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RESEARCH ARTICLE

Information Fusion Method of Power Internet of Things Based on Low-Voltage Power Line and Micro-Power Wireless Communication

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ABSTRACT In order to improve the coverage and reliability of the information perception layer of the power Internet of things, a method of constructing a cross layer fusion network of low-voltage power line and micro-power wireless communication (CPW) is proposed. Firstly, a unified medium access control (MAC) layer model of CPW is established to provide basic support for realizing the integration of CPW network layers; then an improved ant colony algorithm combining Brownian motion and local convergence times control is proposed to complete the networking process of CPW; Distribute the sub-service flow of CPW, and propose the bit error rate requirement factor in the service distribution, and accomplish the cross-layer integration of low-voltage power line and micro-power wireless communication network. The simulation results show that the communication link service quality of the cross-layer fusion network is better than that of the power line and wireless dual-mode or cascaded communication networks. The communication efficiency of CPW is improved to 398.20kbit/s. The coverage of the power line and wireless communication fusion network can be expanded by setting corresponding bit error rate demand factors according to different services. It takes into account the balance of communication link quality and network load.

INDEX TERMS Power Internet of Things, low-voltage power line communication, micro-power wireless communication, cross-layer fusion.

I. INTRODUCTION

Building a widely interconnected power Internet of Things and deeply integrating it with a strong smart grid is an important measure to accomplish the energy Internet integration in the future [1], [2]. The basic guarantee factor for the construction of the power Internet of Things is the comprehensive perception and interconnection of information [3], [4], [5], which should have the characteristics of broad coverage [6], efficient transmission efficiency, and reliable communication quality assurance [7]. The microgrid can be monitored based on the wireless network, of which the estimated performance affected by the wireless network parameters [8].

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The power line communication (PLC) technology is an important communication method in the smart grid, and it is also an effective technical guarantee for realizing the future energy Internet integration. It is widely used in the fields of smart distribution network information collection, remote control and monitoring, but its communication quality is restricted by the complexity of the power line network environment [9], [10]. A cloud-edge collaborative control method based on edge computing is proposed [11]. It has good scalability and high flexibility in wireless communication, but factors such as building occlusion in the wireless communication environment will seriously affect its communication quality in Low-Voltage Networks [12], [13]. It achieves complementary advantages to combine the power line communication technology and wireless communication

technology [14], [15], and the close combination is conducive to ensuring the high coverage and reliability of the network. A new parent selection framework based on a multi-attribute decision-making approach and two new routing metrics were presented to address the single routing metric problem [16], [17].

The transmission media of low-voltage power line communication and wireless communication are different, and the signal frequency is quite different [18], [19], so it is difficult to accomplish the integration of the two at the physical layer. The technical and infrastructure advantages of power line and wireless hybrid communication systems over non-hybrid systems were discussed, and the impact of the environment on hybrid communication networks [20]. The dual interface relay module of power line communication and wireless communication were proposed to complete the integration of the two communication methods [21], and verifies that the capacity and reliability of the hybrid communication network are better than any single network [22]. A hybrid power line communication and wireless communication system were constructed, all nodes were equipped with power line communication and wireless functions [23]. The data information was transmitted in parallel on the power line communication and wireless two links, which reduced the probability of network interruption [24]. The wireless amplifying, forwarding relays and broadcasting information between relays were initialized and synchronized based on power line communication, which saved the overhead of communication between wireless relays [25], [26]. A virtual MAC layer for information perception and link selection decision were proposed to accomplish the integration of power line communication and wireless network [27]. The above research has achieved the integration of power line communication and wireless communication at someone layer, and its communication coverage and transmission efficiency are lower than 200kbit/s. Therefore, the power line communication MAC layer and the wireless communication MAC layer need to periodically report the channel state information to the virtual MAC layer, which increases a lot of signaling overhead and affects the communication efficiency of the network. There is still great potential to be tapped in reducing signaling overhead and improving communication network efficiency.

The CPW method is proposed for the information perception layer of the Internet of Things. Firstly, the topology structure of CPW and the principle of cross-layer fusion of low-voltage power line and micro-power wireless communication are analyzed. Three aspects of the MAC layer, network layer and business layer of CPW are considered to design the communication protocol, networking scheme and industry logistics distribution strategy of CPW, which accomplishes the deep integration of low-voltage power line and micro-power wireless communication. The example simulation based on MATLAB shows that the high coverage and reliability of network-level communication in the power Internet of Things can be ensured by the proposed method.

II. CROSS-LAYER FUSION METHOD OF LOW-VOLTAGE POWER LINE AND MICRO-POWER WIRELESS COMMUNICATION

A. MAC LAYER FUSION

The MAC layer communication protocol of CPW is designed based on the PRIME protocol of power line communication [28] and the IEEE802.15.4 standard of wireless communication [29]. Power IoT covers a large number of power equipment and sensor nodes, which can be connected to the network through low-voltage power lines and micro-power wireless communication [30], [31]. The effective transmission of CPW signals is ensured by establishing relay nodes. CPW is a star structure, using a hub or switch as the central node of the network. The nodes in the CPW are distributed in a star shape, and the core switch is called the central node. The MAC layer of CPW adopts carrier sense multiple access with collision avoid (CSMA/CA) and time division multiple access (TDMA) with collision avoidance, which can avoid transmission collision and improve communication reliability. It divides time into several beacon periods by CPW, and its specific time slot division is shown in Figure 1.

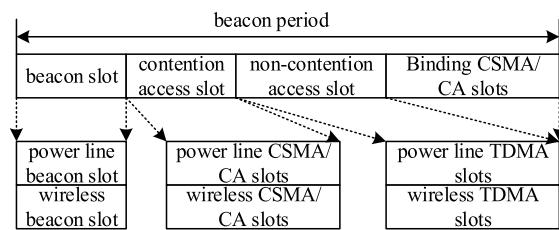


FIGURE 1. Schematic diagram of beacon period time slot division.

