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E2HRC: An Energy-Efficient Heterogeneous Ring Clustering Routing Protocol for Wireless Sensor Networks

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ABSTRACT A heterogeneous ring domain communication topology with equal area in each ring is presented in this paper in an effort to solve the energy balance problem in original IPv6 routing protocol for low power and lossy networks (RPL). A new clustering algorithm and event-driven cluster head rotation mechanism are also proposed based on this topology. The clustering information announcement message and clustering acknowledgment message were designed according to RFC and original RPL message structure. An energy-efficient heterogeneous ring clustering (E2HRC) routing protocol for wireless sensor networks is then proposed and the corresponding routing algorithms and maintenance methods are established. Related messages are analyzed in detail. Experimental results show that in comparison against the original RPL, the E2HRC routing protocol more effectively balances wireless sensor network energy consumption, thus decreasing both node energy consumption and the number of control messages.

INDEX TERMS Wireless sensor network, clustering algorithm, routing algorithm, E2HRC.

I. INTRODUCTION

A wireless sensor network is composed of wireless sensor nodes and a sink node. Nodes are wirelessly interconnected to one another and to the sink. These networks are characterized as Low-power and Lossy Networks (LLNs), as individual nodes possess limited power and operate in harsh environments. If a node is not in direct communication range with the sink, the data it captures is reported in a multi-hop manner. In this way, nodes located closer to the sink end up relaying data for nodes that are farther away, thus creating hotspots near the sink. These hotspot nodes tend to deplete energy faster, thus reducing the wireless sensor networks lifetime. Wireless sensor network energy consumption is a popular research topic [1], [2]. Considering of LLN characteristics and possible applications, the Internet Engineering Task Force (IETF) Routing Over Low-power and Lossy networks (ROLL) group has standardized a low-power and lossy network routing architecture called RPL [3], [4]. This protocol is an open and accepted technical standard in regards to wireless sensor network IP-based development. The salient design feature of RPL is a routing framework that allows the use of different routing metrics and objective functions (OFs) to manage LLNs, including limitations and heterogeneous application requirements.

Many other RPL-based routing protocols have been proposed for different optimization objects. Hakeem *et al.* [5], for example, investigated packet forwarding and other factors to find that when nodes number is 150, the network is stable enough to satisfy practical application general requirements (based on the cortex M3-nodes for original RPL routing protocol in networks [6]). Li [7] utilized an original RPL protocol implemented by TinyRPL and contikiRPL operating systems to test real-world performance per factors including routing fairness and packet delivery rate; the results showed that the protocol merits further improvement in regards to network packet and routing control packet overhead. Gaddour and Koubaa [8] tested energy consumption, packet delay, and packet loss rates of the original RPL protocol to find that energy consumption and packet loss rates significantly increase as the number of network nodes increases.

The original RPL routing protocol is planar and the objective function is singular, rendering it unable to adapt to the excessive packet numbers that accompany an excessive number of nodes. Iova *et al.* [9] performed detailed test and performance analyses of the original RPL routing protocol to explore end-to-end delay, DIO packet transmission, and other parameters. The results showed that the network is flooded with control packets as soon as route maintenance becomes necessary. These control packets substantially impact overall energy efficiency and network stability.

Due to sensor node's nature of limited battery capacity, how to design energy-efficient network architecture has been the important research issue in wireless sensor networks. the method by grouping sensor nodes in to clusters has been widely applied in wireless sensor network in order to achieve energy-efficient and long-lived objective[10]. Cluster based structure is seen to have more advantages than other network model, including scalability, ease of dada fusion and robustness. A cluster composed of normal sensor nodes and cluster heads. The normal sensor nodes are responsible for sending the real-time data. Cluster heads are the core units of WSNs[11]. Cluster heads communicate directly with sensor nodes and forward sensor data to the sink. The sink can also be called the gateway node which is a special node with relatively strong computation power in the WSNs. The gateway nodes are responsible for receiving and forwarding the relevant data to the user and sensor node[12].

