Routing Algorithm for Information Transmission in Neighborhood Area Network towards Smart Grid

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***Abstract*—Neighborhood area network is the most important part of smart grid communication system, where there is a variety of wired and wireless information transmission technologies to achieve information exchanged with other networks. Since Power Line Communications (PLC) technology is a natural candidate to build the neighborhood area network, we consider the use of PLC to connect network nodes (smart meters) through multi-hop transmission. In consideration of the strict requirements of transmission delay and packet-loss rate in smart grid, we proposed a hybrid multi-hop routing algorithm based on ant colony optimization and simulated annealing. Simulation results demonstrate that the hybrid algorithm can provide an optimal route in the neighborhood area network with delay and reliability guarantee compared with traditional ant colony algorithm.**

***Index Terms*—smart grid, neighborhood area network, routing, delay, packet-loss**

I. Introduction

New challenges are emerging in traditional power grid, e.g., rising demand, increasing greenhouse gas emission, and overload at peak hours etc. These challenges have become a global problem, so smart grid is widely considered to be the next generation of power grid [1]. The control, data acquisition, and power protection of smart grid require support of powerful communication technology, so establishing of the communication system is the first step towards smart grid.

The communication technology is one of the most critical elements that enable smart grid applications. In smart grid environment, a communication network can be represented by a multi-layer architecture. It is classified by data rate and coverage range, this architecture comprises as depicted in Fig. 1: Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN) [2], [3].

HAN is an essential component of the smart grid, providing demand response and management services [4], [5]. HAN applications include home automation and building automation, which are related to sending or receiving electrical measurement data from an appliance to a controller within a customer premises. Communication technologies that provide data rate up to 100 kbps with short coverage distance (up to 100m) are generally sufficient. The WAN provides communication links for smart grid backbones and covers long-haul distances from NAN to a control center [6]. For WAN applications, such as supports real-time monitoring, control and protection applications, which can help prevent cascading outages with real-time information related to the state of the power grid.

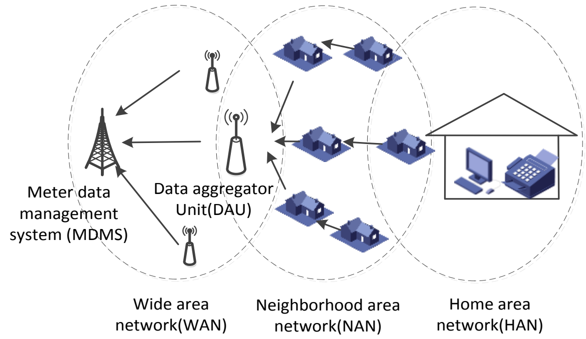

Figure 1. The smart grid communication network distribution.

NAN is responsible for smart meter interconnect, data exchanged between the end-user and Meter Data Management System (MDMS) in WAN [7[, [8]. According to the different network topology and the network communication technology, there may have hundreds of smart meters in every NAN. Due to NAN need to carry a lot of information, so it plays a highly important role in the smart grid communication network.

Since Power Line Communications (PLC) has an advantage over the other communication systems because power line infrastructures exist everywhere, communication through PLC enables distributed, efficient and economical power management in NAN. Because of the multihop characteristic in PLC, routing (from smart meters, sensors converge to a gateway node) is essential for information transmission [9], [10]. The requirements for reliability as well as latency in smart grid are summarized in Table I. Dynamic routing algorithm can be dynamically selected multi-hop routing, which can improve the reliability and delay requirements of the transmission data. Therefore, we use heuristic propose a new dynamic routing algorithm to guarantee real time and reliability in this paper.

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TABLE I. NAN APPLICATIONS IN SMART GRID

Table Head	***Application***	***Latency***	***Reliability (%)***
1	Meter reading from meters to utility	<15s	>98
2	Pricing from utility to meters	<1min	>98
3	Demand response from utility to customer devices	<1min	>99.5
4	Outage and Restoration management	<20s	>98

II. SYSTEM TOPOLOGY STRUCTURE AND COMMUNICATION REQUIREMENTS

A. Topology Structure

In the NAN with power line carrier system, the whole descending network line constitute concentrator and a certain number of meters; we focus on the concentrator as a gateway and each meter as communication terminal node in the logical topology structure. Due to the interference of the low voltage power line, the signal attenuation and load join and withdraw; it makes the signal transmission distance in power line not ideal, some node will not communicate directly with the gateway node. In order to establish the whole NAN communication topology and make sure that concentrator can communicate with each meter, we must set up the communication route between some meters and concentrator, which is relay nodes for data transmitting, expanding communication distance. Then all meter nodes may connect to power line communication network, achieving the purpose of timely and reliable data transmission.