It can be seen that the beacon frame is sent from the beginning of the beacon period, and the synchronization of network time and information between nodes can be achieved by sending the networking beacon. In the competitive access time slot of the beacon period, the central node and other sub-nodes access the channel through the CSMA/CA mode to complete the CPW networking and data transmission. In the non-contention access time slot of the beacon period, the node accesses the channel through TDMA, and transmits a service with a selected priority. The nodes with certain special properties access the channel through competition in the bound CSMA/CA time slot. The beacon period for CPW medium and low voltage power line and micropower wireless communication has the same time slot division.

The optimal path networking method for CPW accomplishes the integration of low-voltage power line and micro-power wireless communication at the network layer, and the communication at the network layer must be supported by the MAC layer. The frame header and the frame end respectively identify the start and end of the data frame. The frame control code is used to identify the type of the data frame. The network type identifies the transmission network of the data frame. The source node and the destination node are the numbers of the data sending and receiving nodes respectively. The relay routing table records the number of

the relay node passed between the source node and the destination node. The bit error rate requirement factor represents the Quality of Service (QoS) requirement of the service. The data length and data fields are used to identify the information of the data to be sent. The cyclic redundancy check (CRC) check is responsible for checking all bytes of data.

B. NETWORK LAYER FUSION

1) CPW COMMUNICATION PATH QUALITY OF SERVICE PARAMETER SETTINGS

In order to improve the reliability of the communication between the central node and other sub-nodes, an optimal communication path between each sub-node and the central node is constructed. The parameters such as delay, communication rate and bit error rate are usually used to evaluate network performance in the communication network of CPW. There may be multiple relay nodes in the communication path from the source node to the destination node. The number of relay nodes is called routing hops. These factors determine whether the selected communication path is the optimal communication path. The communication network topology is represented by a graph using the knowledge of graph theory. The weights of its edge sets are the delay, bit error rate, communication rate and routing hops of the low-voltage power line communication link and the micro-power wireless communication link. Suppose a complete communication path is $R(v_s, v_d)$, there are n nodes in the path, the starting node is v_s . The destination node is v_d , then the service quality parameter of the communication path $R(v_s, v_d)$ is as formula (1) shown.

$$\begin{cases} D_N [R(v_s, v_d)] = \sum_{i=1}^{n-1} D_N(e_{i,j}) \\ E_N [R(v_s, v_d)] = 1 - \prod_{i=1}^{n-1} [1 - E_N(e_{i,j})] \\ B_N [R(v_s, v_d)] = \min \{B_N(e_{i,j})\} \\ H_N [R(v_s, v_d)] = n - 2 \\ s.t. \quad n \geq 2, N = P, W, C, j = i + 1 \end{cases} \quad (1)$$

where, when N is taken as P , W , and C , it corresponds to the low-voltage power line communication network, the micro-power wireless communication network, and the CPW, respectively. When $N = P$, $D_P[P_R(v_s, v_d)]$, $E_P[P_R(v_s, v_d)]$, $B_P[P_R(v_s, v_d)]$, $H_P[P_R(v_s, v_d)]$ are the delay, bit error rate, communication rate, routing hops of the communication path in the low-voltage power line communication network respectively. There, $D_P(e_{i,j})$, $E_P(e_{i,j})$, $B_P(e_{i,j})$ are the delay, bit error rate and communication rate of the medium and low voltage power line communication link of the edge $e_{i,j}$ weights respectively. When $N = W$ and $N = C$, the parameters are defined as above. The problem of choosing the best transmission path can be transformed into solving the subset E_0 based on the communication path evaluation function. E_0 is a subset of the optimal value of the objective function under the condition of satisfying certain parameter constraints.

2) OPTIMAL COMMUNICATION PATH MODEL IN CPW

The importance of each parameter cannot be directly reflected by the proportion coefficient due to the different units and magnitudes of the QoS parameters of the communication network. A method is proposed to balance the numerical differences between parameters to solve the problems above. The delay weight γ_d , bit error rate weight γ_e , bandwidth weight γ_b and routing hop weight γ_h are defined as shown in formula (2). The importance of each parameter can be intuitively reflected through a simple proportional coefficient.

$$\begin{cases} \gamma_d = \frac{2f_d}{\left[1 - (1 - E_{Cavg})^{H_{Cmax}/2} \right] B_{Cavg} H_{Cmax}} \\ \gamma_e = \frac{4f_e}{D_{Cavg} B_{Cavg} H_{Cmax}^2} \\ \gamma_b = \frac{4f_b}{D_{Cavg} \left[1 - (1 - E_{Cavg})^{H_{Cmax}/2} \right] H_{Cmax}^2} \\ \gamma_h = \frac{2f_h}{D_{Cavg} \left[1 - (1 - E_{Cavg})^{H_{Cmax}/2} \right] B_{Cavg} H_{Cmax}} \end{cases} \quad (2)$$

where, D_{Cavg} is the average delay between two nodes in CPW. E_{Cavg} is the average bit error rate between two nodes in CPW. B_{Cavg} is the average communication rate between two nodes in CPW. H_{Cmax} is the maximum communication path between two nodes in CPW routing hop count.

The equations (3) and (4) can be used to describe the problem of finding the optimal communication path from node v_s to v_d that satisfies the quality of service constraints based on the above analysis. It subjects to formula (4), while setting the minimum value of S_C .

$$\min \{S_C [R(v_s, v_d)]\} \quad v_s, \quad v_d \in V(G) \quad (3)$$

$$\text{s.t. } \begin{cases} D_C [R(v_s, v_d)] \leq D_{max} \\ E_C [R(v_s, v_d)] \leq E_{max} \\ B_C [R(v_s, v_d)] \geq B_{min} \\ H_C [R(v_s, v_d)] \leq H_{max} \end{cases} \quad (4)$$

where, D_{max} is the maximum delay of the communication path. E_{max} is the maximum bit error rate of the communication path. B_{min} is the minimum communication rate of the communication path. H_{max} is the maximum number of routing hops of the communication path. The optimal communication path between the central node and all other nodes is established, and a fusion network of low-voltage power line and micro-power wireless communication with the best communication quality is formed.

