algorithms is further compared in Table IV. From the results presented in Fig. 6 and Table IV, it can be seen that APSO has good convergence performance and operational speed. Thus, APSO is used in this paper to determine objective function 1.

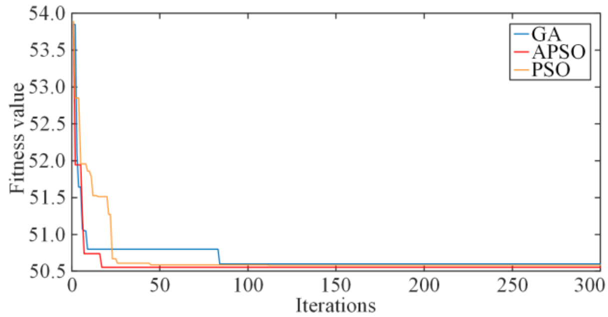

Fig. 6. Comparison of algorithm convergence.

The optimal numbers of base stations of 5G and 4G are obtained, as shown in Table V.

TABLE IV
Comparison of Iterative Time and Elapsed Time

Algorithm	Iterative time for convergence	Elapsed time (s)
GA	82	24.43
PSO	21	15.62
APSO	16	11.24

TABLE V
Base Stations Number in Each Scenario

Scenarios	Way of communication	Number of computer rooms	Number of base stations
City	5G	4	16
	4G	2	6
Town	5G	2	6
	4G	2	3

For the deployment of 5G base stations, existing research typically assumes that the deployment of 5G base stations is evenly distributed. However, in real life, the deployment of 5G base stations is often related to the geographical distribution of communication nodes. The more concentrated the distribution of communication nodes, the more concentrated the deployment of 5G base stations. In view of this, this paper adopts the idea of node clustering and uses K-means clustering to reasonably select the number of clusters of communication nodes. To associate the deployment of 5G base stations with the distribution of communication nodes, for the selection of the number of clusters, the optimized number of base stations is used as the number of clusters for the K-means algorithm.

After the number of base stations is obtained, it is used as the clustering number of K-means, so as to cluster the nodes of the distribution network. Each cluster center after the clustering is taken as the base station installation position in the corresponding communication mode.

Figures 7 and 8 show the schematic diagrams of the results after K-means clustering and using each cluster center as the distribution location of the base station. Figs. 7(a) and 7(b) are the distribution locations of 5G and 4G base stations in the city scenario, respectively. From the distributions, it can be seen that the base station signals cover all the grid nodes in the calculation example. In the city scenario, several factors, such as a large amount of data of power service terminals and the number of power services, need to be considered. To ensure the reliability of terminal service signal transmission within the coverage area of the base station, it is desirable to use a smaller coverage radius when optimizing the number of base stations.

