IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 29, 2022, accepted May 3, 2022, date of publication May 9, 2022, date of current version May 16, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3173415

Decentralized Self-Organizing Networks for Poor Reconfigurability of Loom Networks

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This work was supported in part by the Science and Technology Plan Project of Jiangsu Province under Grant BRA2020244.

ABSTRACT The intelligent weaving of looms requires networking and intelligent industrial production systems that use industrial equipment with network communication and data computing, creating a ‘‘smart factory’’. However, limited by the development of industrial technology, existing industrial loom equipment does not have sufficient communication or computing capabilities: communications primarily rely on bus and Ethernet communication, which is limited to wired connections; and computations primarily rely on the host computers and cloud computers that only provide weak real-time computing. Currently, the remote management system used in the loom industry can be constructed using a cloud platform, but machine-machine interconnections between the loom control terminals are ignored. To solve the problem of poor reconfigurability in loom networks that rely on cloud servers, this study analyzes the networking requirements of a loom network and uses mesh network technology to build a wireless self-organizing loom network. A mesh network can be formed with clouds, loom equipment, and other equipment. By constructing an experimental platform with a decentralized self-organizing network to build a remote loom monitoring system, an anti-destruction experiment of the developed self-organizing loom network is performed. After the self-organizing network is constructed, key nodes in the network are disconnected, and the network is automatically reconfigured to resume normal work. The reconfigurability and stability of the network are demonstrated via destructive experiments. Results show that the self-organizing network construction method developed in this study can build a loom self-organizing network, which is anti-destructive and mitigate the poor reconfigurability of existing loom networks. Compared with the wireless communication network of the previous loom remote monitoring system, the loom interconnection self-organizing network is more reliable and anti-interference, which can better meet the network demand of intelligent manufacturing for loom equipment. This study provides an effective example of loom networking technology for the industry and is important when promoting the construction of smart loom factories.

INDEX TERMS Loom, industrial interconnection, self-organizing network, mesh network.

I. INTRODUCTION

Loom intelligent weaving uses networking and intelligent industrial production that requires industrial equipment with network communication and data computing to create a ‘‘smart factory’’. However, limited by the development of industrial technology, existing industrial loom equipment does not have sufficient communication and computing capabilities: communications primarily rely on bus and Ethernet communication, which is limited by wired connections; calculations primarily rely on the host computer and cloud computer for weak real-time computing, which is limited by real-time computing. Currently, a remote management system used in the loom industry can be constructed using a cloud platform, but machine-machine interconnections between loom control terminals are ignored. To mitigate the poor reconfigurability of a loom network that relies on cloud servers, a decentralized self-organizing network formed by the loom control terminal is needed.

In the future, the new generation of the textile industry is considered to be an industrial technology that uses collaborative networks and information sharing among field

The associate editor coordinating the review of this manuscript and approving it for publication was Javed Iqbal.

production equipment, manufacturing execution systems (MESs), and enterprise resource management (ERP), with a higher degree of automation, flexibility, and openness. The textile industry must achieve industrial upgrading using a production collaboration network to improve its competitiveness and survive in the more intense competition of the future [1]. How to achieve information sharing and collaborative production among all production participants via network technology is a key issue that is important to resolve. Deng Yuwen's team designed a network management system for airjet high-speed looms based on the CAN bus and Web technology, which achieved information exchange between airjet high-speed looms, databases, and Web servers [2]. Wang Quan's team designed a high-speed loom monitoring system with a browser/server (B/S) architecture using MTConnect protocol technology that allows remote users to monitor the production of high-speed looms in real-time without geographical restrictions [3]. Wang Songsong's team achieved the interconnection of knitting machines through network protocols, established a cloud platform to provide MES services for knitting machines, and provided cloud platform management systems for enterprises [4].

This technology only provides an effective production process monitoring system for the production site and fails to achieve intelligence, networking and informatization in the true sense. It is thus necessary to learn from advanced industrial internet technology to perform in-depth research on interconnected loom networks.

Existing network connection methods of looms cannot meet the requirements of flexible and reconfigurable network connections for intelligent weaving. Whether it is a wired or wireless connection, a network connection is achieved by connecting a fixed IP address. Typically, equipment in a loom network is directly connected to the IP address of the server. Although this connection method can be used to build a network quickly, it is difficult to connect devices to the network because all data transmission must go through the server. When the number of devices in the network is large, and the amount of data transmitted is large, the data transmission between devices will cause communication congestion; some loom networks establish connections by connecting to the IP addresses of adjacent devices. To meet the needs of the device moving in the network, the failure of a certain device, and the change in the communication requirements between the devices, the connection method of the self-organizing network of the loom must be reconfigurable.

Self-organizing network technology is the networking requirement proposed in the Internet-of-Things era. [5] Wang Yali from the Beijing University of Posts and Telecommunications investigated online self-organizing network data transmission and content sharing mechanisms; applied an ant colony algorithm to optimize the QoS routing mechanism and green energy-assisted wireless mesh rotation mechanism; and proposed a better content storage strategy than the Zipf content storage mechanism. [6] Zhang Tinghui from the University of Electronic Science and Technology of China studied the efficient intelligent access mechanism in the self-organizing network of UAVs and proposed a reinforcement learning backoff algorithm based on policy search. [7] Wang Zhen from the Beijing University of Posts and Telecommunications investigated the adaptive algorithm of wireless ad hoc networks and proposed an adaptive on-demand weighted clustering algorithm and a low-power adaptive clustering layered protocol algorithm. [8] Song Xiaoxue from the University of Electronic Science and Technology of China investigated the time synchronization technology of wireless ad hoc networks and improved the synchronization delay and flood broadcast time synchronization algorithm to reduce the synchronization error. [9]–[14] Decentralized networks are likely to become mainstream in future network technologies, making it important to study decentralized self-organizing networks. [15]–[20] Self-organizing networks meet the needs of future industrial networks, also making it necessary to study industrial self-organizing networks. This development in self-organizing network applications show that self-organizing networks play an important role in industrial networks.

Because the architecture of a mesh network supports multihop communication, it can effectively expand the communication range, effectively solve the problem of network congestion, and improve the efficiency of network communication, which plays an important role in the intelligent manufacturing of communication equipment. However, the bandwidth of the ad hoc network architecture is limited, which cannot fully meet the needs of industrial production and data transmission, and the application of peer-to-peer networks in the industry is not sufficiently mature. Therefore, this study uses a mesh network to achieve the stated research goals. Compared with the wireless communication network of the previous loom remote monitoring system, the loom interconnection self-organizing network is more reliable and anti-interference, which can better meet the network demand of intelligent manufacturing for loom equipment.

The remainder of this paper is organized as follows. The second chapter analyzes the theoretical analysis of the loom self-organizing network and the construction of the communication protocol. The third chapter studies the self-organized computing power network of the loom. The fourth chapter introduces the experimental platform and anti-destructive characteristics of the loom self-organizing network system. The fifth chapter is the conclusion of the full text.