3) IMPROVED ANT COLONY ALGORITHM AND ITS PATH SEARCH METHOD

An improved ant colony algorithm controlled by Brownian motion and local convergence number is proposed to

solve the networking problems in cross-layer integration of low-voltage power line and micro-power wireless communication. In the ant colony algorithm with the maximum number of iterations T_{max} , if the same result occurs in consecutive iterations of T_{local} , the algorithm may be in a local convergence state, and T_{local} is called the number of local convergence in this paper. The influencing factors of Brownian motion of pheromone are defined as the number of iterations and local convergence times of ant colony algorithm. In the early stage of the algorithm, the update of ant colony pheromone is almost not affected by Brownian motion. With the increase of the number of iterations or the phenomenon of local convergence, the Brownian motion of pheromone is used to randomly adjust the pheromone distribution, which is beneficial to the algorithm to jump out of the local optimal solution and enhance its global search ability. When the number of iterations is large enough, the Brownian motion of the pheromone is weakened to speed up the convergence of the algorithm. The improved Ant colony algorithm controlled by Brownian motion and Local convergence number (ABL) combines Brownian motion and local convergence times to dynamically control the pheromone update of the path taken by the ant colony to improve the problem that the algorithm is prone to fall into local optimal solutions.

ABL adopts an optimization method similar to the ant colony algorithm. It selects the optimal path and updates the pheromone iteratively, and obtains the stable path with the largest pheromone concentration, which is the optimal path. The maximum communication distance between nodes and the constraints of service quality are combined to find n candidate nodes and calculate the probability of selecting each candidate node, as shown in equations (5) and (6).

$$\left\{ \begin{array}{ll} P(e_{i,j}) & \left\{ \begin{array}{l} \frac{(\tau(e_{i,j}))^\alpha (\eta(e_{i,j}))^\beta}{\sum_{j \in A_{select}} (\tau(e_{i,j}))^\alpha (\eta(e_{i,j}))^\beta} \quad j \in A_{select} \\ 0 \quad \quad \quad \quad \quad \quad \quad \quad \quad others \end{array} \right. \\ \eta(e_{i,j}) = \frac{f_{\eta_b} B_C(e_{i,j})}{f_{\eta_d} D_C(e_{i,j}) + f_{\eta_e} E_C(e_{i,j})} \end{array} \right. \quad (5)$$

$$\left\{ \begin{array}{l} f_{\eta_b} = \gamma_b D_{Cavg} E_{Cavg} \\ f_{\eta_d} = \gamma_d E_{Cavg} B_{Cavg} \\ f_{\eta_e} = \gamma_e D_{Cavg} B_{Cavg} \end{array} \right. \quad (6)$$

where, $P(e_{i,j})$ is the probability of node j being selected. $\tau(e_{i,j})$ is the concentration of pheromone on the path $e_{i,j}$. $\eta(e_{i,j})$ is the heuristic information on the path $e_{i,j}$. Where, α and β are the influence coefficient of pheromone and the influence coefficient of heuristic information respectively. A_{select} is the set of n nodes to be selected. It can be seen from equation (5) that the greater the pheromone concentration on the communication link and the better the communication service quality, the greater the probability of the node to be selected is selected. Taking the path cost function as the standard, the optimal path and the sub-optimal path are obtained by statistics, and the ants who walk through the optimal path release pheromone to enhance the probability

of the path being selected. The pheromone update of this positive feedback mechanism is as follows (7) shown.

$$\left\{ \begin{array}{l} \tau(v_s, v_d) = (1 - \rho) \tau(v_s, v_d) + \Delta \tau(v_s, v_d) \\ \Delta \tau(v_s, v_d) = \frac{Q}{S_C [R(v_s, v_d)]} \end{array} \right. \quad (7)$$

where, $\tau(v_s, v_d)$ is a vector, which contains the pheromone of the node passed by the optimal communication path. $\Delta \tau(v_s, v_d)$ is the pheromone variable. The ρ and Q are the volatility coefficient and intensity coefficient of the pheromone, respectively. The corresponding pheromone concentration becomes larger on the communication path with better communication quality after the pheromone update. The pheromone volatilization coefficient of the algorithm is adaptively adjusted according to the number of iterations and the number of local convergence, as shown in formula (8).

$$\rho = \left\{ \begin{array}{ll} \max \left\{ \rho_0 \sqrt{\frac{T_{local}}{T}}, \rho_{min} \right\} & 0 < T \leq \frac{T_{max}}{3} \\ \min \left\{ \frac{\rho_0 (T_{local} + T)}{T}, \rho_{max} \right\} & \frac{T_{max}}{3} < T \leq \frac{2T_{max}}{3} \\ \max \left\{ \frac{\rho_0 T_{local}}{T}, \rho_{min} \right\} & \frac{2T_{max}}{3} < T \leq T_{max} \end{array} \right. \quad (8)$$

where, T is the number of iterations. ρ_0 is the initial value of the pheromone volatilization coefficient. ρ_{min} and ρ_{max} are the minimum and maximum values of the pheromone volatilization coefficient, respectively. The pheromone volatilization coefficient is small in the early and late iteration of the algorithm,, which is conducive to the rapid convergence of the algorithm, and the pheromone volatilization coefficient is large in the middle of the iteration, which is conducive to enhancing the global search ability of the algorithm.

