

An Automatic Networking and Routing Algorithm for Mesh Network in PLC System

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Abstract. Power line communication (PLC) is considered to be one of the best communication technologies in smart grid. However, the topology of low voltage distribution network is complex, meanwhile power line channel has characteristics of time varying and attenuation, which lead to the unreliability of power line communication. In this paper, an automatic networking and routing algorithm is introduced which can be adapted to the "blind state" topology. The results of simulation and test show that the scheme is feasible, the routing overhead is small, and the load balance performance is good, which can achieve the establishment and maintenance of network quickly and effectively. The scheme is of great significance to improve the reliability of PLC.

1. Introduction

Power line communications have great potential for smart grid services, as it uses the grids for the grid. The first smart grid deployment is more related to automatic metering infrastructure (AMI) network, where narrow-band PLC has played and been playing an important role. There are increasing need to build up reliable and low latency ICT network in MV/LV distribution network to support more advanced smart grid applications, such as distribution automation, control of renewable, control of electrical vehicles to grid and more. Power lines are everywhere in modern life, and they are used for communication almost without the need of daily maintenance and infrastructure investment [1]. However, the power line channel is not designed for signal transmitting [2]. Low voltage power line channel has problems like serious channel noise, frequency selective attenuation, load connection complexity and multipath effect, which leads to high bit error rate, low success rate, large signal attenuation and short transmission distance of power line communication, which seriously affects the reliability of the whole communication network [3-5]. The reliability of power line communication network has been one of key problems that hinder its wide application. Nowadays, the research on reliability of power line communication is mainly based on physical layer, LLC layer and network layer.

In this paper, we design an automatic networking and routing algorithm based on beacon frame. Also, we propose distributed routing algorithm to solve asymmetric channel problem. The rest of this paper is organized as follows. Section II analyses the topology of low voltage PLC network, and determined the necessity of automatic networking. Section III proposes an automatic networking algorithm based on beacon frame. Section IV proposes a distributed and symmetric multipath routing algorithm to improve the reliability and flexibility of PLC. Final remarks are presented in Section V.



2. Analysis of LVPLC topology

2.1. Physical topology structure of LVPLC

In this paper, the background of the application is low-voltage 48V/DC power line industrial field equipment monitoring system. Compared with the conventional centralized power line communication system [6], nodes of this system are equal and there is no master node. In order to facilitate the maintenance and management of the network, nodes connected to the power network through different channels need to logically select a master node, and the master node is also responsible for data interaction with the upper monitoring system. Various plant equipment are physically interconnected through power line, but because the signal transmission is affected by the transmission power, transmission distance, channel conditions and other factors, any two devices may be logically disconnected. At the same time, the topology of power line network may change at any time due to the uncertainties in the running state of the plant equipment (access, exit, shutdown and operation). On the other hand, load of access power network will bring noises, which affect channel environment and existing established logical communication link. Generally, the number of devices and the distribution of devices are unknown. Routing algorithm can adapt to the dynamic time-varying power line network, solve the problem of establishing and maintaining the unknown logical topology, logically choose master node to guarantee network integrity and connectivity.

2.2. Logical topology structure of LVPLC

At present, logical topologies of PLC networks mainly include non-overlapping cluster topology, overlapping cluster topology, layered artificial cobweb topology and clustering-cobweb hybrid topology [7-10]. However, these topologies cut the available communication links and discarded redundant communication links, failing to meet the reliability and flexibility requirements of communication networks. Therefore, this paper selects Mesh topology, and various logical topologies are shown in Fig.1. In Mesh topology, all nodes are equal and any node can join and leave the network at any time. Faults on nodes or links do not affect the operation of the entire network. In addition, each node has the function of routing and proxy forwarding, and only communicates with its neighbour nodes. It can be found that Mesh network is a self-organizing and self-managing network.

From Fig.1 we can see that non-overlapping cluster topology only has one communication link and communication is not reliable. Overlapping cluster topology increases the redundant communication link but loses horizontal communication routes. Clustering-cobweb hybrid topology is the combination of non-overlapping cluster topology and artificial cobweb topology. Although to some extent to avoid the shortcomings of the two, but loses vertical communication links. Only Mesh topology adds vertical and horizontal redundant routes, guarantee the integrity of the PLC network. However, Mesh network topology is too complex, which raises new challenges and requirements for network routing algorithm.