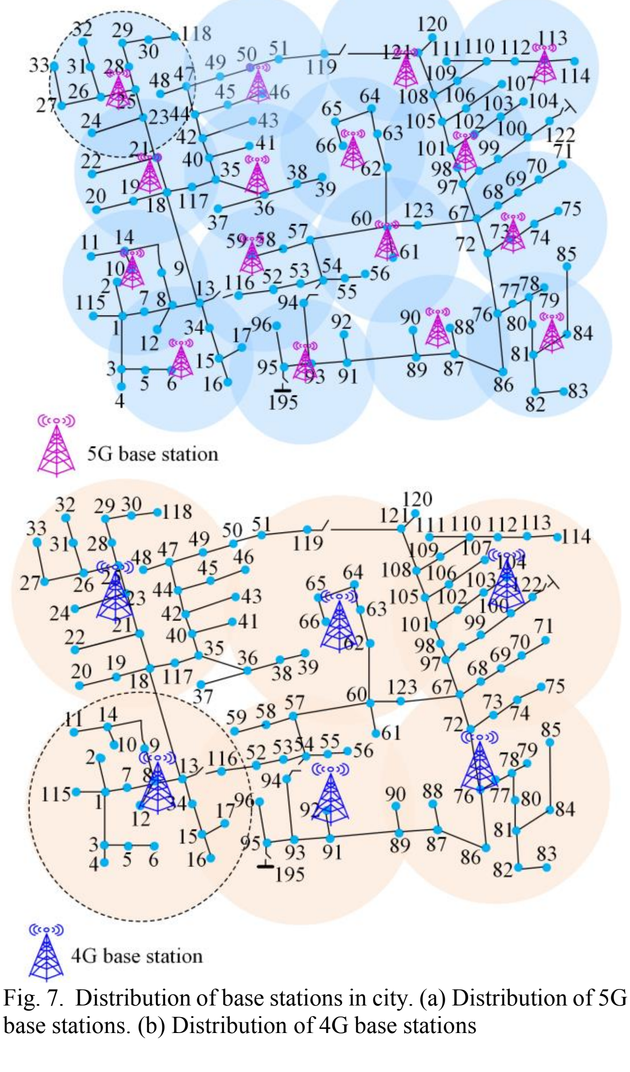

Fig. 7. Distribution of base stations in city. (a) Distribution of 5G base stations. (b) Distribution of 4G base stations

Figure 8 shows the location distributions of 5G and 4G base stations in the town. It can be seen that the base station signal covers most of the grid nodes in the distribution network. In the town, the number of terminals and communication traffic is smaller than those in the city. Therefore, when optimizing the number of base stations, the coverage radius of the base station is larger than that in the city. The number of base stations finally obtained is small and the locations are scattered. This ensures that the communication base stations can better cover the nodes and terminals of the distribution network.

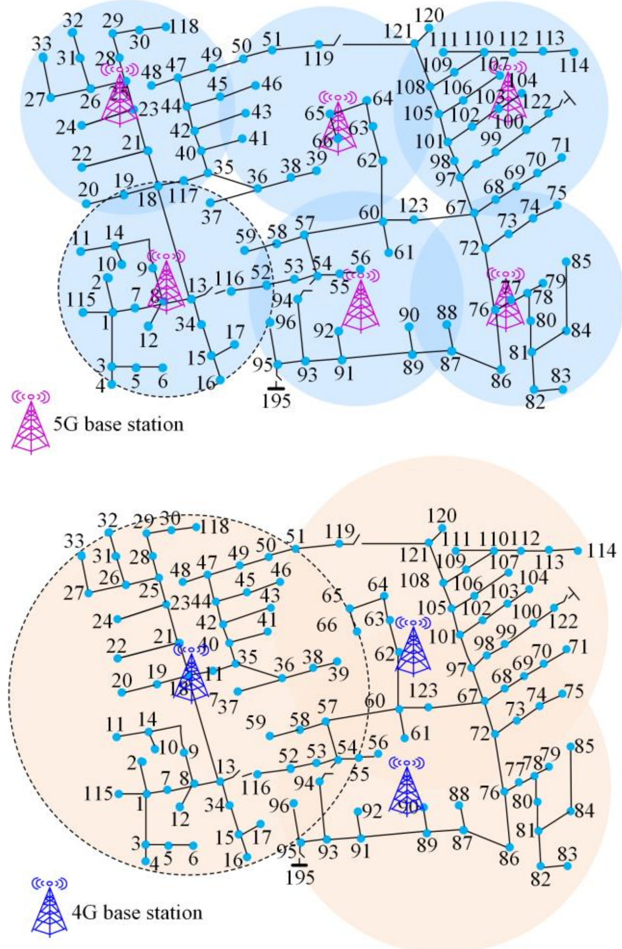

Fig. 8. Distribution of base stations in towns. (a) Distribution of 5G base stations. (b) Distribution of 4G base stations.