We consider a simplified system topology for NAN between the concentrator and meters as shown in Fig. 2, in which smart meters can be viewed as the nodes in NAN topology structure. This example network will also be considered for numerical results in Section IV. Simulation experiment in the area of 100*100, where consists of 50 randomly distributed nodes connected via power lines. The nodes labeled 50 represent the concentrator, the other distributed nodes 1-49 represent ordinary nodes in the network.

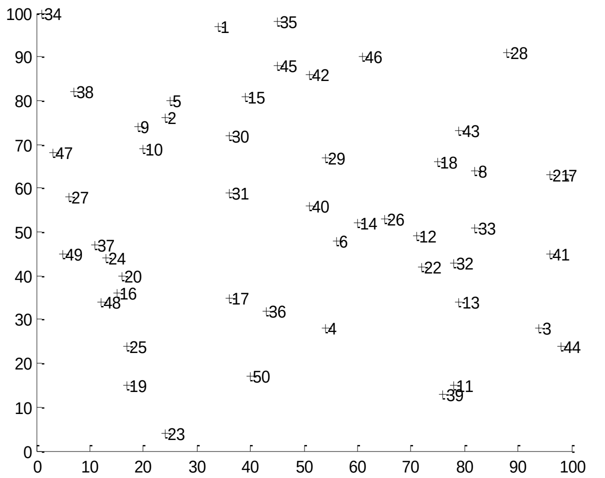

Figure 2. Network topology.

Since node locations are absolutely static, every node can connected with other node in its effective communication distance. According to the distance between the nodes, connection matrix is generated as:

$$A[i,j]=\begin{cases}1\ , & if\,(d_{ij}\le d)\\ \infty, & if\,(d_{ij}>d)\end{cases} \tag{1}$$

d_{ij} denotes the distance between the *i*th node and the *j*th node, d denotes an effective communication distance.

B. Communication Requirements

The NAN communication infrastructure has to be robust enough to accept inputs from the user of HAN and make it an integral part of the process. Meanwhile, the user must be capable of getting the appropriate level of information from the WAN through NAN. Therefore, the major requirements for NAN communication infrastructures affect the routing way of NAN, which are discussed in the rest of this section.

a) The communication topology dynamic change. The noises and load factors makes the communication logical topology time-varying, which require routing algorithm to adapt to these changes.

b) The real-time operational data communications in smart grid include online sensor/meter reading and power system control signals. The communication is characterized by the fact that most of interactions must take place in real time, with hard time bound. The communication requirements define the design of the technical solutions. For real-time transmitted information, it should be transmitted within a very short time frame.

c) Electrical power demand is random in nature, and the optimal power supply can be achieved only with the complete and timely power usage data. However, due to physical data transmission error or network congestion, data packet loss is inevitable. With data packet loss in the communications network used in NAN, the accuracy of estimation of electrical power demand deteriorates, which can result in more cost for the utility companies to supply power to the consumers.

Above all, the study of PLC-based NAN should resolve the multi-objective (reliability and latency) end-to-end QoS optimization problems in multi-hop transmission. To achieve the goal, a Dynamic routing algorithm aiming to minimize the delay and packet-loss rate is proposed, which can efficiently ensure the QoS requirements of NAN.