2.3. Reliability analysis of network models

The reliability of network topology is the basis for the design of networking and routing algorithm. It describes the connectivity of nodes and communication links. Analysis of the reliability of network topology is computing the probability of reliable communication between any two nodes in the network. That is, the probability that network topology remains connected when node or link is faulty.

2.3.1. Contribution rate of nodes to network reliability. Definition of invulnerability degree is the proportion of E_c (working links) in E_{all} (all links) after a node in the network fails. Simulation results are shown in Fig.2, the invulnerability degree of each node in different topology varies in the same trend. Mesh network topology has the highest invulnerability degree, while non-overlapping cluster topology with the lowest invulnerability degree.

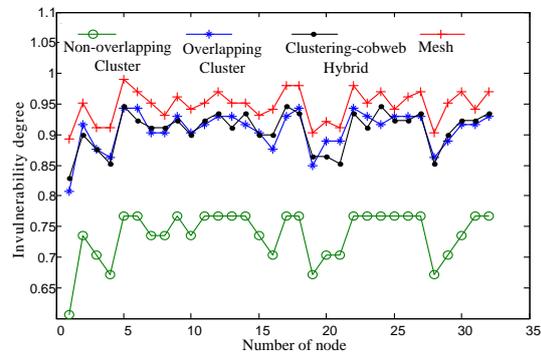
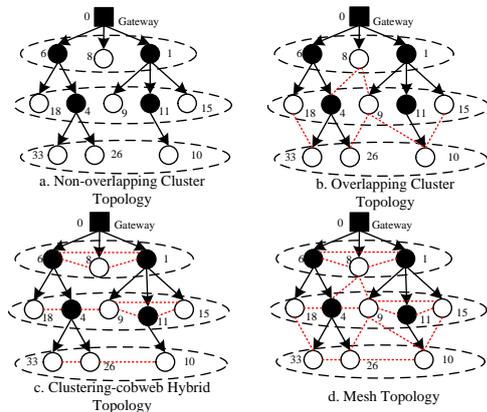


Figure 1. Logical topologies of LVPLC network **Figure 2.** Node invulnerability degree comparison

2.3.2. *Contribution rate of links to network reliability.* According to two-state Markov probability theory model [11], factorization method is used to analyze the influence of links on the reliability of the network. We theoretically analyze the full-end reliability of the network mentioned above. The theory calculation formula is shown as (1).

$$R_{ALL}(G, P_g) = P_g R(Ge) + (1 - P_g)R(G - e) \tag{1}$$

Where G is the topology of network; P_g is the probability that any two nodes in the network G can communicate with each other by link e , that is, the probability of channel in good state; $R_{ALL}(G, P_g)$ is the full-end reliability of network G , that is, the probability of reliable communication between any two nodes in the network; Ge is the topology of a new network obtained by combining two nodes connected by link e in the network G ; $G-e$ is the new network topology obtained by deleting link e . The full-end reliability of network is determined by the number of nodes and links in the network. To ensure the rationality of the reliability analysis results of different networks, the number of nodes in this paper is 32, and the above four network topologies are analysed respectively.

Simulation results are shown in Fig.3, we can clearly see that in the same link working state, the full-end reliability of Mesh network topology is much higher than other topologies. From node and link to the network reliability contribution rate aspect, Mesh network topology has obvious superiority in reliability aspect.

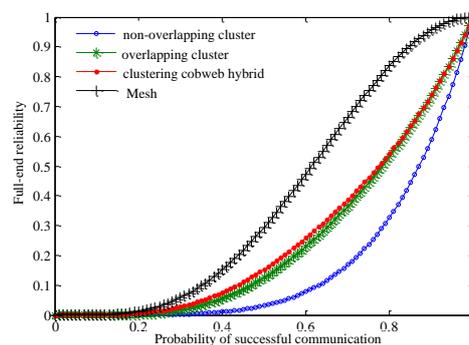


Figure 3. Simulation results of the full-end reliability

3. Automatic networking algorithm

3.1. Node state

In the process of networking, there are five kinds of node states, $INIT$, UC_STA , UC_CCO , C_STA , C_CCO . $INIT$ represents the initial state. All nodes are in initial state after powered on. UC_STA represents the slave node in uncoordinated state. The slave nodes haven't join the network are in

UC_STA state. *UC_CCO* represents the master node in uncoordinated state. Master nodes with no slave nodes are in *UC_CCO* state. *C_STA* represents the slave node in coordinated state. The slave nodes have joined the network are in *C_STA* state. *C_CCO* represents coordinated master node. Master nodes with slave nodes are in *C_CCO* state. In a stable network, all nodes are in *C_STA* or *C_CCO* state.