II. THEORETICAL ANALYSIS OF A LOOM SELF-ORGANIZING NETWORK AND CONSTRUCTION OF ITS COMMUNICATION PROTOCOL

A. THEORETICAL ANALYSIS OF A LOOM MESH NETWORK

A mesh network supports multihop transmission, and the nodes of a mesh network can be divided into mesh router nodes and mesh client nodes according to the identity mode of the network nodes. Mesh routing nodes provide mesh network access and external network functions for mesh

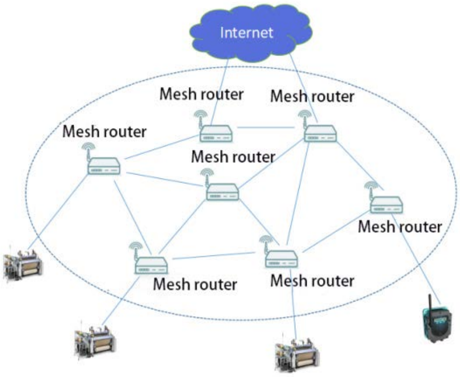


FIGURE 1. Backbone mesh structure.

clients. Mesh routing nodes connected to the external network are normally fixed. Mesh routing nodes can communicate directly with mesh clients. A mesh client is a node that is directly connected to the mesh router but does not act as a relay. Mesh network nodes generally provide relay and forwarding functions to provide routing and forwarding services for the communication of other nodes. Wireless mesh networks can be subdivided into backbone mesh structures, client-side mesh structures, and hybrid mesh structures.

(1) There are multiple layers of nodes in the backbone mesh structure. The backbone mesh structure is composed of mesh router nodes and is connected to the external network through some mesh routing nodes. In this structure, the mesh client does not provide relaying and forwarding functions, and must rely on Mesh. The router's relay forwarding service can communicate with other nodes. When a node in the network must communicate with the external network, it must initiate a network request to the external network through the mesh router node connected to the external network, which is suitable for a large number of devices in the network. The structure is shown in Figure 1.

(2) The client-side mesh structure is relatively simple, consisting only of mesh clients. There is no need for relaying and forwarding services of the mesh router, and each mesh client provides relaying and forwarding functions. Without a specific central access point, any two nodes can communicate through multihop forwarding. The construction of this structure is relatively simple and flexible, and it is suitable for situations with less equipment, as shown in Figure 2.

(3) The hybrid mesh structure is composed of both the backbone and client mesh structures. In this structure, several mesh routers are used to form an upper-layer network directly connected to the external network. Each mesh client is formed into an underlying network that can communicate with each other. Mesh clients can communicate between subnets and access external networks through mesh routers. This structure can be deployed; be built flexibly; integrate cellular networks, Wi-Fi networks, WiMAX networks, and other types of networks; and is suitable for heterogeneous networks with complex situations, as shown in Figure 3.

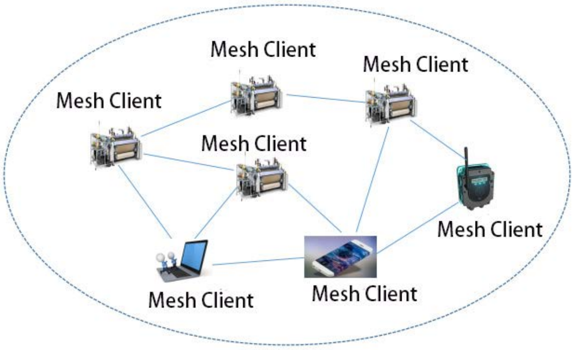


FIGURE 2. Client-side mesh structure.

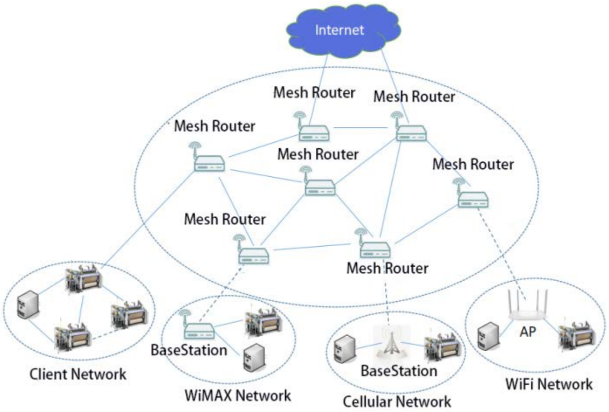


FIGURE 3. Hybrid mesh structure.

Due to the large number of IoT devices that are likely to be in use in the future, communication capabilities are limited, and service quality requirements are widely differentiated. For the data collection service in the centralized control network, many MTD (machine-type device) nodes directly connected to the base station will cause uplink congestion; multihop access can reduce the number of nodes accessing the network concurrently and improve network energy efficiency; nodes cannot communicate directly with other nodes outside the communication range; and multihop routing can communicate between any two nodes, improving the connectivity and effectiveness of network communication [21], [22]. Therefore, the study of multihop routing technology is important for the popularization and application of IoT technology in intelligent weaving in the future.

B. CONSTRUCTION OF SELF-ORGANIZING NETWORK COMMUNICATION PROTOCOL FOR LOOMS

The communication module that is used to create the self-organizing network uploads the loom equipment data to the cloud to achieve the remote monitoring of loom equipment. According to the loom monitoring requirements, the loom monitoring cloud platform establishes the asset module of the loom, and the asset model contains all the data points required for the monitoring of the loom. Data points are distinguished by data point identifiers according to their structure and function, and are divided into detection data points that can only be read, control data points that can be modified, and command data points that perform special functions such as alarms. Data points are packaged in JSON format and parsed. The data monitoring the loom is collected by the loom primary control board, the data corresponding to the data points are packaged and parsed according to the static JSON data format of the cloud loom asset module, and the data are exchanged with the cloud through the communication module of the loom equipment.

Loom equipment uses ESP32-S2 chips as its core communication modules. The south interface of the communication module is RS485 and RS232 in CAN and UART, which communicate with the primary control board of the loom; the north interface supports WIFI and WIFI MESH. Loom equipment builds a self-organizing network, completes the task of mutual data exchange, and decentralizes information transmission between devices. For example, the onboard monitoring system of the loom can monitor other loom equipment without a cloud center through the loom ad hoc network, which reduces the computational burden on the cloud and increases system reliability. This system is connected to the external network through WIFI to provide communications with the cloud, as shown in Figure 4. Self-organizing network of loom equipment is built by using ESP32-S2 as the core communication module. The south-facing interface interacts with the main control board of the loom equipment. The north-facing interface is used to build a self-organizing network and to transfer data between loom equipment. Due to the limited resources of the communication module, the MQTT protocol suitable for lightweight communication is used to communicate with the cloud.

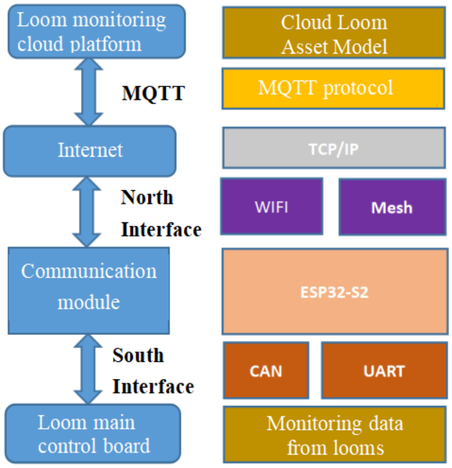


FIGURE 4. Loom communication protocol structure.

ESP-WIFI-MESH is a set of self-organizing mesh network protocols built on the Wi-Fi protocol that allows many devices (hereafter referred to as nodes) distributed in a large area (indoor and outdoor) to connect in the same WLAN (Wireless Local Area Network). The ESP-WIFI-MESH is self-organizing and self-healing, which means that the network can be constructed and maintained autonomously.

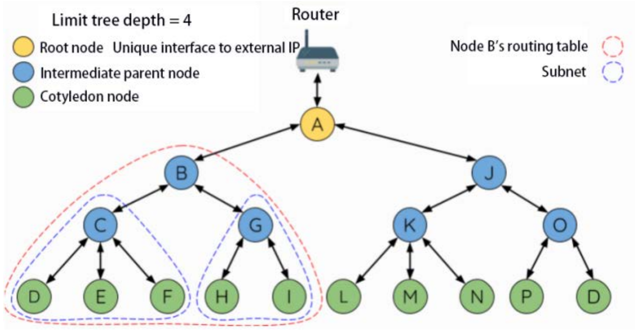


FIGURE 5. ESP-WIFI-MESH routing structure.