III. THE HYBRID ROUTING ALGORITHM

A. Ant Colony Algorithm

Ant colony algorithm is a heuristic algorithm [11], [12]. Supposing m is the number of ant colony. τ_{ij} is the residual amount of information in the sub road. When $t=0$, various concentrations of pheromone on the path are equal, $\tau_{ij}(0)=C$ (C is the constant). All the ants have been placed to the distribution node. In the course of the campaign, ant $k\,(k=1,2,\cdots,m)$ chooses the moving direction according to the amount of information on the various paths. P_{ij}^k is the probability that ant k moves from node i to node j.

$$P_{ij}^k = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^{\alpha} * \left[\eta_{ij}(t)\right]^{\beta}}{\sum\limits_{s \in allow_k} \left[\tau_{is}(t)\right]^{\alpha} * \left[\eta_{is}(t)\right]^{\beta}}, & s \in allow_k \\ 0 \qquad , & s \notin allow_k \end{cases} \quad (2)$$

The natural ant colony is different from the artificial ant that has a memory function. Set $tabu_k\left(k = 1, 2, \cdots, m\right)$ was utilized to record the current traversed nodes and dynamically adjusted by the process of evolution. η_{ij} is the heuristic function, which denotes the expectation of ant transferred from node i to node j. $allow_k\left(k = 1, 2, \cdots, m\right)$; denotes the nodes allow to be accessed of ant k. As time progresses, the element declining until empty, it means that all nodes have access to finish. α is the pheromone importance factor, the larger of the value, pheromone concentration play a greater role in metastasis. β is the heuristic function importance factor, the larger the value, heuristic function play a greater role in metastasis.

As time goes on, the previous pheromone left gradually decays. After the completion of a cycle, the pheromone was adjusted according to (3).

$$\begin{cases} \tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij} \\ \Delta\tau_{ij} = \sum\limits_{k=1}^{n} \Delta\tau_{ij}^k \end{cases}, \quad 0 < \rho < 1 \quad (3)$$

ρ denotes pheromone evaporation degree. Where, $\tau_{ij}(t+1)$ is the amount of pheromone on the path, $\Delta\tau_{ij}$ is the pheromone increment of this cycle path.

Ant cycle system model through the use of the whole path information (the total length of the path) calculate the degree of pheromone release [9]. In ant cycle system model, the formula is show as (4).

$$\Delta\tau_{ij}^k = \begin{cases} Q / L_k, & if\ ant\ k\ travel\left(i, j\right) in\ the\ circle \\ 0 \quad , & others \end{cases} \quad (4)$$

B. Simulated Annealing

Simulated annealing algorithm (SA) is a kind of heuristic random optimum algorithm [13]. It attempts to avoid being trapped in a local optimum by sometimes allowing the temporal acceptance of inferior solutions. The acceptance or rejection of an inferior solution is probabilistically determined by Metropolis and repeats sampling process with the temperature declining and finally gains the problem's global optimal solution.

The steps of the SA algorithm are illustrated as follow.

a) Initial solution: Select a initial state, the main control parameters need to be set are cooling rate k, the initial temperature T_0, the end temperature T_{end} and each iteration times M.

b) Generation a new solution: Perturb the current state ω randomly to generate a new solution ω'.

Metropolis criterion: Calculate the increment $\Delta f = f\left(\omega'\right) - f\left(\omega\right)$, $f\left(\omega\right)$ is the evaluation function.

$$P = \begin{cases} \exp\left(-\Delta f / T\right), & \Delta f < 0 \\ 1 \qquad , & \Delta f \ge 0 \end{cases} \quad (5)$$

If $\Delta f < 0$, accept the new path with probability 1, else accept the new path with probability P.

Cooling: Gradually reduce the temperature T by cooling rate i.e. $T = k * T$, make sure let the $T \to 0$, if $T < T_{end}$ then output the optimal solution, the program would be terminated.