3.2. Master node selection algorithm

In order to facilitate the management and maintenance of the network, a node is selected as the master node to manage and maintain the reliable operation of the network. For a newly powered on node, it is necessary to know whether there is a communication network in the area, and whether all the nodes in the area are powered on at the same time, and whether it can become the master node of the area. In the process of master node selection, node state transition is shown as Fig.4.

- After powered on, node keeps silent for a period of time. During the silence period, it can only listen to the channel but can't send any frames. The length of the silence period is determined by beacon period, at which time the node state is *INIT*.
- In the silence period, if there is a communication listened by the node, that indicates a network exists. The node should exit the master node selection process, and wait for the reception of the beacon frame and register to join the network. The node state switches to *UC_STA*
- In the silence period, if there is no communication listened by the node, the node sends master node beacon frame and switches to *UC_CCO*.
- For a node in *UC_CCO* state, if there are other nodes registering to join the network in a certain period of time, the node becomes the master node and the node state switches to *C_CCO*. The nodes joining the network switch to *C_STA* and begin networking process. The MAC address of the selected master node is used as the network identifier (NID).
- For the node in *UC_CCO* state, if no node registers to join its network for a certain period of time, it will exit the master node selection process, and the state will be switched to *INIT*.
- For the node in *C_STA* state, if there is no networking beacon frame received from local network within a certain period of time, the state will be switched to *UC_STA*.

After the completion of network constructing, there is only one master node in PLC network. But for PLC network, nodes are not concentrated, that means the physical distribution between the nodes are scattered, the distance is relatively far, or some channel status is not good. There are two or more master nodes in the networking process. How to make multiple master nodes converge to one master node becomes the key point, that is, network convergence. Whenever a node receives a beacon frame with a higher priority (smaller NID), the state switches to *UC_STA* and re-registers to the network.

3.3. Networking algorithm

Network constructing is the process that all nodes switch to *C_STA* state under master node's control. The flowchart of new node joining an existing network is shown in Fig.5. The formats of frames during the networking process are shown from Table I to Table IV respectively. TEI represents the logical address of node allocated by master node. Ability represents the role that node plays in the network, including master node, proxy node and terminal node.

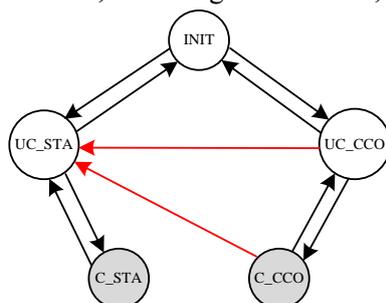


Figure 4. State transition

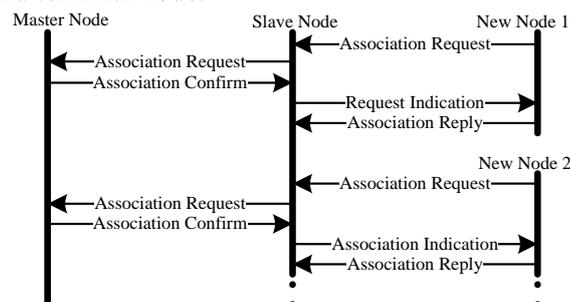


Figure 5. Flowchart of new node joining an existing network

Table I. Format of Association Request Frame

Field	Size(bit)	Definition
EX_TEI	16	Expected TEI
MAC_ADDR	48	MAC Address

Table II. Format of Association Indication Frame

Field	Size(bit)	Definition
TEI	16	TEI allocated by master node
CCO_TEI	16	TEI of master node
CCO_MAC	48	MAC Address of master node
Proxy_TEI	16	TEI of proxy node
Proxy_Level	8	Level of proxy node

Table III. Format of Association Reply Frame

Field	Size(bit)	Definition
TEI	12	TEI of local node
LEVEL	8	Level of local node
Ability	8	Ability of local node

Table IV. Format of Association Confirm Frame

Field	Size(bit)	Definition
TEI	12	TEI allocated by master node
CCO_TEI	12	TEI of master node
CCO_MAC	48	MAC address of master node

3.4. Simulation results

We select OMNeT++ as the platform of simulation, to verify the networking algorithm. The simulation parameters are shown in Table V.