A traditional infrastructure Wi-Fi network is a "point-to-multipoint" network. The central node of this network architecture is an access point (AP), and other nodes (stations) are directly connected to the AP. The AP is responsible for arbitration and forwarding between the stations, and some APs also exchange data with the external IP network through the router. In the traditional Wi-Fi network architecture, the coverage area is relatively limited because all stations must be directly connected to the AP and cannot be too far away from the AP. Due to the limitation of AP capacity, the number of stations allowed in the network is relatively limited, making the network easy to overload. The difference between ESP-WIFI-MESH and Wi-Fi networks is that nodes in the network do not need to be connected to a central node but can be connected to adjacent nodes. Each node is responsible for the data relay of connected nodes. Because all nodes can still be interconnected without being limited by the location of the central node, the coverage area of the ESP-WIFI-MESH network is wider. Similarly, because it is no longer limited by the capacity of the central node, ESP-WIFI-MESH allows more nodes to be accessed and is not easily overloaded.

Each node in the ESP-WIFI-MESH network maintains its routing table and sends packets to the correct destination node along the correct route according to the routing table. The routing table for a particular node contains the MAC addresses of all nodes in that node's subnet, as well as the node's own MAC address. Each routing table is divided into multiple sub routing tables, corresponding to the subnet of each subnode. As shown in Figure 5, the routing table of Node B will contain the MAC addresses of the subnet from Node B to Node I, which is Node B. The routing table of Node B can be divided into sub routing tables of Node C and G, which respectively contain MAC addresses from Node C to Node F and MAC addresses from Node G to Node I. The entire network is built by extending intermediate nodes by the root node and then extending child nodes by the intermediate nodes.

The ESP-WIFI-MESH network will first select the root node and then form downstream connections layer by layer until all nodes join the network. The layout of the network may depend on factors such as root node selection, parent node selection, and asynchronous power-on reset. However, in simple terms, the construction process of an ESP-WIFI-MESH network can be summarized as the following steps:

1. Root node selection: The root node is directly designated or elected by the node with the strongest signal strength. Once selected, the root node will connect to the router and begin to allow downstream connections to form. As shown in the figure above, node A is selected as the root node; thus, node A is connected to the router upstream.

2. Formation of the second layer: Once the root node is connected to the router, idle nodes within the range of the root node will start connecting with the root node, thus forming the second layer network. Once connected, the second layer node becomes the intermediate parent node, which in turn forms the next layer. As shown in the figure above, Nodes B to D is all within the connection range of the root node. Therefore, Node B to Node D form an upstream connection with the root node and become an intermediate parent node.

3. Formation of the other layers: The remaining idle nodes are connected with the intermediate parent nodes in the range and form a new layer. Once connected, idle nodes become intermediate parents or leaf nodes, depending on the maximum allowed hierarchy of the network. This step is repeated thereafter until all idle nodes in the network have joined the network or the maximum allowed level of the network has been reached. As shown in the figure above, nodes E/F/G are connected to nodes B/C/D and become intermediate parent nodes.

4. Limiting the tree depth: To prevent the network from exceeding the maximum allowed level, the nodes on the maximum allowed level will become leaf nodes after completing the connection. Thus, other idle nodes will not be able to form connections with leaf nodes on these maximum allowed levels; thus, the maximum allowed level will not be exceeded. However, if an idle node cannot find other potential parents, it will remain idle indefinitely. As shown in the figure above, the maximum allowed level of the network is four. Therefore, node H will become a leaf node after completing the connection to prevent any downstream connections from forming. The networking process of the ESP-WIFI-MESH is shown in Figure 6. At the beginning of the network, the root node is selected first, then the parent node is selected to form the second layer, after that the other remaining layers are formed, and finally the child layers are selected.

III. LOOM SELF-ORGANIZED COMPUTING POWER NETWORKS AND COMMUNICATION MODULE DESIGN ANALYSIS

A. LOOM SELF-ORGANIZED COMPUTING POWER NETWORKS

Loom networks are complex and highly dependent on key nodes, and the failure of a key node in the network may lead to the collapse of part or even the whole network. Therefore, research on loom self-organizing arithmetic networks is needed to make the network reconfigurable, so that the computational resources in the network can be used more efficiently and have resistance to destruction.

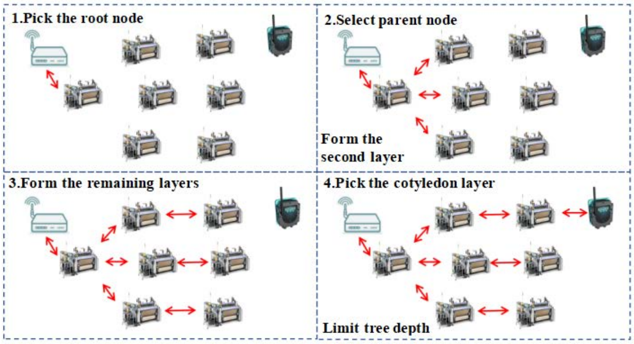


FIGURE 6. **ESP-WIFI-MESH networking process.**

In existing remote fault diagnosis expert loom systems, a loom's primary control chip of the local execution end communicates with the ESP8266 wireless module through the serial port and transmits data between the local execution end and the cloud server. The system uses the socket interface to write the TCP/IP communication protocol to communicate between the local system and the cloud for required data transmissions. The cloud server first uses JSON for data interaction and uses the data processing module to process the loom's fault data. The server then simplifies the collected loom parameter information through rough sets to obtain the smallest decision table. Finally, the server uses the Bayesian network for fault diagnosis; determines the cause of the system fault and the fault solution; and feeds it back to the remote client. The cloud server uses the Redis database for real-time equipment operating parameter information, operating status information, and fault information. This information is saved for user reference and is also used as the basis for fault diagnosis and determining operating status. The cloud server uses Ajax technology for data interaction processing between the client and cloud to complete both local and client data transmission tasks. The client uses the remote monitoring webpage to remotely monitor the local execution terminal by the client. The fault diagnosis knowledge base of the equipment is built by the industrial internet platform, and the real-time fault data and historical fault data of the equipment are obtained through the industrial network for on-site monitoring and intelligent fault diagnosis of equipment [3], [4], [27], [31]. In the IoT measurement and control system shown in Figure 7, all operations pass through the IoT platform, which reduces computational speed and creates complex computing procedures and slow response speed in the system [23]–[27]. Compared with the data that must be completed in the cloud to complete the primary work of the data processing of the IoT measurement and control system, the measurement and control system that requires additional computing power and the network to the edge has marked advantages. The decentralized loom network is this study focuses on this trend.

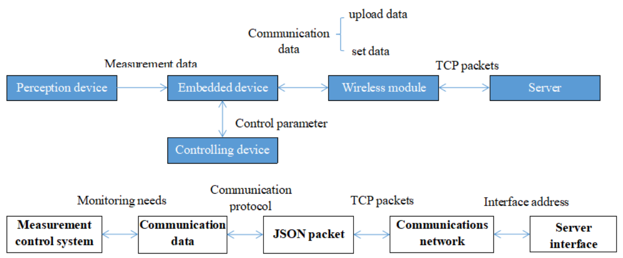


FIGURE 7. **IoT measurement and control system.**

Because edge cloud computing is arranged on the edge of the network near the object or data source, the on-site loom equipment can form a self-organizing micro cloud with the edge cloud computing. Conversely, this system can share computations with the cloud platform and, conversely, can integrate the use of the device's idle computing and storage resources when possible.