Let the optimal path taken by the ant be $R(v_s, v_d)$, and its pheromone vector be $\tau(v_s, v_d)$. The Brownian motion pheromone update for $\tau(v_s, v_d)$ is beneficial for ABL to jump out of the local optimal solution, as shown in equation (9).

$$\tau(v_s, v_d) = \left\{ \begin{array}{ll} \tau'(v_s, v_d) + \delta u(l) \sqrt{\frac{T_{local}}{T}} & 0 < T \leq \frac{T_{max}}{3} \\ \tau'(v_s, v_d) + \frac{\delta u(l) (T_{local} + T)}{T} \frac{T_{max}}{3} & \frac{T_{max}}{3} < T \leq \frac{2T_{max}}{3} \\ \tau'(v_s, v_d) + \frac{\delta u(l) T_{local}}{T} \frac{2T_{max}}{3} & \frac{2T_{max}}{3} < T \leq T_{max} \end{array} \right. \quad (9)$$

where, $\tau'(v_s, v_d)$ is the pheromone vector before updating. δ is the step size parameter of Brownian motion. $u(l)$ is a random number vector of length l , the elements of which conform to the standard normal distribution. The central node implements the above path search method for all other nodes, establishes the optimal communication path between each node and the central node, completes the networking process and dynamic maintenance of the CPW, that is, accomplishes

low-voltage power line and micro-power wireless communication at the network layer.

C. BUSINESS LAYER INTEGRATION

The low-voltage power lines have the same MAC layer protocol as micro-power wireless communications in CPW. The service data to be transmitted is divided into 2 sub-service flows at the source node, which are transmitted in two communication networks respectively, and the received sub-service flows are combined at the destination node. The data transmission between the source node and the destination node is completed based on the fusion network.

The sub-service flow distribution at the service layer of the CPW can accomplish the deep integration of the low-voltage power line and the micro-power wireless communication network, which is beneficial to accomplish the load balance between the low-voltage power line and the micro-power wireless communication. If the load difference between the two communication networks is too large, it may cause the problem of excessive data traffic and heavy network load on one of the communication networks, increasing the transmission delay. When the channel quality of a certain communication mode changes abruptly, it has a great impact on the overall communication quality of the hybrid network. Maintaining the load balance between the low-voltage power line and the micro-power wireless communication network can enhance the survivability of the hybrid communication network. The delay and communication rate of the communication link of converged network have been determined, and the allocation of sub-service flows is related to the bit error rate of the link. A service bit error rate (BER) requirement factor is proposed considering the load balancing between networks and the BER requirements of different services, which acts on the sub-service flow allocation process of the network service layer of CPW. It is assumed that each node can use power line communication and wireless communication, the service quality parameters between two adjacent nodes in the CPW are shown in formula (10).

$$\begin{aligned}
 D_C(e_{i,j}) &= \max\{D_P(e_{i,j}), D_W(e_{i,j})\} \\
 B_C(e_{i,j}) &= B_P(e_{i,j}) + B_W(e_{i,j}) \\
 E_C(e_{i,j}) &= E_X(e_{i,j}) C_X + E_Y(e_{i,j}) C_Y \\
 E_X(e_{i,j}) &= \min\{E_P(e_{i,j}), E_W(e_{i,j})\} \\
 E_Y(e_{i,j}) &= \max\{E_P(e_{i,j}), E_W(e_{i,j})\} \\
 C_X &= \frac{B_X(e_{i,j}) + B_Y(e_{i,j}) I}{B_X(e_{i,j}) + B_Y(e_{i,j})} \\
 C_Y &= \frac{B_Y(e_{i,j}) - B_X(e_{i,j}) I}{B_X(e_{i,j}) + B_Y(e_{i,j})} \\
 I_{max} &= \min \left\{ \frac{(B_X(e_{i,j}) + B_Y(e_{i,j}) - Z_b) B_X(e_{i,j})}{Z_b B_Y(e_{i,j})}, 1 \right\} \\
 0 < Z_b &\leq B_X(e_{i,j}) + B_Y(e_{i,j}) \\
 \begin{cases} X = P, Y = WEP(e_{i,j}) \leq E_W(e_{i,j}) \\ X = W, Y = PEP(e_{i,j}) > E_W(e_{i,j}) \end{cases}
 \end{aligned} \tag{10}$$

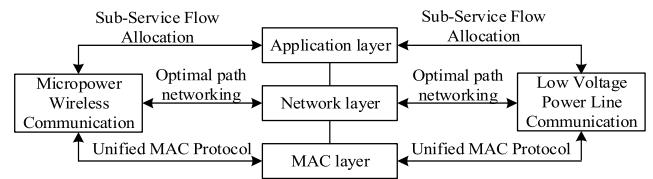


FIGURE 2. Schematic diagram of CPW.

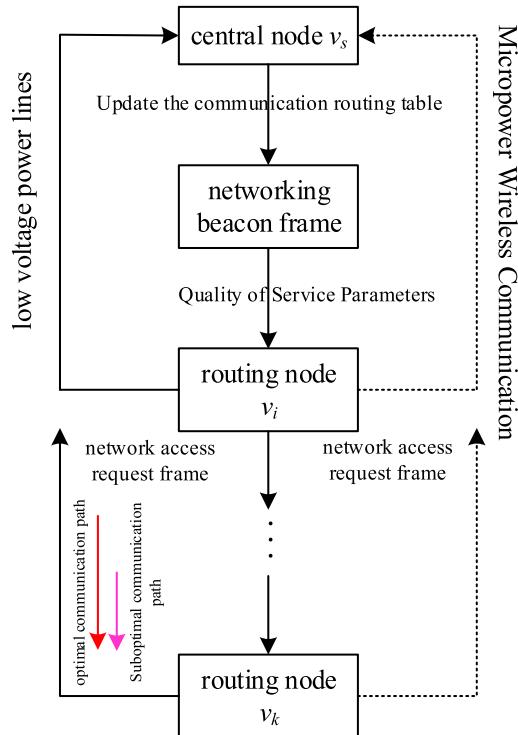


FIGURE 3. Cross-layer fusion process of CPW.

where, C_X and C_Y are the proportions of sub-service flows in communication network X and Y , respectively. $B_X(e_{i,j})$ and $B_Y(e_{i,j})$ are the communication rates of the communication networks X and Y at $e_{i,j}$, respectively. I_{max} is the maximum value of the bit error rate demand factor of service Z . Z_b is the communication rate required to transmit service Z . The BER demand factor of a service is related to the BER between CPW nodes and load balancing between networks. The corresponding BER demand factors can be set to improve user QoS requirements and load balance for services with different QoS requirements. The cross-layer fusion of low-voltage power line and micro-power wireless communication for the information perception layer of the Internet of Things is completed, which is shown in Figure 2.