Table V. Parameter Settings

Parameters	Value
Silent period (s)	5
Master node selection period (ms)	600
Time slot (ms)	200
Beacon period (s)	8
UC_STA to INIT period (ms)	25
UC_CCO to INIT period (ms)	50
C_STA to UC_STA period (ms)	25

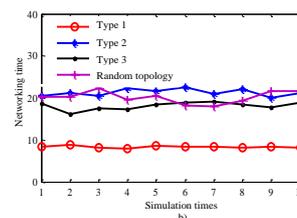
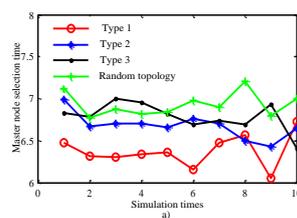
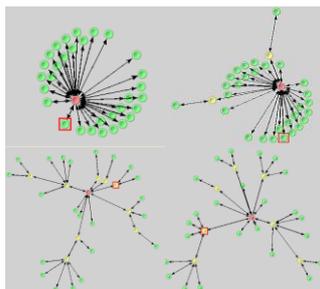


Figure 6. Networking simulation results

The simulation results of 32 nodes networking are shown in Fig.6. As shown in the figure, with networking algorithm proposed in this paper, all types of physical topologies can construct a stable network.

Master node selection time indicates the time when node in C_CCO state appears in the network, and the network construction time indicates the time when all nodes join the network. At the moment, there is only one master node in the network, and all nodes in this network are in C_CCO or C_STA state. As shown in the Fig.7, master node selection and network construction time are related to the physical topology.

Figure 7. a) Comparison of master node selection time, b) Comparison of network construction time**4. Distributed and symmetric multipath routing algorithm**

Conventional centralized management routing algorithm abandons the communication link redundancy, communication link has been cut, limiting the flexibility and reliability of data transmission. In addition, the existing routing algorithms are based on the premise that communication link is symmetric, without considering the problem of single-pass channel. This paper proposes a routing arbitration mechanism, which allows nodes to identify the communication link status and select the best communication link.

4.1. Routing table design

Routing table is established during the process that nodes join the network. The routing table needs to be updated and maintained when local nodes rejoin the network or neighbor node's state changes. The size of routing table is $(n-1)*14$ bytes, n represents the maximum number of nodes. The routing table format is shown as Table VI.

Table VI. Routing Table Format

Field	Definition	Size (bit)
ODTEI	TEI of destination node	16
Next_hop[6]	TEI of next_hop	6*16

ODTEI represents TEI of original destination node. Next_hop[6] restore the TEI of next hop to destination node, 6 routes at most. The routes restored in Next_hop[6] are classified by priority. In the process of communication, node selects the highest priority route. Only when this route fails or doesn't exist, node selects next route.

4.2. Routing arbitration mechanism

To avoid communication failure caused by single-pass channel problem, in this paper, we propose routing arbitration mechanism based on beacon frame and neighbour table. Neighbour table format is shown in Table VII.

Table VII. Neighbour Table Format

Field	Definition	Size (bit)
TEI	TEI of neighbour node	16
Level	Level of neighbour node	8
CM	Connection status	8

Each node in the network send beacon frame periodically. When local node receives beacon frame from other nodes, add their information to neighbour table. To estimate communication link status, beacon frame should contain TEI of neighbour node. For example, node A receives beacon frame from node B, which means the communication link from node B to node A is in good condition. But if the beacon frame doesn't contain TEI of node A, that means the communication link from node A to

node B is disconnected. Node A adds the link status to neighbour table. After two beacon periods, link from each node to its neighbour nodes can be known.