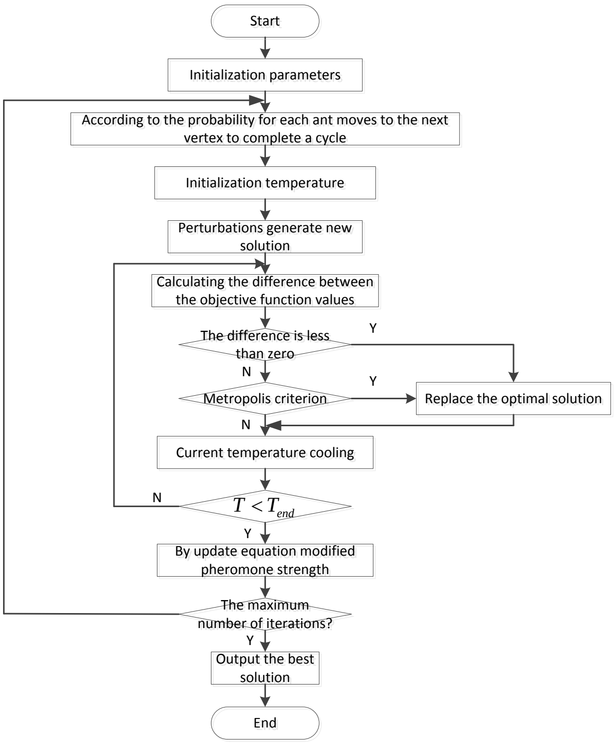

Figure 3. The flowchart of hybrid algorithm.

C. Hybrid Algorithm ACA-SA

As a result of the advantage and shortage of the ant colony algorithm and simulated annealing, ACA-SA hybrid algorithm is considered to utilize the advantages of two algorithms to optimize the control parameters of ant colony algorithm to solve these problems.

By analyzing the needs of neighborhood networks of different service types, focused on the delay and packet loss rate of the use path is designed to evaluate the function of the target, transmission delay and packet loss rate constraints included at the same time.

The time delay between source node s to the target node d as (6).

$$f_{delay}\left(Path\left(S, d\right)\right) = \sum delay\left(Path\left(s_i, d_j\right)\right) + \sum delay\left(s_i\right) \quad (6)$$

Packet loss rate between the source node s to the target node d as (7).

$$f_{packet\_loss}\left(Path\left(s, d\right)\right) = \prod\left(1 - \left(f_{packet\_loss}\left(Path\left(s_i, d_j\right)\right)\right)\right) \quad (7)$$

The routing algorithm objective function is defined as (8).

$$F\left(Path\left(s,d\right)\right)=\min[\alpha * f_{delay}\left(Path\left(s,d\right)\right)+ \beta * f_{packet\_loss}\left(Path\left(s,d\right)\right)] \quad (8)$$

St.

$$f_{delay}\left(Path\left(s,d\right)\right)\le D_{\max}, \quad D_{\max} \textit{ is the } \max \textit{ delay} \quad (9)$$

$$f_{packet\_loss}\left(Path\left(s,d\right)\right)\le L_{\max}, \quad L_{\max} \textit{ is the } \max \textit{ packet loss} \quad (10)$$

Among them $\alpha+\beta=1$, α and β is the proportion of time delay and reliability, which can change its size according to the different types of transmission services.

ACA-SA algorithm using ant colony algorithm to achieve precise searching local optima, and the global optimal judgment based on simulated annealing. The flowchart of hybrid algorithm is show in Fig. 3.

IV. Units Simulation Results

In order to verify the validity of the algorithm, this article through simulation experiment of three aspects, convergence performance, delay and bit error rate of the ACA-SA algorithm are analyzed and compared, then verify the performance of the proposed algorithm.

In the simulation experiment, parameters of the algorithm are ant colony size (the number of ants) $m=50$, pheromone importance factor $\alpha=6$, heuristic function importance factor $\beta=7$, pheromone evaporation factor $\rho=0.1$, pheromone total release $Q=50$, The maximum iterations $iter\_\max=100$, cooling rate $k=0.95$, the initial temperature $T_0=20$, end temperature $T_{end}=0.1\wedge 5$, each iteration times $M=20$.

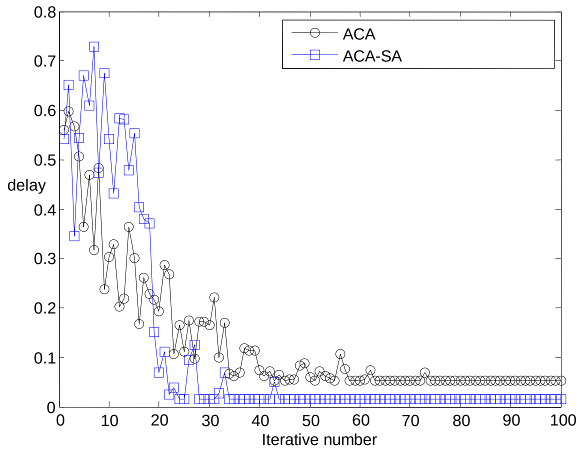

Figure 4. Comparison of delay.