III. CPW CROSS-LAYER FUSION DESIGN

The relay nodes are selected by ABL according to the pheromone concentration of the path between nodes during the networking process, and the optimal communication path is selected according to the cost function value. It is assumed that the communication node can perceive the channel state

TABLE 1. Routing table of power line communication.

| routing node | delay | bit error rate | communication rate |
|--------------|----------------|----------------|--------------------|
| v_1 | $D_P(e_{s,1})$ | $E_P(e_{s,1})$ | $B_P(e_{s,1})$ |
| v_2 | $D_P(e_{s,2})$ | $E_P(e_{s,2})$ | $B_P(e_{s,2})$ |
| \vdots | \vdots | \vdots | \vdots |
| v_k | $D_P(e_{s,k})$ | $E_P(e_{s,k})$ | $B_P(e_{s,k})$ |

TABLE 2. Routing table of wireless communication.

| routing node | delay | bit error rate | communication rate |
|--------------|----------------|----------------|--------------------|
| v_1 | $D_W(e_{s,1})$ | $E_W(e_{s,1})$ | $B_W(e_{s,1})$ |
| v_2 | $D_W(e_{s,2})$ | $E_W(e_{s,2})$ | $B_W(e_{s,2})$ |
| \vdots | \vdots | \vdots | \vdots |
| v_k | $D_W(e_{s,k})$ | $E_W(e_{s,k})$ | $B_W(e_{s,k})$ |

information between the links through data transmission. The cross-layer fusion process of CPW is shown in Fig.3.

The quality of service parameters for the low voltage power line and micropower wireless communication links are stored in the corresponding routing tables. The power line communication routing table and the wireless communication routing table of the node are set up as shown in Tables 1 and 2, respectively. The cross-layer fusion process of CPW is based on the establishment of its unified MAC layer communication protocol. The optimal communication path is searched to form a network at the network layer. The load balancing and business service quality requirements at the business layer are considered about the sub-business flow allocation. The deep integration of low-voltage power line and micro-power wireless communication are achieved.

IV. SIMULATION RESULTS AND ANALYSIS

A. SIMULATION CONDITIONS

In order to simulate the actual power line channel state, it is necessary to set reasonable relevant physical parameters to verify the communication fusion method proposed in this paper. Simulation experiments are carried out on the premise of the following assumptions.

- (1) It can calculate the communication rate, delay, and bit error rate between it and the previous node after each node receives the data packet, and store them in the corresponding routing table.
- (2) All nodes are equipped with low-voltage power line/micro-power wireless hybrid communication modules. The hybrid communication module can adjust the proportion of business volume in the low-voltage power line and micro-power wireless communication network according to the bit error rate demand factor of the business.
- (3) There, 2 send buffers and 2 receive buffers should be set up, when the buffer data reaches half full, synchronously synthesize the data stream. It is dynamically adjust the receiving delay of the two channels to overcome the problem of transmission jitter.

TABLE 3. Value of parameters.

| parameter | value | parameter definition |
|------------|----------------------|--|
| n | 70 | number of nodes |
| T_{max} | 80 | the maximum number of iterations |
| α | 0.1 | the influence coefficient of pheromone |
| β | 0.3 | the influence coefficient of heuristic information |
| ρ | 0.9 | the volatility coefficient |
| Q | 30 | intensity coefficient of the pheromone |
| γ_d | 0.4 | the delay weight |
| γ_e | 0.2 | bit error rate weight |
| γ_b | 0.4 | bandwidth weight |
| γ_h | 0.1 | routing hop weight |
| H_{max} | 10 | the maximum number of routing hops of the communication path |
| D_{max} | 4×10^{-2} s | the maximum delay of the communication path |
| E_{max} | 3.5×10^{-4} | the maximum bit error rate of the communication path |
| B_{max} | 64 kbit/s | the minimum communication rate of the communication path |

B. PARAMETER SETTING

The simulation parameters in this paper are based on reference [30]. The time delay between any two points in the low-voltage power line and the micro-power wireless communication network is set as the compliance interval $[2 \times 10^{-3}, 8 \times 10^{-3}]$ s and the compliance interval as $[1 \times 10^{-3}, 7 \times 10^{-3}]$ uniform distribution of s. The data buffer delay obeys a uniform distribution with an interval of $[1 \times 10^{-4}, 2 \times 10^{-4}]$ s. The bit error rates are set to obey a normal distribution with a mean of 6×10^{-5} and a variance of 2×10^{-5} and a mean of 7×10^{-5} and a variance of 3×10^{-5} . The communication rates are set to obey a normal distribution with a mean of 200kbit/s and a variance of 3(kbit/s)² and a mean of 200kbit/s and a variance of 5(kbit/s)². There are 70 communication nodes distributed in the range of 500m×600m, including 1 central node and 69 sub-nodes. All nodes are equipped with low-voltage power line/micro-power wireless hybrid communication modules, and the services that need to be transmitted in the network have higher requirements on time delay and communication rate. In order to simulate the signal attenuation of low-voltage power line communication and micro-power wireless communication in the case of being blocked by buildings and obstacles, the maximum communication distance between nodes is set to 85~95m. Other simulation parameters are shown in Table 3.