4.3. Route learning mechanism

Route learning mechanism is designed for establishing and maintaining routing table during communication process. Each node in the network start route learning when receives frame from other nodes. Route learning mechanism includes following situations:

- In the process of joining network, when a new node creates association request frame, set ODTEI and Next_hop to the TEI of proxy node.
- When master node receives association request frame of a certain node, it judges whether the proxy in the request frame is CCO. If yes, both ODTEI and Next_hop in the routing table are set as the TEI of the node. If not, ODTEI is set as the TEI of that node and Next_hop is set as STEI (Source TEI) in the association request frame.
- When proxy node receives association confirm frame, both ODTEI and Next_hop in the routing table are set as the TEI of the new node.
- When new node receives association indication frame, in routing table, ODTEI is set as the TEI of master node, and Next_hop is set as the STEI in association request frame.
- When local node receives beacon frame from other node, in routing table, ODTEI and Next_hop are set as the TEI of that node.
- When local node forwards the frame, in the routing table, ODTEI is set as the OSTEI in the transferred frame and Next_hop is set as the STEI in the transferred frame.
- When creating routes based on neighbour nodes, in routing table, ODTEI is set as the TEI of neighbour node in neighbour table and Next_hop is set as the TEI of neighbour node.

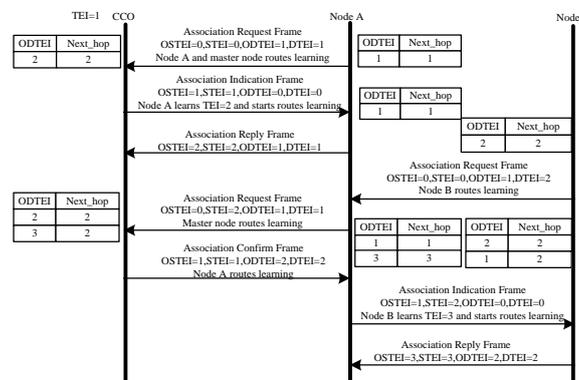


Figure 8. Route learning in the process of association

It can be found that the routing table is established by the route learning mechanism, mainly in the process of node association, beacon transmission, frame transfer, and neighbour table establishment and maintenance. Fig.8 shows route learning in the process of node joining network, and route learning of other process is similar.

In ideal conditions, local nodes restore at least one route to all the other nodes in the network to satisfy communication need. The first time that nodes belong to different clusters communicate with each other, there is no routing information restored in routing table. But there is routing information to master node restored in routing table, so the source node transmit data packet to master node.

4.4. Route selection mechanism

In a Mesh network, there are multiple communication links between two nodes. We can select symmetric links by routing arbitration mechanism. In order to improve communication efficiency, routes learned by route learning mechanism are prioritized, and the routes of higher priority are selected in the communication process.

The priority of route is based on source node level and destination node level.

- If the level of source node is lower than the level of destination node, that means the communication process of uplink. The lower the level of nodes stored in the routing table, the higher the priority is.
- If the level of source node is higher than the level of destination node, that means the communication process of downlink. The higher the level of nodes stored in the routing table, the higher the priority is.
- If the level of source node is equal to the level of destination node, that means the communication process of same level. If the level of nodes stored in the routing table is same as the level of source node or destination node, with the highest priority.

According to this priority division mechanism, in the communication process, it is easier to select a symmetrical communication link with fewer hops between nodes.

4.5. Routing maintenance mechanism

Routing maintenance is divided into two parts: time-driven and event-driven. Routes learned through route learning mechanism situation e) and g) are time-driven. The maintenance of such routes depends on beacon frame, and beacon frame transmission is cyclical and regular. Routes learned through route learning mechanism from situation a) to situation d) are event-driven. This kind of routes are essentially an on-demand routing mechanism, if and only if there are communication requirements between the nodes.

Route aging mechanism is that if a route stored in routing table is not used for a long period of time, it considers the route as a useless route. To avoid wasting the limited resources of routing table, the route is removed from routing table. Using above-mentioned mechanism, we can ensure that the routing information in routing table is always the best in current communication link and the network utilization is the highest.

4.6. Simulation Results

We select OMNeT++ as the simulation platform. According to the routing algorithm proposed in this paper, the routing information of all nodes in the network is obtained by simulation based on Mesh topology. The routing table information of part nodes is given here, as shown in Table VIII.

Table VIII. Routing Table of Part Nodes

	ODTEI	1	10	11	13
Node 1	—		3	2	2
Node 2	1 3		3 8	5 7	7
Node 3	1 2		10 9 8	7	7 9
Node 4	2		empty	5	empty
Next_	Node 5	2	empty	11 7	11 7
hop	Node 7	2 3	3 8 9	11 5 12 13	13 12 11 9
	Node 8	3 2	10 3 9	7	7 9
	Node10	3	—	empty	9
	Node11	7	empty	—	13 12 7

- Communication from master node to slave node, take node 1 and node 11 for example. From routing table of Node 1, we can find ODTEI=1, Next_hop [0] = 2. From routing table of Node 2, we can find ODTEI=1, Next_hop[0]=5, Next_hop[1]=7. Node 5 and Node 7 are in the same level, so they have the same priority. From routing table, we can find Node 5 and Node 7 are directly connected to Node 11. Therefore we can figure out two communication routes from master node to Node 11, 1-2-7-11 and 1-2-5-11 respectively.