Fig. 4 shows the path delay curve of ACA and ACA-SA algorithm. ACA-SA algorithm path delay is better than ACA algorithm, described ACA-SA convergence accuracy has been effectively improved. ACA-SA algorithm tends to converge at the 30th iteration, but the ACA algorithm tends to converge in 50 iterations, so its convergence rate than the ACA-SA algorithm significantly slower. During the first 20 iterations, ACA-SA algorithm converges much slower than ACA algorithm, this is because the ACA-SA algorithm can accept suboptimal solution with a certain probability to escape from local optima. ACA-SA algorithm can be seen with a smaller number of iterations to achieve higher accuracy and reduce the computational complexity of the system, while also bringing to improve the accuracy of the delay.

Fig. 5 is the comparison of packet-loss rate, through the comparison of the two curves we can know that the packet loss rate of two algorithms with the convergence of the algorithm tends to be stable. The rate of packet loss of the ACA-SA routing algorithm is relatively lower than ACA algorithm and convergence rate of the trend is relatively slow, this is because the ACA-SA algorithm can break out the local solution with a certain probability, expand the search space, and avoid the algorithm falling into local optimum prematurely. So it has better performance than ACA and has a lower packet loss rate.

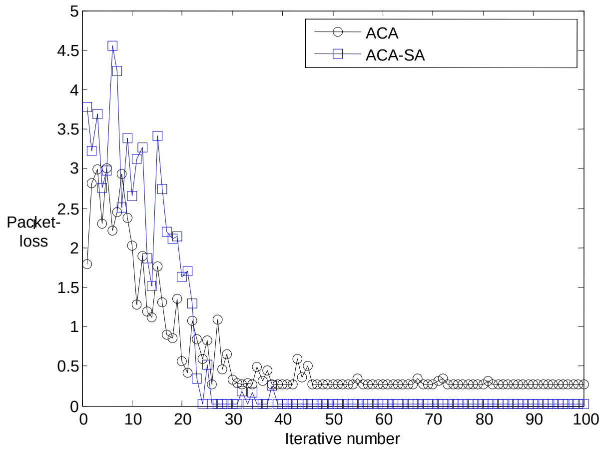

Figure 5. Comparison of packet-loss.

Fig. 6 shows the optimal path ACA-SA algorithm searched, which verify that the ACA-SA algorithm can be applied to the power line carrier communication network. The ACA-SA algorithm can find an effective communication routing and can converge to the optimal route, so simulation results proved the feasibility of ACA-SA dynamic routing algorithm.

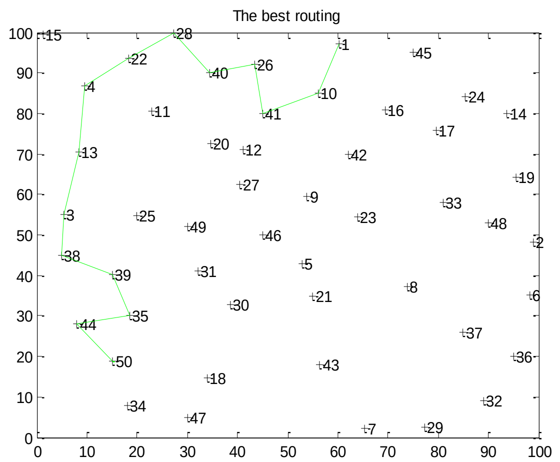

Figure 6. The best path of ACA-SA algorithm.

V. Conclusion

An effective hybrid Ant colony algorithm and Simulated Annealing is proposed to apply to find the optimal path. ACA-SA can effectively avoid convergence to local optimal solution and provide a new idea for solving complex combinatorial optimization problems. This paper completes find optimal routing problem by the ACA-SA algorithm. Simulation results show that the quality of optimization is superior to the ACA, including convergence performance, delay and bit error rate.

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