Cloud computing provides access to cloud service providers through the Internet, while computing and communication resources in the mobile edge computing model are physically closer. Mobile edge computing directly connects edge servers with network edge devices, such as base stations (BSs), access control points (APs), and routers. Computing and communication resources often belong to the same network provider. Therefore, from the perspective of resource owners, computing resources and communication resources must be allocated as a whole in the mobile edge computing model. The Mobile Edge Computing (MEC) reference architecture is shown in Figure 8.

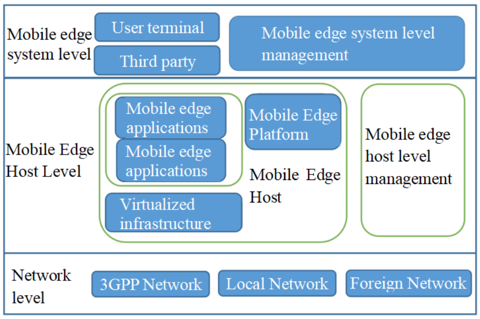


FIGURE 8. **Mobile edge computing reference architecture.**

Mobile edge computing is generated to overcome the high transmission delay in mobile cloud computing and is more suitable for computationally intensive and delay-sensitive tasks with high task delay requirements. Therefore, unlike resource allocation in mobile cloud computing, which pays more attention to the computing resources of the data center and ignores the network resources in the transmission process, the resource management in mobile edge computing must consider the task offloading to the edge server and the transmission time for the edge server to return the task result. Because transmission time accounts for a large proportion of the total execution time of delay-sensitive tasks, finding the best matching solution for computing resources and communication resources can minimize task delays.

B. LOOM COMMUNICATION MODULE ANALYSIS DESIGN AND COMMUNICATION TEST

For the IoT module of the loom equipment, the northbound interface requires wired, wireless, positioning, and other functions. The southbound interface must support the communication of 485 and 232 buses in CAN and UART [28]–[30]. The device uses ESP32 as the core communication module, and the northbound interface supports WIFI, WIFI MESH and Bluetooth, and Bluetooth MESH communication but lacks wired communications and GPS positioning. The southbound interface supports UART communication and CAN bus communication interfaces but lacks a CAN transceiver. Therefore, the new loom circuit board should provide the interface circuit of the communication module because the core communication module is ESP32. To increase circuit reliability, the ESP32 circuit should be added. The ESP32 communicates with the primary control chip through UART and CAN, and the CAN transceiver is added. The circuit that defines the pins of ESP32 provides 2 UART interfaces (RS232, 485) and 1 CAN interface (connecting the CAN transceiver) to connect with the UART and CAN of the primary control board to meet the requirements of the southbound interface of the loom communication module. In addition, the application reserves the serial port of the ESP32 programming program, which is convenient for device upgrading and debugging. In addition to the existing WIFI, Bluetooth, and MESH network of ESP32, the northbound interface must include a wired network interface to increase network reliability. The wired network uses the Ethernet MAC of ESP32, and a PHY is attached for wired communications and uses UART to connect with the GPS module for positioning. In addition, by adding a peripheral interface, other functional modules can be connected according to requirements, such as sensors, RFID readers, LORA, etc.

ESP32 is thus expanded according to the above requirements. The required schematic diagram and PCB are drawn to include the loom PCB board, ESP PCB board and CAN transceiver, Ethernet PHY, and GPS module. The reference hardware of the loom communication module is shown in Figure 9.

The mesh nodes in the mesh network can be used as reconfigurable routing nodes, and the technology of the mesh network can be used to realize the self-organization and reconfiguration of the network. With a router, the device can connect to a wireless ad hoc network after entering the routing SSID and password. During a connection, the first module connects with the router, becomes the root node, and establishes a self-organizing network. The other 3 modules are connected to the root node as the second layer of the self-organizing network, reporting the signal strength of the network, passing the MAC address in the routing table, and trying to find the next layer node. This process goes through

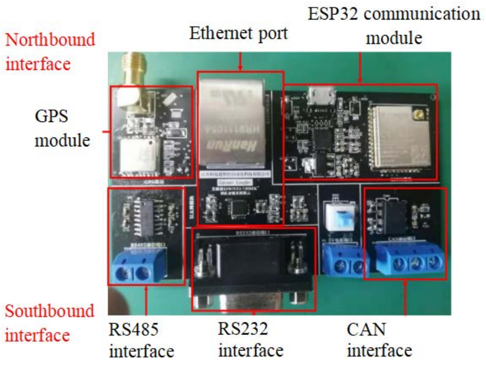


FIGURE 9. Loom communication module reference hardware.

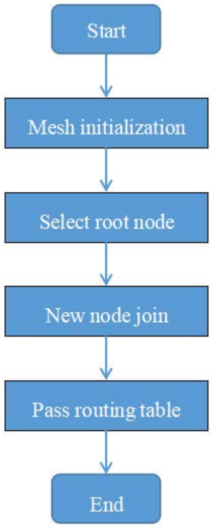


FIGURE 10. Schematic diagram of the ad hoc network networking process.

device mesh initialization; connecting routes and selecting root nodes; finding the next layer of nodes; and adding new devices to and transferring the routing table, as shown in Figure 10. The following messages are shown on the device monitor:

1. Mesh initialization message:

```
I (5550) mesh: [S2]TP_LINK_106, 8a:25:93:31:cd:62, channel:6, rssi:-70
I (5560) mesh: find router:[ssid_len:11]TP_LINK_106, rssi:-70, 8a:25:93:31:cd:62(encrypted), new channel:6, old channel:0
I (5560) mesh: [FIND][ch:0]AP:3, otherID:0, MAP:0, idle:0, candidate:0, root:0[8a:25:93:31:cd:62]router found
I (5570) mesh: [FIND:1]find a network, channel:6, cuff<channel:0, router:TP_LINK_106, 00:00:00:00:00:00>
```

2. Connection routing and selection of root node packets:

```
I (5580) mesh_main:
<MESH_EVENT_FIND_NETWORK>new channel: 6, router BSSID: 00:00:00:00:00:00
I (5590) wifi:mode: sta (7c:df:a1:00:b5:cc) + softAP (7c:df:a1:00:b5:cd)
W (5600) wifi:<MESH AP>adjust channel:1, secondary channel offset:1(40U)
I (5600) wifi: Total power save buffer number: 16
W (5620) wifi:<MESH AP>adjust channel: 6, secondary channel offset: 1(40U)
I (5620) wifi:Total power save buffer number: 16
I (5920) mesh: [SCAN][ch:6]AP:1, other(ID:0, RD:0), MAP:0, idle:0, candidate:1, root:0,
topMAP:0[c:0,i:0][8a:25:93:31:cd:62]router found<>
I (5930) mesh: 1330[SCAN]init rc[7c:df:a1:00:b5:cd,-69], mine:0, voter:0
I (5930) mesh: 1368, vote myself, router rssi:-69 > voted rc_rssi:-120
I (5940) mesh: [SCAN:1/10]rc[128][7c:df:a1:00:b5:cd,-69],
self[7c:df:a1:00:b5:cc, -69,reason:0,votes:1,idle]
[mine:1,voter:1(1.00)percent:1.00][128,1,7c:df:a1:00:b5:cd]
```

3.Find the next layer node message:

```
I (6250) mesh: [SCAN][ch:6]AP:1, other(ID:0, RD:0), MAP:0, idle:0, candidate:1, root:0, topMAP:0[c:0,i:1]
[8a:25:93:31:cd:62]router found<>
I (6260) mesh: 1330[SCAN]init rc[7c:df:a1:00:b5:cd,-69], mine:0, voter:0
I (6260) mesh: [SCAN:2/10]rc[128][7c:df:a1:00:b5:cd, -69], self[7c:df:a1:00:b5:cc, -69,reason:0,votes:1,idle]
[mine:1,voter:1(1.00)percent:1.00][128,1,7c:df:a1:00:b5:cd]
```