- Communication from slave node to master node, take Node 7 and Node 1 for example. From routing table of Node 7, we can find ODTEI=1, Next_hop [0] = 2, Next_hop[1]=3. Node 2 and Node 3 are in same level, so they have the same priority. From routing table, we can find Node 2 and Node 3 are directly connected to master node. Therefore we can figure out two communication routes from Node 7 to Node 1, 7-3-1 and 7-2-1 respectively.
- Communication from one slave node to another slave node, take Node 4 and Node 13 for example. Referring to routing table of Node 4, we can find ODTEI=1, Next_hop[0]=2. According to routing algorithm, we can find when ODTEI=1, Next_hop[0]=2, so referring to routing table of Node 2, we can find ODTEI=13, Next_hop[0]=7. Referring to routing table of Node 7, we can find that it is directly connected to Node 13. Therefore, we can figure out the communication route from Node4 to Node 13, 4-2-7-13.

4.7. Performance analysis

As the size of the network increases, the size of routing table also increases. In address routing algorithm [12], each node in the network stores a routing table with a size of n bytes. In conventional centralized transmission matrix routing algorithm, master node stores routing table of all nodes, with a size of n^2 bytes. In the distributed multi-path symmetric routing algorithm, the routing table information is evenly distributed by each node, and the size is $15n$ bytes. The routing table overhead of three routing algorithms is shown in Fig.9, we can see that with the increase of n , the routing table overhead of centralized transmission matrix routing algorithm is much larger than that of distributed routing algorithm. The routing table in the distributed routing algorithm is managed and maintained by all nodes in the network. On one hand, it can avoid the shortcomings of centralized management flexibility and scalability. On the other hand, the routing overhead is greatly reduced and the hardware storage requirements are reduced.

Network load balance performance mainly refers to the degree of transmission congestion when data traffic increases in the channel. Good load balance performance refers to the number of proxy nodes in the network is large, and they can evenly share data traffic in the network. So as to avoid a large number of data concentrated in one or several proxy nodes, thus to some extent alleviate the transmission delay, packet collision and packet congestion.

We select Matlab as the platform of simulation. In 100m*100m area, we set the maximum communication distance as 20m, and simulate four kinds of logical topologies mentioned in sector one. The simulation results are shown in Fig.10.

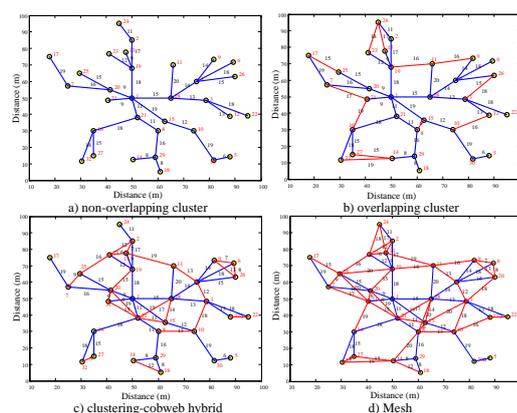
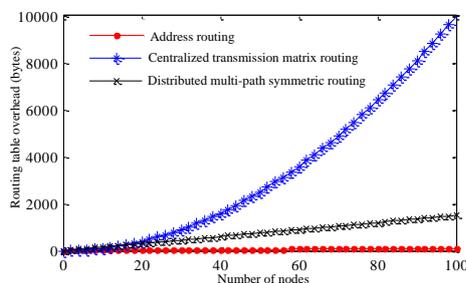


Figure 9. Routing table overhead comparison **Figure 10.** Logical topologies of PLC networking

According to four logical topologies shown in Fig.10, times of each node as proxy node in the network is counted and the number of proxy nodes is counted too. Finally the standard deviation is calculated. The smaller the standard deviation is, the better the load balance is. As can be seen from Fig.11, Mesh network topology load balance performance is the best.