If the inter-cluster transmission mode in the wireless sensor network clustering routing algorithm is single-hop transmission, the outer cluster head nodes will be located far away from the base station. Inner cluster head node energy consumption is greater than that of other nodes due to lengthy transmission distance [13], [14]. If the inter-cluster transmission mode is multi-hop, the inner nodes will be close to the sink and consume more energy due to the large amount of data transmitted to them from outer cluster head nodes [15]. In a ring domain multi-sector cluster network, the inter-cluster transmission mode is generally multi-hop, meaning the outer cluster head nodes send data layer-by-layer through the cluster head node of the adjacent ring to the sink [16]. The optimal cluster number of each ring makes the size of the outer cluster larger than that of the inner cluster, thus intra-cluster transmission energy consumption carried out by the outer cluster head nodes is higher than that of intra-cluster transmission carried by the inner cluster head nodes [17]. In a uniform split ring, the larger area of the outer cluster produces additional transmission energy consumption [18]. Inner and outer cluster region shape is thus made more uniform by imposing a non-uniform split ring structure [19]. However, an uneven split ring can also balance inner and outer cluster head energy consumption owing to an increase in outer ring spacing.

In this study, we designed a heterogeneous ring clustering algorithm and E2HRC routing protocol that minimizes overall energy consumption and balances the consumed energy. Relative messages were also designed and implemented based on original RPL routing protocol message structure.

The remainder of this paper is organized as the follows: Section II elaborates on related works and our contributions; Section III establishes a topology control model based on the ring communication area; Section IV describes the E2HRC clustering algorithm; Section V presents the E2HRC routing algorithm; Section VI presents the results of our experiments; and Section VII offers a conclusion.

II. RELATED WORKS

The RPL is an IPv6 distance vector routing protocol designed for networks with limited resources (energy, computation, etc.) [20]. The RPL works by constructing a connection tree, called Destination Oriented Acyclic Graph (DoDAG), to relay traffic from many sensors to all nodes.

To build this DoDAG, RPL calculates an objective function defined as a combination of metrics and constraints. This function allows the best path to the destination to be chosen. Metrics and constraints are managed as RPL introduces new ICMPv6 (Internet Control Messages Protocol) messages. Each node periodically broadcasts a DIO (DoDAG Information Object) message to advertise graph characteristics (objective function, node rank, etc.). Each node joins a DoDAG and maintains its path towards the sink [21]. A node broadcasts a DIS (DoDAG Information Solicitation) when it needs to join the DoDAG and immediately receive DIO. The DAO (DoDAG Destination Advertisement Object) is transmitted by each node to validate the path choice and to notify the selected parent. This parent then sends a DAO acknowledgment to the sender node when it receives the DAO.

Kim *et al.* [22] addressed the downward routing reliability problem in RPL and designed an asymmetric transmission power-based network where the root directly transmits downlink packets to destination nodes using higher transmission power than low power nodes possess. Ko *et al.* [23] proposed the interoperability problem of two operation modes (MOPs) defined in the RPL standard, ultimately demonstrating that there is a serious connectivity problem when two MOPs are mixed within a single network. The DualMOP-RPL, which allows nodes with different MOPs to communicate gracefully in a single network while preserving the high bi-directional data delivery performance, was established to solve this problem. None of these studies have investigated RPL load balancing problems over a real multi-hop LLN testbed, however [24].

Many energy consumption algorithms have been proposed to optimize and improve original RPL routing protocol. Gaddour *et al.* [25], for example, proposed the CO-RPL, which functions by using multiple route selection to improve the original RPL object function. CO-RPL exhibits better energy consumptions and packet pass rates than original RPL, but packet congestion and control packet flooding are still possible in large-scale wireless sensor networks. Zhang *et al.* [26] established a new RPL routing object function based on energy-efficiency, but only energy conservation (not energy balancing) is considered during routing.