C. SIMULATION ANALYSIS

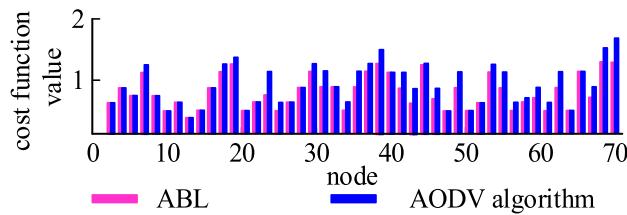
1) VALIDATION OF ABL

a: PERFORMANCE COMPARISON OF ABL AND ANT COLONY ALGORITHM

An optimal communication path with all other nodes are established with the central node in CPW. The average

TABLE 4. Performance comparison between ABL and ant colony algorithm.

| Algorithm | Average number of iterations for the algorithm to converge | The average cost function value of the optimal communication path |
|----------------------|--|---|
| ABL | 14.477 | 0.853 |
| Ant Colony Algorithm | 8.870 | 0.916 |

**FIGURE 4.** The optimal communication path cost function value of each node of the ABL and AODV algorithms.

number of iterations required for the convergence of ABL and ant colony algorithms and the average cost function value of the optimal communication path of all nodes are counted, which is shown in Table 4.

It can be seen from Table 4 that ABL has better global search ability than ant colony algorithm based on the number of iterations required for ABL convergence is more than that of ant colony algorithm, and the corresponding average cost function value is lower than that of ant colony algorithm. The networking work of the central node to all other nodes can be accomplished, and the performance is better than that of ant colony algorithm.

b: PERFORMANCE COMPARISON OF ABL AND WIRELESS AD HOC NETWORK ON-DEMAND DISTANCE VECTOR ROUTING ALGORITHMS

AODV (Adhoc On-demand Distance Vector routing) algorithm is a typical routing algorithm applied to wireless ad hoc networks. The central node is set up with all other nodes to establish an optimal communication path in CPW, and the cost function value of each node's optimal communication path is obtained. The cost function value comparison of optimal communication path are shown in Figure 4.

It can be seen from Figure 4 that the cost function value of the optimal communication path found by some nodes (about 43% of total number of nodes) using ABL is lower than the cost function value of the optimal communication path found by using the AODV algorithm. The optimal communication path found by other nodes (about 57% of total number of nodes) using the two algorithms are same, so the performance of ABL is better than the AODV algorithm.

c: ABL ROUTING SEARCH VERIFICATION FOR DIFFERENT QUALITY OF SERVICE TYPES

The different networking solutions according to different service quality requirements can be provided by ABL. The voice

TABLE 5. Comparison between CPW and dual-mode communication network.

| service quality requirements | communication path | Delay/s | bit error rate/ % | communication rate/ kbit·s-1 | cost function value |
|------------------------------|--------------------|------------------------|------------------------|------------------------------|---------------------|
| S_1 | optimal | 2.496×10^{-2} | 3.365×10^{-4} | 392.80 | 1.630 |
| | suboptimal | 2.766×10^{-2} | 3.136×10^{-4} | 398.20 | 1.664 |
| S_2 | optimal | 3.178×10^{-2} | 2.802×10^{-4} | 396.78 | 6.775 |
| | suboptimal | 3.196×10^{-2} | 2.818×10^{-4} | 396.76 | 6.810 |

and video services that require high service quality of delay and communication rate, the service quality requirements of which are denoted by S_1 . The file transmission services that require lower bit error rates, the service quality requirements of which are represented by S_2 . The corresponding optimal communication path can be searched by adjusting the weight of the QoS parameters. For S_1 , there $\gamma_d = 0.3$, $\gamma_e = 0.2$, $\gamma_b = 0.4$, $\gamma_h = 0.1$, the optimal communication path from node 1 to node 70 is 1-25-40-43-41-70, and the second optimal communication path is 1-25-24-43-41-70. For S_2 , set $\gamma_d = 0.1$, $\gamma_e = 0.5$, $\gamma_b = 0.1$, $\gamma_h = 0.1$, the optimal communication path from node 1 to node 70 is 1-60-12-31-57-70, and the second optimal communication path is 1-60-12-31-41-70. Other parameter values are shown in Table 5.

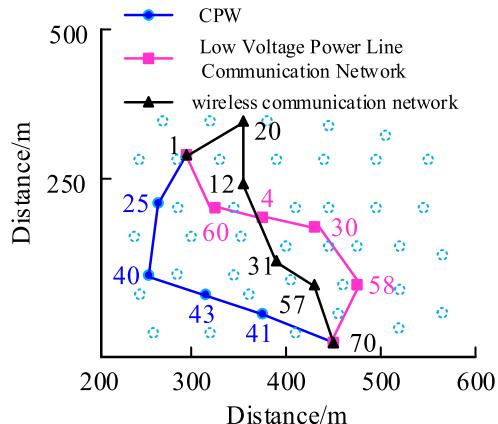
It can be seen from table 5 that the delay of the optimal communication path of S_1 is shorter than that of S_2 , and the bit error rate of the optimal communication path of S_2 is lower than that of S_1 . It verifies that ABL can search for the corresponding optimal communication path according to different service quality requirements. The optimal path communication rate of S_1 is slightly lower than that of S_2 , and a communication path with a higher communication rate can be obtained by adjusting the parameter weight when necessary. It should be pointed out that the cost function value of the optimal communication path of S_2 is much larger than the cost function value of the optimal communication path of S_1 . When the weights of quality of service parameters are differently, the corresponding cost function values are not comparable, it mean that the values of the cost functions are different. The optimal communication path is also searched under the corresponding QoS requirements.