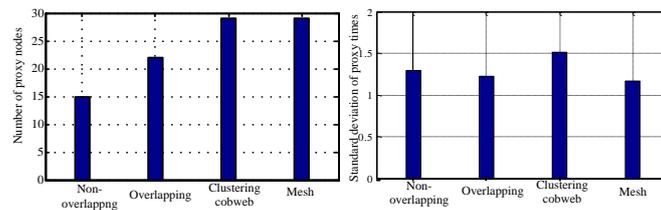


Figure 11. Load balance performance comparison

5. Conclusion

Based on the background of industrial field equipment monitoring system, this paper proposes a complete automatic networking algorithm based on beacon frame to improve the reliability of power line communication.

Firstly, the physical topology and logical topology of low voltage DC power line network are compared. From node invulnerability and link invulnerability points, we verify the superiority of Mesh network topology and confirm the necessity of automatic networking and distributed routing.

Secondly, automatic networking algorithm based on beacon frame is designed. Node automatically joins the network after powered on, and maintains the integrity of network automatically under the coordination of master node. The simulation results show that the networking process can be completed in 30 seconds for the topology with 32 nodes.

Finally, a distributed multipath symmetric routing algorithm is designed to guarantee the validity of the algorithm through routing arbitration mechanism, route learning mechanism and route selection mechanism. At the same time, the algorithm proposed in this paper is compared with conventional routing algorithms from routing table overhead and load balance aspects. Simulation results show that routing table overhead of the proposed routing algorithm is small, load balance performance is good.

Acknowledgments

This work is supported by National Nature Science Foundation of China (51677034).

References

- [1] S. Galli, A. Scaglione, Z. Wang, "For the Grid and Through the Grid: The Role of Power Line Communications and for the Grids", *Proceedings of the IEEE*, Vol. 99, No. 6, June 2011.
- [2] M.Babic, M.Hagenau, K. Dostert and J. Bausch, *Theoretical Postulation of PLC Channel Model*, European Union FP6 R&D Project OPERA1, Document D4, March 2005.
- [3] Yang Lu and Weilin Liu, "Spectrum Analyzer Based Measurement and Detection of MW/SW Broadcast Radios on Power Lines for Cognitive PLC", *Power Line Communications and Its Application (ISPLC)*, 2013 17th IEEE International Symposium on, pp. 103~108, 24~27 March 2013.
- [4] H.P. Widmer, etl. "Effect of Channel Characterisation on PHY", European Union FP6 R&D Project OPEAR1, Document D46, July 2004.
- [5] H.C. Ferreira, Lutz Lampe, John Newbury and Theo G. Swart, "Power Line Communications: Theory and Applications for Narrowband and Broadband Communications Over Power Lines", ISBN 978-0-470-74030-9, 2010.
- [6] Qi Jiajin, Liu Xiaosheng, Xu Dianguo. Simulation study on cluster-based routing algorithm and reconstruction method of power line communication over lower-voltage distribution[J]. *Proceedings of the CSEE*, 2008, 28(4): 65- 71.
- [7] Ran Qinghua, Wu Yucheng, Qi Meijuan. Research on automatic routing method of low-voltage power line carrier network[J]. *Power System Protection and Control*, 2011, 39(10): 53-58.
- [8] Liu Xiaosheng, Zhang Liang, Xu Dianguo. Networking algorithm and communication protocol of novel power line communication based on cobweb[J]. *Power System Protection and Control*, 2012, 40 (16):27-33.

- [9] Zhang L, Liu X, Zhou Y, et al. A Novel Routing Algorithm for Power Line Communication over a Low-voltage Distribution Network in a Smart Grid[J]. *Energies*, 2013, 6(3):1421-1438.
- [10] Liu Xiaosheng, Li Yanxiang, Wang Juan, Zhu Honglin, Xu Dianguo. Clustering-cobweb hybrid multipath blind routing algorithm and communication protocol design for low voltage power line communication[J]. *Transactions of China Electrotechnical Society*. 2015, (7):88-91.
- [11] Liu Xiaosheng, Zhang Liang, Zhou Yan. Reliability analysis of artificial cobweb structure for power-line communication of low-voltage distribution networks[J]. *Proceedings of the CSEE*, 2012, 32(28):142- 149.
- [12] Li Teng, Zhu Jinda, Jiang Yuanyuan. Prime based method for constructing power-line carrier communication networks in low voltage distribution networks[J]. *Automation of Electric Power Systems*, 2014, 38(24): 73-79