4. New device join message:

```
I (13600) wifi: new:<6,2>, old:<6,2>, ap:<6,2>, sta:<6,2>, prof:6
I (13600) wifi:station: 7c:df:a1:00:b6:2e join, AID=1, bgn, 40D
I (13610) mesh_main: unknown id:25
W (13620) mesh_main:
<MESH_EVENT_ROUTING_TABLE_ADD>add 1, new: 2
I (13620) mesh: <nvs>write assoc:1
I (13620) mesh_main:
<MESH_EVENT_CHILD_CONNECTED>aid:1,
7c:df:a1:00:b6:2e
I (13700) esp_netif_lwip: DHCP server assigned IP to a station, IP is: 10.0.0.2
I (15050) esp_netif_lwip: DHCP server assigned IP to a station, IP is: 10.0.0.3
```

5. Routing table message:

```
I (20009) mesh_main: Tried to publish layer:2 IP:10.0.0.3
I (20009) mesh_mqtt:
sent publish returned msg_id=39629
I (21649) mesh_main: Received Routing Table [0] 7c:df:a1:00:b5:cc
I (21649) mesh_main: Received Routing Table [1] 7c:df:a1:00:b6:2e
I (21649) mesh_main: Received Routing Table [2] 7c:df:a1:00:b6:84
```

In the self-organizing network reliability experiment, when a node that is not the root node is disconnected, the corresponding MAC address of the disconnected node is removed from the routing table of the other nodes. After the disconnected node is reconnected, its MAC address is added to the routing table. When the root node is disconnected, the entire self-organizing network is destroyed, and the routing table cannot be generated. The self-organizing network begins to reconstruct, and other nodes count the signal strength RSSI of the networking between nodes and select a new root node according to the algorithm. The new root node connects to the router and establishes an ad hoc network, and the routing table is retransmitted in each node. After the original root node is reconnected, it joins the reconstructed network. The packets of the routing table of the monitored node in these four processes are as follows:

1. The routing table message in the initial state is:

```
I (124229) mesh_mqtt: Other event id:7
I (124229) mesh_main: Tried to publish layer:2 IP:10.0.0.4
I (124699) mesh_main: Received Routing Table [0] 7c:df:a1:00:b5:cc
I (124699) mesh_main: Received Routing Table [1] 7c:df:a1:00:b6:2e
I (124699) mesh_main: Received Routing Table [2] 7c:df:a1:00:b6:7e
I (124709) mesh_main: Received Routing Table [3] 7c:df:a1:00:b6:84
```

2.After the root node is destroyed, there is no routing table, and the packet of the root node is reselected:

```
I (169929) mesh: 2004<arm>parent monitor, my layer: 2(cap:6)(idle), interval:7576ms, retries:1<>
I (170189) mesh: [SCAN][ch:6]AP:3, other(ID:0, RD:0), MAP:2, idle:0, candidate:2, root:1, topMAP:0
[c:2,i:0][8a:25:93:31:cd:62]router found<>
I (170189) mesh: 7364[selection]try rssi_threshold:-78, backoff times:0, max:5<-78,-82,-85>
I (170199) mesh: 7441[parent]not found, rssi_threshold: -78, backoff:0
I (170209) mesh: 7699[parent]not found, rssi_threshold: -78, backoff[1/max:5], try_layer:0, backoff[0/max:2]
I (170219) mesh: [FAIL][22]root:21, fail:1, normal:0, <pre>backoff:0
```

3. Routing table packet after self-organizing network reconstruction:

```
I (206619) mesh_main: Tried to publish layer:3 IP:10.0.0.4
I (206619) mesh_mqtt: sent publish returned
msg_id=31384
I (206669) mesh_main:
<IP_EVENT_STA_GOT_IP>IP:10.0.0.3
I (208559) mesh_main: Received Routing Table [0] 7c:df:a1:00:b6:2e
I (208559) mesh_main: Received Routing Table [1] 7c:df:a1:00:b6:84
I (208559) mesh_main: Received Routing Table [2] 7c:df:a1:00:b6:7e
```

4. Routing table message after node reconnection:

```
I (222509) mesh_main: Received Routing Table [0] 7c:df:a1:00:b6:2e
I (222509) mesh_main: Received Routing Table [1] 7c:df:a1:00:b6:84
I (222519) mesh_main: Received Routing Table [2] 7c:df:a1:00:b6:7e
I (222519) mesh_main: Received Routing Table [3] 7c:df:a1:00:b5:cc
```

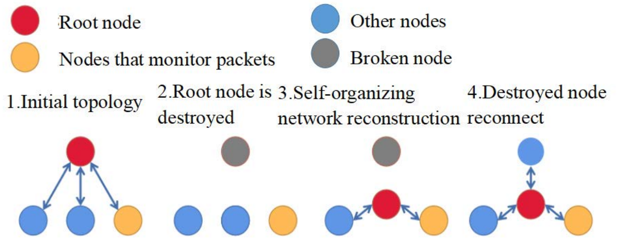


FIGURE 11. Root node failure test process.

The root node failure experiment is shown in Figure 11. When the original root node is destroyed, a new root node is selected based on the signal strength rssi size. The new root node connects to the router and establishes a self-assembling network, and the routing table is re-passed among the nodes. The original root node is reconnected and joins the reconfigured network.

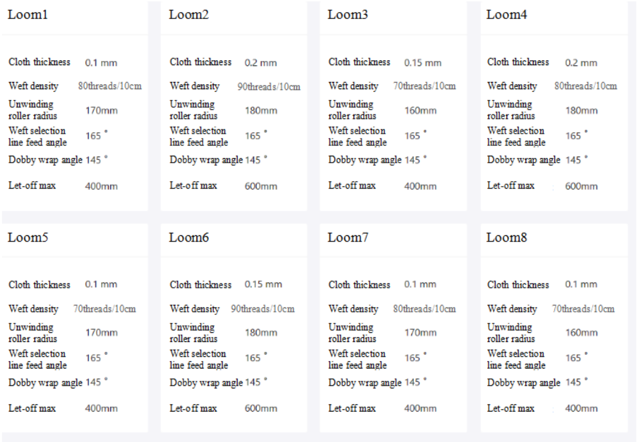
This chapter discusses the computing power network of the loom self-organization, analyzes the design requirements of the loom communication module, and lists reference hardware. The anti-destruction experiment of the key nodes of the mesh network verifies that the loom self-organization network is reconfigurable. A self-organizing computing power network for looms is proposed in this chapter, and a loom computing power network constructed by edge technology is discussed, which provides a theoretical basis for the application of edge computing in the loom self-organizing network. The simulation experiment shows that the network has the advantages of self-organization and reconfiguration, which provides theoretical support for the application of self-organization network technology in loom networks.

IV. EXPERIMENTAL PLATFORM AND TEST RESULTS

According to the requirements of the loom self-organizing network for the loom remote monitoring system, the existing B/S structure looms remote monitoring system is improved. To quickly build the loom remote monitoring system and reduce the development time, the AIRIOT low-code Internet of Things is used. The platform development tool is used to develop the application platform of the loom remote monitoring system.