2) COMPARISON OF CPW AND SINGLE COMMUNICATION METHOD

In order to compare the performance of CPW, low-voltage power line communication network and micro-power wireless communication network, the optimal communication path between central node and node 70 is searched in three kinds of networks respectively. The QoS parameters and cost function values of the optimal and sub-optimal communication paths of the three networks are shown in Table 6. The CPW optimal communication path is 1-25-40-43-41-70, and the second optimal communication path is 1-25-24-43-41-70. The optimal communication path of low-voltage power line communication network is 1-60-4-30-58-70, and the second optimal communication path is 1-60-4-42-57-70. The optimal

TABLE 6. Comparison between CPW and single mode communication network.

| network | communication path | Delay/s | bit error rate/ % | communication rate/ kbit·s ⁻¹ | cost function value |
|---|--------------------|------------------------|------------------------|--|---------------------|
| CPW Low Voltage Power Line Communication Network | optimal | 2.496×10^{-2} | 3.365×10^{-4} | 392.80 | 1.630 |
| | suboptimal | 2.766×10^{-2} | 3.136×10^{-4} | 398.20 | 1.664 |
| | optimal | 2.373×10^{-2} | 2.123×10^{-4} | 192.10 | 2.848 |
| | suboptimal | 2.178×10^{-2} | 2.771×10^{-4} | 196.53 | 2.856 |
| Micropower Wireless Communication Network | optimal | 1.392×10^{-2} | 2.472×10^{-4} | 195.72 | 2.235 |
| | suboptimal | 1.823×10^{-2} | 2.627×10^{-4} | 201.12 | 2.512 |

**FIGURE 5.** Optimal communication paths of three communication networks.

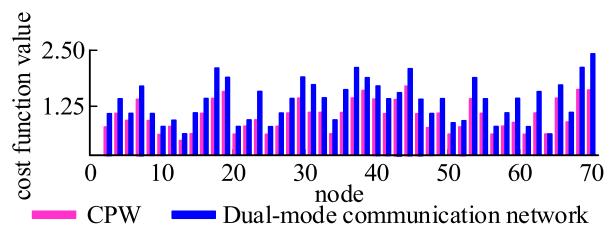
communication path of the micro-power wireless communication network is 1-20-12-31-57-70, and the second optimal communication path is 1-20-12-31-41-70. The optimal communication paths of the three networks are shown in Figure 5. It can be seen from Table 5 and Figure 5 that the performance of the optimal communication path between the central node of CPW and node 70 in terms of delay and bit error rate is lower than that of the single communication network, but the communication rate of CPW is much higher than that of low-voltage power lines or micro-communication networks. Therefore, its comprehensive performance is better than any single communication network.

3) COMPARISON OF CPW AND DUAL MODE COMMUNICATION

The communication mode that uses low-voltage power line and micro-power wireless communication as backup for each other is called dual-mode communication mode. When the dual-mode communication network is networked, a better communication method can be selected for information transmission according to the channel state of the low-voltage power line and the micro-power wireless communication link. The central node searches for the optimal communication path for the node 70 in the CPW and dual-mode communication networks, respectively. The parameters such as the quality of service are shown in Table 6. The optimal

TABLE 7. Comparison between CPW and dual-mode communication network.

| | communication path | Delay/s | bit error rate/ % | communication rate/ kbit·s ⁻¹ | cost function value |
|--|--------------------|------------------------|------------------------|--|---------------------|
| CPW Dual-mode communication network | optimal | 2.496×10^{-2} | 3.365×10^{-4} | 392.80 | 1.630 |
| | suboptimal | 2.766×10^{-2} | 3.136×10^{-4} | 398.20 | 1.664 |
| | optimal | 1.057×10^{-2} | 2.560×10^{-4} | 195.72 | 2.048 |
| | suboptimal | 1.465×10^{-2} | 2.813×10^{-4} | 195.85 | 2.395 |

**FIGURE 6.** The optimal communication path cost function value of each node of CPW and dual-mode communication network.

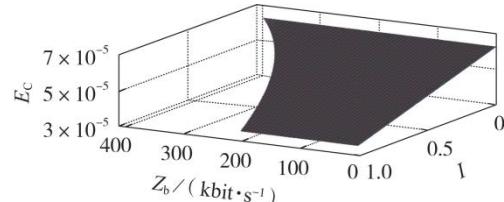
communication path of the dual-mode communication method is 1-20-12-31-57-70, and the second optimal communication path is 1-60-4-42-57-70. The optimal communication path of the center node-to-node 70 of the dual-mode communication network is the same as the optimal communication path of the micro-power wireless communication, and the sub-optimal communication path is the same as the sub-optimal communication path of the low-voltage power line communication network. It can be seen from Tables 5 and 6 that the communication paths are the same, because the dual-mode communication method selects the optimal communication method in all links. The service quality of the communication path is better than any single communication mode, so that the dual-mode communication network needs to be connected. The central node network with all other nodes are networked in the CPW and dual-mode communication networks, respectively. The cost function value of the optimal communication path of each node is obtained, which is shown in Figure 6. The dual-mode communication mode selects the optimal communication mode in low-voltage power line or micro-power wireless communication, while CPW needs to take into account the delay and bit error rate of the two communication modes of low-voltage power line and micro-power wireless communication. It can be seen from Table 7 and Figure 6 that the optimal communication path between the central node of the dual-mode communication network and the node 70 is better than CPW in terms of delay and bit error rate. The communication rate of CPW is much higher than that of the dual-mode communication network. It has a significant impact on all nodes. The cost function value of the optimal communication path of the networking is lower than that of the dual-mode communication network, that is, its comprehensive communication service quality is better than that of the dual-mode communication network.