A multi-father node routing strategy was proposed for the original RPL by Iova *et al.* [27] that can increase wireless sensor network redundancy, increase stability, balance energy consumption, and extend lifespan. Even with this routing maintenance and routing reconstruction, the network is still congested by a large number of packets; node memory becomes exhausted with an increase in redundant routes, necessitating more node memory to satisfy the performance requirement.

Research indicates that hierarchical networks have unparalleled advantages over other networks. Yu *et al.* [28] proposed an energy-aware clustering algorithm to solve unbalanced energy dissipation accompanied by a new routing algorithm based on this clustering algorithm; the routing algorithm operates by dividing a nodes competitive radius when attempting to join a cluster. The node with the most energy is then selected.

Yan *et al.* [29] built a clustering topology control algorithm based on a wireless sensor network with an uneven gradient. Other nodes calculate their own weight and send these weights to their neighbors to participate in cluster head selection based on global parameters transmitted by the sink. Nodes with powerful communication capabilities are effectively selected as cluster head nodes, however, this causes nodes to send too many campaign control messages, resulting in a flood of control messages to the wireless sensor network and essentially wasting node energy.

Liu *et al.* [30] proposed the EDUC algorithm based on the probability model with regards to energy and distance. To be specific, the avoiding time message that the candidate cluster heads send to campaign control is calculated according to node energy and distance: The more energy a node has and the closer it is to the sink, the shorter the avoiding time. It is thus likely that a certain node becomes a real cluster head. This algorithm may cause a large number of nodes close to the sink to become cluster head nodes, however. When cluster head nodes are unevenly distributed in the wireless sensor network, the traffic is increased in the clusters; further, the routing convergence time is longer due to low network power and low loss.

Liu and Qiu [31] proposed a multiple hop clustering routing algorithm (RBMC) based on ring structure in which the communication area is divided into uniformly spaced concentric circles, thus realizing multiple hop communication between clusters supposing there is equal energy consumption in each ring. The number of cluster head nodes in each ring can then be calculated successfully. This algorithm can balance energy consumption in the wireless sensor network, while uniformly spaced concentric circles create an inner ring coverage area that is smaller than the outer ring thus preventing an energy hole in the inner nodes; the packet loss rate increases greatly due to signal interference from crowded nodes in inner clusters, however.

In the scheme proposed by Krishnan *et al.* [32], each node confirms the avoiding time associated with their sending clustering establishment message by calculating its own threshold. If the threshold is greater, the cluster establishment situation is better and avoiding time is shorter. This method can effectively distribute cluster heads very evenly, however, undesired nodes will be elected to the cluster head if each nodes avoiding time is too short or the communication link is not stable enough. The routing convergence time also increases if the avoiding time of each node is too long. This method is not suitable for low power, low loss networks.

The main contributions of this paper are as follows:

1) A topology control model based on ring domain communication routing is proposed. Nodes are divided into different levels in this model based on different positions. Various ring domains are also divided based on different levels. This causes the next hop node with optimal direction angle to be selected during inter-ring domain communication, thus reducing the energy consumed by sending and receiving data packets.
2) A clustering algorithm for a routing protocol based on energy balance is proposed. A clustering probability model is used to divide the network into various sized heterogeneous clusters based on node residual energy and relative node position in the cluster. A combination of heterogeneous cluster and cluster head rotation mechanisms serves to balance node energy consumption in the network to avoid the generation of a network energy hole.
3) The E2HRC routing protocol based on energy-efficient heterogeneous ring clustering is described in detail, including those messages for clustering, clustering rotation, route establishment, and route maintenance.