A. LOOM REMOTE MONITORING SYSTEM

The loom data model is designed on a platform using AIRIOT modeled management and supports multiple protocols, including the MQTT protocol for data collection and control, which meets the platform requirements of the loom self-organizing network based on the MQTT messaging mechanism. In addition, AIRIOT has a graphical human-machine interface development process and a variety of additional functions; supports the graphical development of the



Loom1
Cloth thickness 0.1 mm
Weft density 80threads/10cm
Unwinding roller radius 170mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 400mm

Loom2
Cloth thickness 0.2 mm
Weft density 90threads/10cm
Unwinding roller radius 180mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 600mm

Loom3
Cloth thickness 0.15 mm
Weft density 70threads/10cm
Unwinding roller radius 160mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 400mm

Loom4
Cloth thickness 0.2 mm
Weft density 80threads/10cm
Unwinding roller radius 180mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 600mm

Loom5
Cloth thickness 0.1 mm
Weft density 70threads/10cm
Unwinding roller radius 170mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 400mm

Loom6
Cloth thickness 0.15 mm
Weft density 90threads/10cm
Unwinding roller radius 180mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 600mm

Loom7
Cloth thickness 0.1 mm
Weft density 80threads/10cm
Unwinding roller radius 170mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 400mm

Loom8
Cloth thickness 0.1 mm
Weft density 70threads/10cm
Unwinding roller radius 160mm
Weft selection line feed angle 165 °
Dobby wrap angle 145 °
Let-off max 400mm

FIGURE 12. **Schematic diagram of the working data monitoring of looms.**

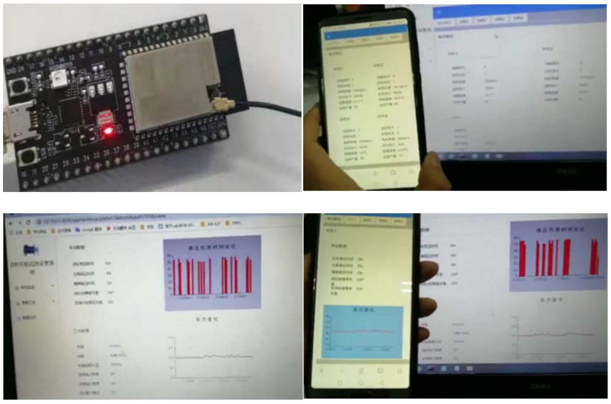


FIGURE 13. **Network communication effect of the loom remote monitoring system.**

human-machine interface, and; can quickly build a loom remote monitoring interface. The use of the AIRIOT human-machine interface development tool to remotely monitor multiple looms is shown in Figure 12. Part of the working data of multiple looms can be viewed through the loom work interface.

Network communication of the loom remote monitoring system is shown in Figure 13. The communication module builds the loom self-organizing network according to the communication requirements, transmits the loom data to the server of the loom remote monitoring system, and accesses the front-end loom monitoring through the mobile phone or computer. Loom data are shown on the interface, including the monitoring interface of a mobile phone and computer in the upper right picture and the lower right picture. The communication module is successfully connected to the router, establishes a connection with the MQTT server, and publishes the loom data to the MQTT server. The server of the loom remote monitoring system successfully subscribes to the loom data on the MQTT server. Loom data are shown on the man-machine interface. Both the mobile phone interface and the computer interface conform to the size, which can not only monitor the important equipment parameters of multiple looms, such as looms 1 through 4 in the upper right picture, but also monitor the important data of a single loom in detail and can make data reports to facilitate the analysis of data, such as the monitoring interface of single loom equipment in the lower left and lower right pictures. Therefore, the self-organizing loom network meets the needs of the loom remote monitoring system. The self-organizing loom network designed by the project provides communication between loom equipment, and loom data transmission can be achieved through the loom MQTT message transmission mechanism.

Through the self-organizing network communication, the loop self-organizing network can perform required communications. However, wireless communication is not as reliable as wired communication. When the signal between the wireless communication module and the router is poor, loom data will be missed or inaccurately transmitted. The nodes in the loom self-organizing network periodically test the signal strength of the connection with the neighboring nodes. When the signal strength of the connection between the node in the loom self-organizing network and the upper-level node decreases, the signal strength of the upper-level node and the adjacent node will be compared, and the upper-level node will be reselected. Therefore, the self-organizing network of the loom is more suitable for the industrial field with a complex environment than the traditional wireless network.

To demonstrate this effect, a communication experiment, as shown in Figure 14, is designed. The communication scenario during normal work is simulated by letting the communication module send a fixed set of data to the server of the loom remote monitoring system cyclically. We thus perform the following experimental steps:

1. First, we prevent the communication module from joining the self-organizing network to communicate directly with the router. The module must then send data to the node with a better signal to the router and thus determine the correct loom data on the remote monitoring interface;

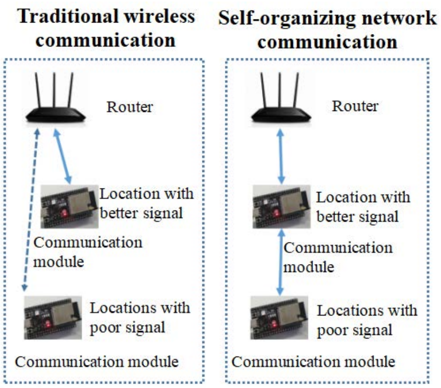


FIGURE 14. **Experimental design of loom self-organizing network communication.**

2. Then, we send data at the position where the signal of the router deteriorates, where some loom data failed to be transmitted successfully on the remote monitoring interface;
3. We then let the communication module join the self-organizing network. There are nodes in the network where the router signal is better. We let the communication module send data at the position where the signal of the original router is worse, and the correct loom data can be shown on the remote monitoring interface.

A comparison of the data collected by the loom remote monitoring interface is shown in Figure 15. Line 1 shows the tension data collected under a good signal using the ordinary WiFi network; Line 2 shows the tension data collected under the poor signal using the ordinary WiFi network, and; Line 3 shows the tension data collected under a poor signal using the self-organizing network. The tension data collected by the self-organizing network under a poor signal coincide with the tension data collected by the ordinary Wi-Fi network under a good signal, and the experimental results generally agree with expectations, demonstrating that a self-organizing loom network performs better and is more suitable for industrial sites with complex environments than a traditional wireless network.

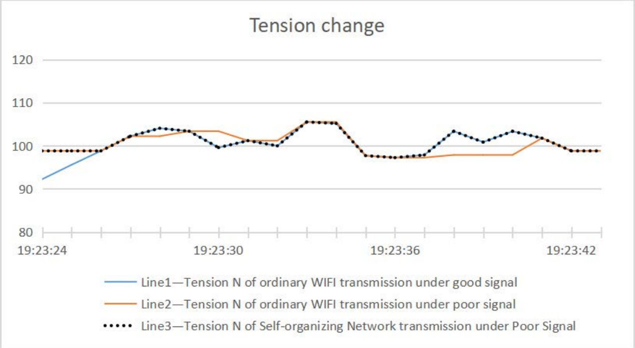


FIGURE 15. **Experimental effect of loom self-organizing network communication.**

B. LOOM SELF-ORGANIZING NETWORK RELIABILITY AND ANTI-JAMMING TEST

When the loom network communicates wirelessly, it is affected by controllable factors, such as communication module transmission power, receiving sensitivity, anti-interference ability, the antenna type, and gain, and by environmental interference, communication blocking, and other uncontrollable factors. Therefore, the reliability of the conventional wireless communication method must be improved. QoS can improve network performance and ensure network service security. The QoS of a network is comprehensively measured by the transmission bandwidth, transmission delay, data packet loss rate, and network jitter, and is closely related to the networking method. The self-organizing network can switch objects connected to a wireless network. When the connection of some two nodes in the self-organizing network is disturbed, and the QoS is too low, these two nodes can connect to other nodes that are not disturbed or suffer less interference to improve the QoS of the network connection.

The reliability test of the self-organizing loom network is shown in Figure 16. When a normal wireless network is interfered by an interference source, it causes the QoS of the nodes to be too low, which affects the network communication. In the same case, when a self-organizing network is interfered by an interference source, the interfered node will connect to the node on the other side of the interference source, thus reducing the impact of the source.