4) COMPARISON OF CPW AND CASCADE COMMUNICATION

The cascaded communication network can also accomplish all the access of nodes, which is compared with CPW. It is

TABLE 8. Comparison between CPW and cascade communication networks.

| network | communication path | Delay/s | bit error rate/ % | communication rate/ kbit·s ⁻¹ | cost function value |
|--------------------|--------------------|------------------------|------------------------|--|---------------------|
| CPW | optimal | 1.734×10 ⁻² | 2.248×10 ⁻⁴ | 392.80 | 1.145 |
| | suboptimal | 1.932×10 ⁻² | 1.886×10 ⁻⁴ | 393.20 | 1.152 |
| Cascaded Network 1 | optimal | 1.316×10 ⁻² | 1.370×10 ⁻⁴ | 192.07 | 1.768 |
| | suboptimal | 1.428×10 ⁻² | 1.801×10 ⁻⁴ | 192.05 | 1.985 |
| Cascaded Network 2 | optimal | 1.316×10 ⁻² | 2.688×10 ⁻⁴ | 195.79 | 2.150 |
| | suboptimal | 1.468×10 ⁻² | 2.495×10 ⁻⁴ | 194.60 | 2.207 |

**FIGURE 7.** Relationship between EC, Zb, I.

assumed that the low-voltage power lines and micro-power wireless communication methods are adopted in nodes 10, 25, and 39. The micro-power wireless communication is adopted in nodes 14, 15, 18, 19, 22, 23, 35-38, and the low-voltage power line communication is adopted in other nodes. A low-voltage power line and micro-power wireless communication cascade communication network is constituted. The optimal communication path through route search from the central node to node is 1-25-38-14-15, and the second optimal communication path is 1-25-40-14-15. If nodes 14, 15, 18, 19, 22, 23, 35-38 only use low-voltage power line communication, and other nodes only use micro-power wireless communication, the micro-power wireless communication cascade low-voltage power line communication network is formed. The optimal communication path through route search from the central node to node 15 is 1-25-40-14-15, and the second optimal communication path is 1-10-38-14-15. The parameters such as path quality of service parameters and cost function values of CPW and each level of communication network are shown in Table 8. In the table, the cascade network 1 and the cascade network 2 represent the low-voltage power line and the micro-power wireless communication cascade communication network.

5) INFLUENCE OF BUSINESS FLOW ALLOCATION STRATEGY BASED ON BUSINESS SERVICE QUALITY REQUIREMENTS ON CPW

When node 1 communicates with node 16, considering load balancing and service bit error rate requirement factors, the sub-service flow is allocated by setting the service bit error rate requirement factor I . It is assumed that the communication rate required by the service is Z_b , the relationship between E_C , Z_b , and I is shown in Figure 7.

When $Z_b = 300\text{kbit/s}$, $E_p(e_{1,16}) = 9.017 \times 10^{-5}$, $E_w(e_{1,16}) = 3.585 \times 10^{-5}$, $B_p(e_{1,16}) = 198.38\text{kbit/s}$, $B_w(e_{1,16}) = 201.70\text{kbit/s}$. The maximum value of the bit error rate demand factor $I_{max}=0.338$ is known from equation (10). Table 9 shows The transmission bit error rate and

TABLE 9. Influence of I on error rate of communication link and network load.

| I | $Z_p/(\text{kbit}\cdot\text{s}^{-1})$ | $Z_w/(\text{kbit}\cdot\text{s}^{-1})$ | E_C |
|-----|---------------------------------------|---------------------------------------|------------------------|
| 0 | 148.78 | 151.24 | 6.280×10^{-5} |
| 0.1 | 133.90 | 166.12 | 6.011×10^{-5} |
| 0.2 | 119.03 | 180.99 | 5.741×10^{-5} |
| 0.3 | 104.15 | 195.87 | 5.472×10^{-5} |

inter-network load information between node 1 and node 16 is shown in table 9. There, E_C is the transmission bit error rate between node 1 and node 16; Z_p and Z_w are the communication rates of the sub-service flows of the low-voltage power line communication network and the micro-power wireless communication network allocated by service Z_b , respectively.

It can be seen from Figure 7 and Table 9 that with the gradual increase of the service bit error rate demand factor, the load gap between the low-voltage power line communication network and the micro-power wireless communication network increases, and the bit error rate of the communication link gradually decreases. The services with lower BER requirements can balance network load at the expense of increasing BER. The services with higher BER requirements can reduce BER at the expense of network load balancing. The transmission service can set the corresponding service bit error rate demand factor according to its service quality requirements, so as to comprehensively consider the service quality of the service communication and the load balance between the networks.

V. DISCUSSION

It is necessary to set reasonable relevant physical parameters to verify the communication fusion method proposed in this paper. An optimal communication path with all other nodes are established with the central node in CPW. The optimal communication path between central node and node 70 is searched in three kinds of networks respectively. When the dual-mode communication network is networked, a better communication method can be selected for information transmission according to the channel state of the low-voltage power line and the micro-power wireless communication link. The sub-service flow allocation strategy on the service layer can improve the effectiveness and reliability of CPW, and accomplish the deep integration of low-voltage power line and micro-power wireless communication network.

VI. CONCLUSION

- (1) The unified MAC protocol of low-voltage power line communication and micro-power wireless communication is designed, and the integration of the two communication methods is accomplished at the MAC layer of CPW, which supports the integration of low-voltage power line and micro-power wireless communication at the network layer.
- (2) The ABL algorithm is proposed to complete the optimal communication path networking of CPW, and the

Brownian motion related to the local convergence times is used to update the pheromone vector, which is beneficial for the algorithm to jump out of the local optimal solution. The simulation results show that the ABL algorithm has stronger global search ability than the ant colony algorithm, and it is not easy to fall into the local optimum.

- (3) A service bit error rate requirement factor is proposed to solve the problem of service quality requirement and load balance between networks in sub-service flow allocation. It is verified that the load balancing of the CPW and the BER of the communication link can be adjusted by bit error rate demand factor.
- (4) A unified communication protocol is established for the MAC layer of CPW, the optimal communication path networking is realized at the network layer, and sub-service flow distribution is performed at the service layer. The cross-layer fusion of low-voltage power line communication and micro-power wireless communication is completed. It is verified that the communication service quality of the cross-layer fusion network is better than other networks, and the communication efficiency of CPW is 398.20kbit/s.

The cross-layer fusion method of low-voltage power line communication and micro-power wireless communication improves the coverage and reliability of the power line and wireless communication fusion network, and provides engineering technical support for ensuring the power line and wireless communication fusion network.

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