2) Quantitative Results of the Coupling Degree

The results of solving ρ_{D}, ρ_{B} and ρ_{c} using the modified Pearson correlation coefficients are shown in Table VI.

TABLE VI
CORRESPONDING WEIGHT AND RESULTS

Parameter	ρ_{D}	ρ_{B}	ρ_{c}
Weights W	0.2920	0.4633	0.2450
Value	0.7153	0.8243	0.7153

Then, the quantification results of the coupling degree ρ are obtained as:

$$\rho = W_{\rho_D}\rho_D + W_{\rho_B}\rho_B + W_{\rho_c}\rho_c = 0.766 \tag{53}$$

As $\rho = 0.766 > 0.7$, it can be judged that there is a strong coupling between the distribution network and the communication network.

3) Node Importance Calculation Results

Connectivity L: The average efficiency value $L_i/(n-1)$ of each point in the distribution network is shown in Fig. 9. The connectivity of the distribution network works out to be $L = 2.0246$.

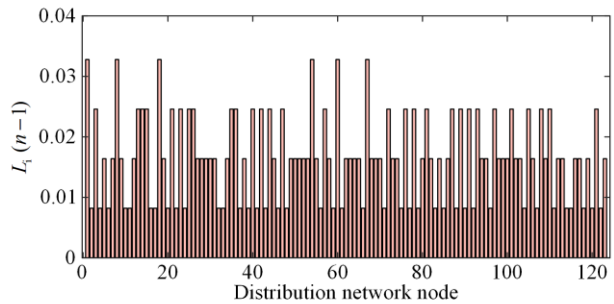

Fig. 9. The result of $L_i/(n-1)$.

Topological entropy E: The node degree of each node in the distribution network is shown in Fig.10. The topological entropy is calculated using (13) as $E = 4.7154$. The results of various parameters of energy flow are shown in Table VII.

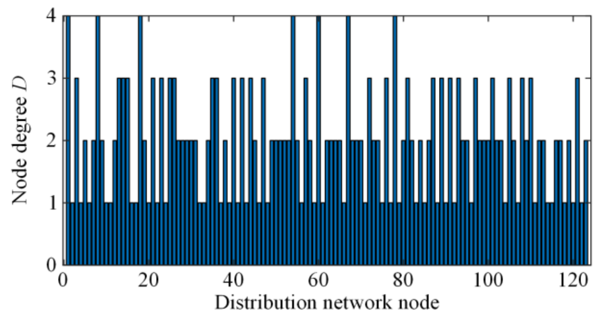

Fig. 10. Node degrees of each node in the distribution network.

TABLE VII
PARAMETERS OF ENERGY FLOW

Index	Result
Connectivity L	2.0246
Topological entropy E	4.7154
Load importance T	0.4862

The scores for the 5 distribution network communication services are shown in Table VIII, where 1) is load control, 2) is distribution automation, 3) is intelligent inspection, 4) is distributed energy resource storage, and 5) is power consumption information collection. The information flow score of each grid node is then obtained as shown in Fig. 11 (normalized results).

TABLE VIII
THE SCORE OF COMMUNICATION SERVICES

Communication services	Score
1)	0.8
2)	1
3)	0.6
4)	0.6
5)	0.4

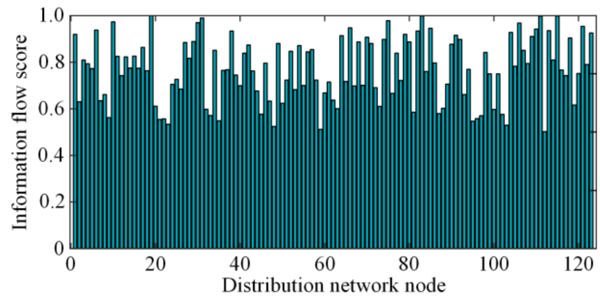

Fig. 11. The score of information flow.