Compared with ordinary wireless networks, ad hoc networks can more easily ensure a certain QoS. A common wireless network is constructed using the loom communication module, and multiple nodes are connected to the router. The QoS of ordinary wireless networks depends on routers, which transmit adjacent frequency interference signals near a certain node, impose communication blocking interference, and make the QoS of the node too low. Due to the limited QoS capability of routers, nodes in ordinary wireless networks cannot communicate normally. The self-organizing network is constructed using the loom communication module, and the same interference is imposed on the previous nodes so that the QoS of the nodes is too low. Self-organizing networks are reconstructed using network optimization algorithms. The interfered node in the self-organizing network disconnects the original interfered connection and establishes a connection with the node conversely of the interferer. The nodes that are reconfigured in the self-organizing network have normal QoS and can communicate normally. Therefore, it is easier for the self-organizing loom network to guarantee the QoS of the network.

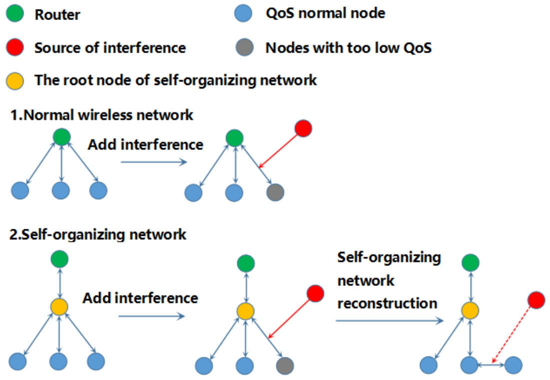


FIGURE 16. **Reliability test of loom self-organizing network.**

The abovementioned self-organized network reliability test is performed on multiple loom equipment in the loom production workshop, and the experimental results agree with expectations. However, when the number of devices in the loom network increases, the data transmission of the loom equipment is affected, and further testing is required. In the loom network, the data collected by the onboard monitoring system of the loom are transmitted to test the effect of the loom data transmission under large-scale data transmission. In the test, the rotation speed and warp tension of the loom equipment are selected as data samples with high real-time requirements. The cutter current, braking distance, temperature, humidity, and oil temperature are selected as data samples with general real-time requirements, and work efficiency is selected as real-time data samples. Data samples with lower requirements are used to test the data transmission of the loom equipment.

After analyzing the data collected by the loom analog, the average loom spindle speed measured via remote monitoring is found to be 330.01 RPM, which is near the real system's set value; the maximum deviation is 1.01 RPM, and the relative error is less than 0.31%, which agrees with the loom spindle speed. The average warp tension value measured via remote monitoring of the loom is 110.00 N, which is the same as the real system set value; the maximum deviation is 0.34 N, and the relative error is less than 0.31%. The data transmission with strong real-time data transmission thus meets the monitoring requirements. The relative error of data sample transmission with general real-time transmission and weak real-time transmission also meets monitoring requirements. The effectiveness analysis of loom data transmission is shown in Table 1. By analyzing the indicators of the attribute data in the table, the loom data is shown to be transmitted stably and reliably.

TABLE 1. Analysis of the effectiveness of loom data transmission.

Attributes	Set value	Sample average	Maximum value	Minimum value	Maximum deviation	Relative error /%
Rotating speed	330.00	330.01	330.75	328.99	1.01	0.31
Warp tension	110.00	110.00	110.25	109.66	0.34	0.31
Cutter current	--	4.23	4.24	4.22	0.02	0.28
Braking distance	--	474.99	476.08	473.54	2.54	0.30
Temperature	--	31.58	31.65	31.48	0.10	0.32
Humidity	--	26.73	26.79	26.64	0.14	0.34
Oil temperature	--	32.11	32.18	32.01	0.10	0.31
Work efficiency	--	87.00	87.20	86.73	0.27	0.31

The production workshop where the self-organizing network of the loom is located is subject to the interference of electrical equipment, the noise of mechanical vibration, the addition and movement of signal sources, the flow of vehicles, the stacking of goods, the change of equipment location, and the blocking of production facilities. Thus, the original connection will be interrupted due to interference, and the disconnected node must rejoin the self-organizing network. Due to interference, the interrupting node cannot restore its previous connection and must wait until the interference disappears or weakens to be reconnected, requiring manual maintenance. In the real production workshop, the nodes of the self-organizing network of the loom are distributed around the workshop, and the interference of a certain direction or a certain area will not affect the connection between nodes in other directions and areas. Therefore, the self-organizing network of the loom should be able to continue operation despite interference; however, it is necessary to perform a network anti-interference test.

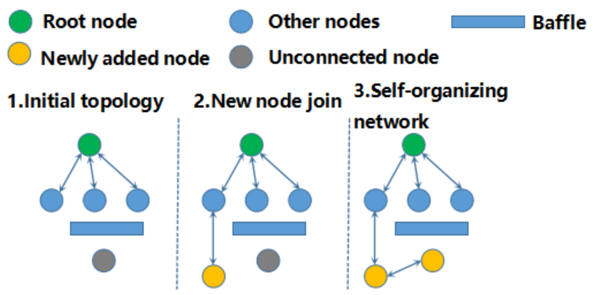


FIGURE 17. Anti-interference test of the loom self-organizing network.

Nodes that are interrupted due to interference in a certain direction can rejoin the loom self-organizing network by establishing connections with nodes in other directions to verify that the loom self-organizing network has certain robustness to interference. First, a loom self-organizing network is constructed by multiple nodes, and the nodes at the edge of the network are blocked by baffles. By monitoring the routing table of the self-organizing network of the root node, we know that this node is disconnected from the self-organizing network of the loom to simulate the situation in which the nodes in the self-organizing network of the loom are disconnected due to interference from a certain direction. Then, a new node is placed on the side of the baffle where the network signal is stronger, and the new node joins the loom self-organization. The MAC of the new node can be monitored at the root node, simulating the situation that there are nodes with less interference in other directions near the disturbed node. Finally, we monitor the routing table of the root node and find that the MAC of the node disconnected due to interference reappears in the routing table. The self-organizing network reconstruction avoids the situation in which the nodes are disconnected due to interference in a certain direction, and the loom cannot be reconnected to the self-organizing network. This test verifies that when the nodes of the self-organizing loom network are distributed around the production workshop, it can resist interference in a certain direction or area. Because the interference that is typically sufficient to force the nodes in the loom network to disconnect is limited to a certain direction or a small area in real production, this test can demonstrate that the loom self-organizing network has anti-interference abilities. The self-organizing network of looms in the production workshop can resist the environmental disturbances that are generally received, and the anti-interference test of the loom self-organizing network is shown in Figure 17.

V. CONCLUSION

Due to the new demands of future industrial Internet development and ‘‘intelligent manufacturing’’ for loom networks, this study applies self-organizing network technology to loom production and investigates loom interconnections and self-organizing networks for the autonomous transmission of information. To solve the problem of poor reconfigurability in loom networks, this study analyzes the networking principle of loom self-organizing networks based on ESP-Mesh technology to construct mesh networks and proposes a loom self-organizing computing power network. This paper discusses the computing power network of the loom constructed by edge technology, analyzes the design requirements of the communication module of the loom, and provides the reference hardware. The simulation experiment shows that the proposed network has the advantages of self-organization and reconfiguration, which provides theoretical support for the application of self-organization network technology in loom networks. The anti-destruction experiment of the key nodes of the mesh network verifies that the self-organizing loom network is reconfigurable. By building the experimental platform for an interconnected self-organizing network of looms, the experiment platform is used to perform network communication experiments, and network reliability and anti-interference tests are performed. The interconnected self-organizing network of looms studied in this paper can meet the industrial requirements of network communication for the remote monitoring system of looms. Compared with the previous wireless communication networks that can achieve remote monitoring of loom systems, the loom interconnection self-organizing network achieves stronger reliability and higher anti-interference ability, and thus better meets the network requirements of intelligent manufacturing for loom equipment. In the actual loom industry, data interaction between looms is required, and data communication can be achieved through the self-organizing network studied in this paper, which can avoid problems such as poor communication efficiency due to interference from the loom weaving environment. This study provides an effective example of loom networking technology for the industry, which has certain significance for promoting the construction of loom smart factories.