III. TOPOLOGY CONTROL MODEL BASED ON RING COMMUNICATION

Sensor node antennas are generally omni-directional in practical applications, allowing wireless signals to spread outward in spherical waves. However, the signal spreads in a circular wave in the two-dimensional plane. Thus, nodes in the same domain in the ring radius also receive wireless signals without considering channel interference. Ring domain communication topology can effectively use 360° signal transduction while also reducing message collision during the transmission process. Here, we determined the domain grade based on the received signal strength indicator (RSSI). Signal intensity decreases during the wireless signal transmission process as transmission distance increases. We can thus transform signal intensity attenuation as signal transmission distance, using the function between signal strength attenuation and signal transmission distance to approximate the distance - this is the principle of distance measurement based on RSSI. We then calculated the radio signal transmission power and the relational expression to determine the distance between the source and the sink, allowing us to determine whether or

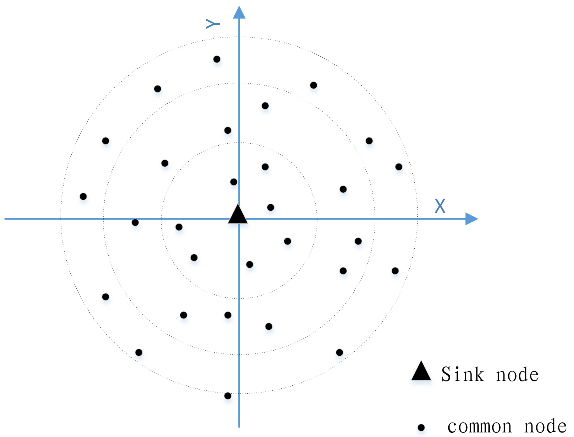

FIGURE 1. Topology of ring communication.

not the node belongs to the gradient ring. This topology is shown in Fig.1.

We then determined the node ring domain levels. The node maximum transmit power and minimum sensing power are specified in IEEE 802.15.4. Per the class divisions, we only specified the relationship between different ring radii and not the specific first-layer ring domain radius size. We then set the third layer loop domain boundary as the minimum sensing power boundary point to guarantee network coverage and routing model availability. The node level ring domain communication topology thus inherits original RPL rank parameters, effectively avoiding routing loopback and maintaining existing routing protocol advantages. This structure was introduced to make clustering boundaries clear and to effectively control the size of the heterogeneous cluster, providing effective input parameters for the sensor network clustering algorithm.

IV. E2HRC CLUSTERING ALGORITHM

In a low-power, vulnerable wireless sensor network, the node location is fixed and the link relatively unstable. This allows only one cluster to form during the network operation period. During cluster head rotation, events are defined based on the cluster head rotation mechanism. There is no need to introduce clustering round number parameters in the cluster probability mode assuming that the initial node energy is isomorphic. Cluster probability threshold $T_{k,j}(s)$ is defined as follows:

$$T_{k,j}(s) = \begin{cases} \frac{C_{ch}(k)}{\frac{N}{C}} * \frac{E_{left}(j)}{E_{init}(j)} * \omega & s \in G(k) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where the subscript k represents the first k layer circle, j represents the first j node in the first k layer circle, $C_{ch}(k)$ represents optimal cluster head nodes in the first k layer, k is total number of nodes in the ring communication area, C is the number of rings in the ring communication area, ch represents a cluster head, $E_{left}(j)$ is residual node energy, $E_{init}(j)$ is initial node energy, ω is a cluster adjustment factor, $G(k)$ represents all nodes in the k layers annular communication regions, and represents any node in $G(k)$.

A. CLUSTERING ALGORITHM DESCRIPTION

Before describing the clustering algorithm, we will first define the following data structure.

Definition 1 (Global Configuration Information I): $I = \{S, N, C\}$, where S is the total area of network coverage; N is the number of nodes in the network; C is the total number of rings of the network.

Definition 2 (DIO_CLUSER Data Packet): Packet contains global configuration information of the Network I belonging to the domain layer k, the ring domain clustering probability threshold $T(k)$, and the optimal cluster head number $C_h(k)$.

Definition 3 (DIO_CCH Data Packet): Candidate cluster head data packet contains the address information Addr, remaining energy E, domain k, and the distance from the cluster head node d_{head} of cluster head candidate node.

Definition 4 (DIO_CH Data Packet): Cluster head notification data packet contains layer domain k belonging to cluster head and address information.