Through the energy flow and information flow scores, the distribution network node importance results are shown in Fig. 12. As shown, the coupled network nodes with node importance greater than 0.7 are regarded as the important nodes.

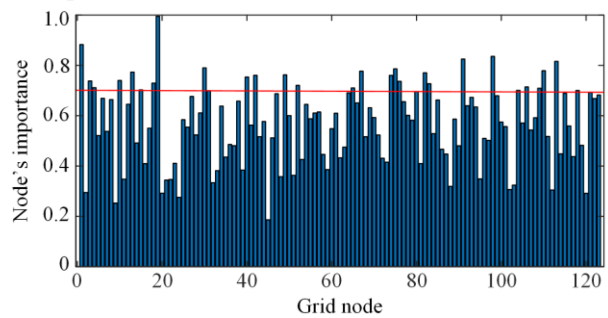

Fig. 12. Node importance results of each node in the coupled network.

As shown in Fig. 13, for the important nodes, various measures are taken at the communication level to improve the reliability of the coupled distribution network.

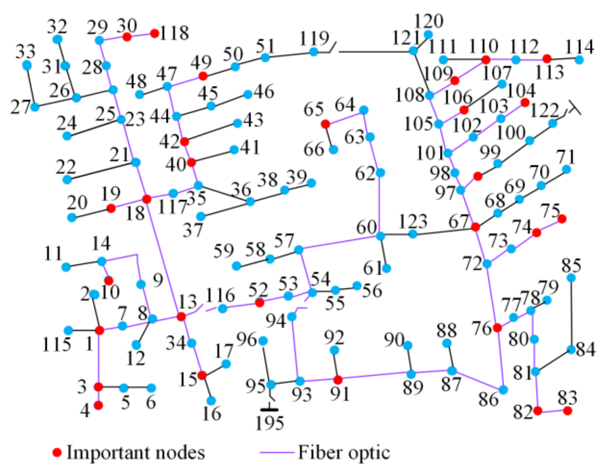

Fig. 13. Important nodes in coupling networks.

In the 5G scenario, micro base stations are added to nodes with node importance greater than 0.7. In the 4G scenario, nodes with node importance of more than 0.7 lay optical fibers to improve node reliability. The specific laying positions are shown in the purple lines in Fig. 13.

4) Calculation Result of Planning Cost

The objective function 2 is solved to obtain the planning costs of 5G and 4G over 10 years, as shown in Fig. 14, where the unit is ¥ 10 000.

Figure 14(a) is the line chart of the cost of distribution network communication planning over 10 years in the city scenario. Since the cost of 5G macro base stations is higher than that of 4G, and the number of 5G base stations optimized in the city scenario is also more than the number of 4G, in the first few years of planning, the planning cost of 5G is higher than that of 4G. However, as time increases, the benefits of 5G communication are gradually reflected so that the 5G planning cost is lower than the 4G planning cost.

Figure 14(b) is the line chart of the cost for distribution network communication planning over 10 years in the town scenario. In this scenario, the number of macro base stations is similar for both communication methods, while 4G communication requires additional fibre to ensure the communication reliability of important nodes, making the planning cost of 4G higher than that of 5G communication.

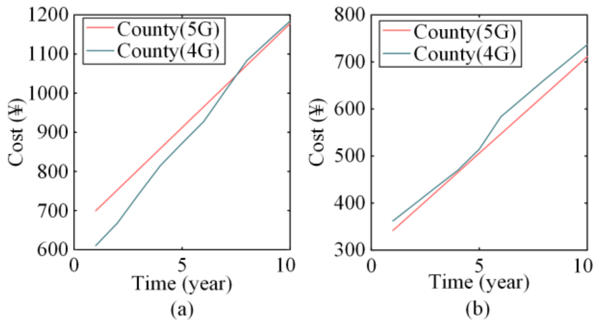

Fig. 14. The costs of communication planning in each scenario. (a) County communications planning. (b) Town communications planning.