With the development of industrial needs in the future, the self-organizing network of looms based on mesh technology provides the following improvements:

1. In this paper, a self-organizing network of looms is designed so that the Internet of Looms has the advantages of self-organization and reconfiguration; improves the reliability of the wireless network of interconnected looms; and provides a low-cost wireless transmission scheme. Restricted by research conditions, the issue of network communication security is not investigated in this study. In the practical application of the loom interconnected self-organizing network, the guarantee of network security is a critical research topic.

2. Due to the limitations of experimental conditions and professional background, the self-organizing network of the loom studied in this paper cannot be verified in a large-scale equipment interconnection network. The ESP-MESH technology used can theoretically build a mesh network of 1000 devices but only in communication. This technology has been verified in the Internet of Things with fewer tasks but has not been verified in industrial applications. With the exponential growth of the number of networked devices and the further development of industrial internet technology, the topic of this study should be investigated in the future and combined with engineering practice.

REFERENCES

[1] Z. Chen and M. Xing, "Upgrading of textile manufacturing based on industry 4.0," in *Proc. 5th Int. Conf. Adv. Design Manuf. Eng.*, 2015, pp. 2143–2146.

[2] Y. W. Deng, "Research and development of intelligent air-jet high-speed loom network management control system based on CAN bus and web technology," Tech. Rep., 2014.

[3] Q. Wang, "Design of air-jet loom remote monitoring system based on B/S architecture," Tech. Rep., 2017.

[4] S. S. Wang, L. H. Peng, C. Y. Shen, and X. D. Hu, "Construction technology of cloud platform for knitting equipment," *J. Tex*, vol. 39, no. 1, pp. 149–155, 2018.

[5] Y. L. Wang, "Research on data transmission and content sharing mechanism of wireless Ad Hoc network," Tech. Rep., 2018.

[6] T. H. Zhang, "Research on efficient intelligent access mechanism in UAV self-organizing network," Tech. Rep., 2020.

[7] X. X. Song, "Research on time synchronization technology of wireless Ad Hoc network," 2018.

[8] X. Q. Qiao and Y. K. Huang, "Decentralized artificial intelligence theory and technology for 6G," *Mobile Commun.*, vol. 44, no. 6, pp. 121–125, 2020.

[9] K. David and H. Berndt, "6G vision and requirements: Is there any need for beyond 5G?" *IEEE Veh. Tech Mag.*, vol. 13, no. 3, pp. 72–78, Jul. 2018.

[10] M. Coutinho, R. de Oliveira Albuquerque, F. Borges, L. García Villalba, and T.-H. Kim, "Learning perfectly secure cryptography to protect communications with adversarial neural cryptography," *Sensors*, vol. 18, no. 5, p. 1306, Apr. 2018.

[11] Y. Liu and M. Peng, "6G endogenous security: Architecture and key technologies," *Telecommun. Sci.*, vol. 1, no. 1, p. 11, 2020.

[12] Y. Zhao, G. Yu, and H. Xu, "6G mobile communication networks: Vision, challenges, and key technologies," *SCIENTIA SINICA Informationis*, vol. 49, no. 8, pp. 963–987, Aug. 2019.

[13] P. Zhang, K. Niu, H. Tian, G. F. Nie, X. Q. Qin, Q. Qi, and J. Zhang, "6G mobile communication technology prospect," *J. Commun.*, vol. 1, 2019.

[14] *5G for Connected Industries and Automation*, 5G ACIA, ZVEI-Ger Elect. Manufactur, Frankfurt, Germany, 2018.

[15] E. A. Jarchlo, J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "To mesh or not to mesh: Flexible wireless indoor communication among mobile robots in industrial environments," in *Proc. Int. Conf. Ad-Hoc Netw. Wireless*, Jul. 2016, pp. 4–6.

[16] C. Sauer, M. Schmidt, and M. Sliskovic, "Delay tolerant networks in industrial applications," in *Proc. 24th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2019, pp. 10–13.

[17] H. I. Kobo, A. M. Abu-Mahfouz, and G. P. Hancke, "A survey on software-defined wireless sensor networks: Challenges and design requirements," *IEEE Access*, vol. 5, pp. 1872–1899, 2017.

[18] C. Sauer, M. Schmidt, and E. Lyczkowski, "On ad hoc communication in industrial environments," *Appl. Sci.*, vol. 10, no. 24, p. 9126, Dec. 2020.

[19] D. J. Renyao, Z. W. Qi, H. B. Guan, and L. Chen, "Current situation and prospects of industrial internet edge intelligence development," *Chin. Eng. Sci.*, vol. 23, no. 2, pp. 104–111, 2021.

[20] K. L. Li and C. B. Liu, "Edge intelligence: State-of-the-art and expectations," *Big Data*, vol. 5, no. 3, pp. 72–78, 2019.

[21] J. S. Fu, Y. Liu, H. C. Chao, B. K. Bhargava, and Z.-J. Zhang, "Secure data storage and searching for industrial IoT by integrating fog computing and cloud computing," *IEEE Trans. Ind. Informat.*, vol. 14, no. 10, pp. 4519–4528, Jan. 2018.

[22] M. Satyanarayanan, "A brief history of cloud offload: A personal journey from odyssey through cyberforaging to cloudlets," *GetMobile, Mobile Comput. Commun.*, vol. 18, no. 4, pp. 19–23, 2015.

[23] G. Hirschfeld and C. Thiele, "Cloud-based simulation studies in R-A tutorial on using doRedis with Amazon spot fleets," *Statist. Med.*, vol. 38, no. 20, pp. 3947–3959, Sep. 2019.

[24] Y. J. Wang, "Research and implementation of high-performance database engine based on Redis," Tech. Rep., 2017.

[25] R. L. Wang, "Research and application of web publishing in substation SCADA system," Tech. Rep., 2015.

[26] M. Barati, Q. Bai, and Q. Liu, "Automated class correction and enrichment in the semantic web," *J. Web Semantics*, vol. 59, Dec. 2019, Art. no. 100533.

[27] C. H. Yuan, "Research on remote monitoring system of lithium battery pole piece rolling mill," Hebei Uni.Tech, Tech. Rep., 2018.

[28] J. W. Wei, "Student IoT management system based on ESP8266," *Shanxi Electr. Tech.*, vol. 4, pp. 66–68, 2019.

[29] D. M. Wang, L. Wang, and G. M. Zhang, "Short-term wind speed forecast model for wind farms based on genetic BP neural network," *J. Zhejiang Univ.*, vol. 46, no. 5, pp. 837–841, 2012.

[30] Y. Xiao, F. Han, Y. Ding, and W. Liu, "Research on fault diagnosis method of rapier loom based on the fusion of expert system and fault tree," *J. Intell. Fuzzy Syst.*, vol. 41, no. 2, pp. 3429–3441, 2021.

[31] Y. Xiao, H. Zhang, C. Yuan, N. Gao, Z. Meng, and K. Peng, "The design of an intelligent high-speed loom industry interconnection remote monitoring system," *Wireless Personal Commun.*, vol. 113, no. 4, pp. 2167–2187, 2020.

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