The algorithm can then be described step-wise as follows:

- The sink is used to calculate clustering probability threshold nodes $T(k)$ in each layer ring communication area based on network global configuration information and cluster probability model. This global configuration information and threshold $T(k)$ are encapsulated in the DIO_CLUSER data packets and multicast.
- The ring domain is determined and $T(k)$ is analyzed in the DIO_CLUSER data packet based on the distance between RSSI and the sink, where a random number h is then generated after receiving the DIO_CLUSER data packet.
- If the random number h is less than $T(k)$, the node becomes the candidate cluster head node and sends the multicast to the DIO_CCH packet.
- If the candidate cluster head A receives the DIO_CCH data packet sent by cluster head B, the packet is first assessed whether it belongs to the same ring domain. If it does not, the packet is discarded; if it does, the candidate cluster head election criterion $\alpha E + \beta d$ is used to calculate and compare the two values, with α and β as weight values and $\alpha + \beta = 1$. E is the ratio of the current energy to the initial energy of the node A, d is the ratio of the distance from node A to its original cluster head to the maximum distance of single-hop communication. If node A has a small value, it reflects the status of candidate cluster nodes, sends DAO_CH data to node B, and selects node B as the network cluster node.
- Before sending the DIO_CH data packet, each candidate cluster head node waits for a certain time to become the cluster head node. Based on target function (Object Function, OF), the common nodes select cluster head nodes and send DAO_CH packets to the cluster.

- Unless the cluster head node has not received any DIO_CH packets, the node initially sends DIS_CH data out to seek cluster head nodes. The node automatically becomes the cluster head node and sends multicast DIO_CH packets if the cluster head node has still not been identified.
- The entire network clustering process is complete once all nodes are successfully integrated into the cluster.

In the clustering process, the entire wireless sensor network contains nodes in the ordinary state, candidate cluster head nodes, and the cluster head nodes defined by different conversion conditions.

B. CLUSTER HEAD ROTATION MECHANISM

Cluster head node energy consumption is much greater than that of a common node because it serves as the message packet forwarder in the present cluster and conducts message forwarding between the backbone networks. If no cluster head rotation mechanism is provided, an energy hole readily forms in the network, leading to local and even entire network paralysis. There is a great deal of control message transmission and data packet transmission interference when conventional regular replacement of the cluster head mechanism is applied to a low-power lossy network, thus inducing network throughput. In this case, cluster head node rotation leads to global repair of the backbone network, consuming a significant amount of energy. We propose an event-based cluster head rotation mechanism with the following packet definitions.

Definition 5 (DIO_CH_POISONING): Cluster head rotation data packet, including cluster head node address Addr belonging to the ring domain class Rank.

Definition 6 (DIO_CH_POISONING_ACK): Clusterhead node rotation response data packet.

Definition 7 (DIO_CH_APP): Cluster head node appointment packet, including cluster head node address Addr appointment.

Definition 8 (DIO_CH_LOSE): Cluster head node lost contact data packet. When cluster nodes fail to connect a certain number of times, data packets are multicast to other cluster nodes.

Cluster head rotation events are triggered when cluster head energy drops to the set energy threshold or when contact with the cluster head node is unexpectedly lost, thus launching a new cluster head selection. Cluster head rotation is triggered under different initiators utilizing two mechanisms: Cluster head node initiation and non-cluster head node initiation.

During cluster head rotation initiated by the cluster head node, cluster head node energy consumption reaches a threshold E_0 and cluster head nodes multicast DIO_CH_POISONING data packets to initiate rotation and local repair in the backbone network within the network structure. After the cluster node receives DIO_CH_POISONING, the cluster head node is sent response packet DIO_CH_POISONING_ACK, and calculates the appropriate candidate cluster head node based on each sending nodes packet parameters followed by the sending of the DIO_CH_APP packet. After the backbone network node receives DIO_CH_POISONING, the routes associated with the node are marked as unreachable and the system waits for the new cluster head node to send network requests. If the new cluster head address is the same as that of the node, it then waits for other nodes in the cluster to send the DAO_CH data packet.