5) Economic Evaluation of 5G and 4G

The obtained planning cost in objective function 2 is brought into the objective function 3. This is solved for the economic evaluation results of 5G and 4G communication planning in the distribution network, as shown in Fig. 15.

It can be seen that the economic performance of 5G in the distribution network is better than that of 4G communication, because the characteristics of 5G, such as large bandwidth, low latency and massive terminal access can be reflected considering the reliability and technical indices. These can be adapted to the service development of a smart distribution network. Because of the communication characteristics of 4G, it is difficult to meet the needs of the services for some intelligent distribution networks, such as large-bandwidth communication services and intelligent robot inspection. This makes it significantly inferior to 5G in terms of reliability and technology. At the same time, the cost has increased significantly considering the laying of optical fibres in the 4G scenario. In addition, the 4G communication revenue is low as are the efficiency index results, all of which ultimately make the economics of 4G worse than that of 5G.

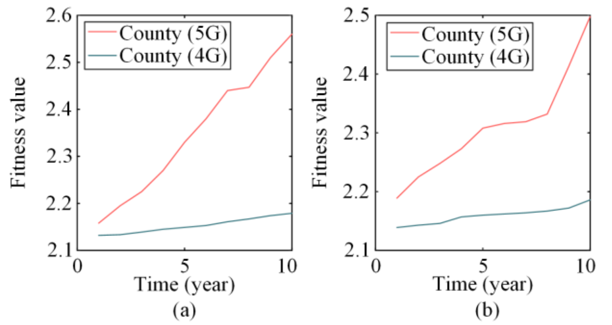

Fig. 15. The fitness value of communication planning in each scenario. (a) County scenario. (b) Town scenario.

VI. Conclusion

In this paper, a method for planning and economic evaluation of 5G communication in a distribution network is proposed, considering the degree of coupling between the two networks and identifying important nodes. The IEEE 123-node model is used as an arithmetic example for simulation calculation, and we can offer the following conclusions:

The coupling relationship between the distribution and communication networks often affects the planning of the communication network. Therefore, in the planning process of 5G, the coupling relationship should be included as an influencing factor. Comparing the planning costs of 5G and 4G in the distribution network, because of the large number of 5G base stations required and the high cost of individual base stations, its planning cost is higher than 4G in the following eight years. However, with the late-stage benefits and excellent communication performance of 5G planning, there is no need to add additional equipment to meet the rapid development of communication services in the distribution network. Therefore, after 8 years, its planning cost becomes lower than 4G. By establishing economic evaluation indicators such as reliability and efficiency, it can be concluded that the economy of 5G in the distribution network is significantly higher than 4G.

5G communications have better adaptability to the rapid development of the distribution network. From the economic evaluation of 5G and 4G in this paper, it can be seen that the application of 5G in the distribution network has very broad prospects.

Nevertheless, there are still some shortcomings in the research in this paper: in real life, differences in geographical location and building feature distribution between different areas cause certain transmission losses in base station signal transmission, resulting in differences in the coverage radius of base stations. In order to simplify the calculation in this paper, the impact of transmission loss of base station communication in the area is ignored, resulting in a certain error between the base station radius and the actual coverage radius of the base station. Therefore, in future research, we will consider the differences in communication propagation losses of base stations in different areas, to establish a more accurate 5G base station planning scheme for distribution networks.

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AUTHORS' CONTRIBUTIONS

Xiaowei Wang: conceptualization and methodology. Qiankun Kang: conceptualization, methodology, software, original draft, review & editing. Liang Guo: formal analysis, data curation, and visualization. Fan Zhang: data curation and visualization. Zhenfeng Liang: data curation and visualization. Jie Gao: data curation and visualization. Xue Wang: formal analysis and data curation. Weibo Liu: formal analysis and data curation.

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AVAILABILITY OF DATA AND MATERIALS

Not applicable.

DECLARATIONS

Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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