Conversely, if the address differs, it sends DAO_CH data to the new cluster head node. This new cluster head node then sends DIO messages to locally repair the backbone network. Cluster head rotation is thus initiated by non-cluster head nodes. The node multicasts the DIO_CH_LOSE packets within the cluster if cluster member nodes connected to the cluster head node time out in the network architecture cluster. After the cluster member node receives the DIO_CH_LOSE data packet, it determines a cluster head node address is its own, thus increasing cluster head node loss count. If this node lost count reaches threshold M, the cluster nodes initiate cluster head rotation. The first initiated cluster head node becomes the temporary proxy cluster head and sends the DIO_CH_POISONING data packet. This completes the cluster head rotation mechanism.

The communication area features a relatively uniform distribution of cluster heads and heterogeneous cluster network topology of each ring domain containing varying cluster sizes. The distribution of the communication ring domain cluster is dense and cluster size is relatively small and attributable to the close proximity of the sink. This network saves energy during data packet forwarding. The system realizes distributed cluster head rotation, avoids empty holes, and effectively reduces cluster head rotation in the network control packets sent, thus reducing network energy consumption, network load rate, and packet conflict, ultimately improving overall network performance.

C. DESIGN AND PROCESS FOR CLUSTERING INFORMATION ANNOUNCEMENT MESSAGE

During the cluster establishment phase, rank value calculation, cluster head competition, or nodes joining in the cluster may occur. Only the clustering information announcement message (DIO_CLUSTER) control message is designed to reduce control message transmission volume. When a node receives the clustering information announcement message, it performs different processing procedures based on its own state. It sends the cluster confirmation message (DAO_CACK) and registers its own address and other information to the node selected cluster head. The sink first sends the clustering information announcement message. Subsequently, the inner node processes the message information according to the node state and modifies part of their related fields in the message before transferring it. The related node states during this process are as follows.

Definition 9 (Dissociated): The initial state in which the rank node value is unknown when in this state, and thus the *node can only send a DIS request message to obtain the DIO information message.*

Definition 10 (Waited): The node receives the clustering information announcement message and becomes the noncluster head node by calculating the clustering probability model. The node then waits to receive the clustering information announcement message.

Definition 11 (Competing): The rank value has been confirmed and becomes the candidate cluster head node. The node waits to receive the DIO message from the cluster head node with the same rank value to calculate the cluster head node and join the cluster.

Definition 12 (Announcing): The node has cluster head node campaigns and announces to the other nodes with the same rank value to join the cluster, telling those with different rank values to build a backbone network routing.

All needed information during clustering should be included in the cluster information announcement message as a node processes different states differently after receiving the cluster information announcement message. The detailed message format is shown in Fig.2.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x0a   | Option Length |  RevSinkPower |   CoverArea   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   NodeCount   |   LeftPower   |  CluserFactor |   NS  |reserve|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 2. DIO_CLUSER option message.

The descriptions of specific options in the message are as follows:

- Type: Message format type, defined as 0x0a.
- Option Length: Length of optional referring to the residual byte number of the message after the length of Type and Option Length are eliminated. (Here, it is 6 bytes.)
- RevSinkPower: Sink sending power, which is used to conveniently calculate the distance between the node and the sink to determine the rank value.
- CoverArea: The coverage area used to calculate cluster threshold probability in each ring region.
- NodeCount: The number of nodes.
- LeftPower: The residual energy of the node used to compete between candidate cluster head nodes and parameter selection in backbone network routing.
- CluserFactor: The clustering adjustment factor, a clustering probability threshold parameter.
- NS: Used to identify sending node state, classified as dissociated, waited, competing, or announcing. The message receiver judges the receiving and processes different state messages.

Nodes with different states finally become common nodes or cluster head nodes by sending the clustering information announcement message, thus finishing the network clustering process. However, when a node wants to join a cluster, it must obtain unicast confirmation information sent by the cluster node to ensure the joining cluster success because each node sends clustering information announcement messages via broadcast.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x0b   | Option Length |    SYN/ACK    |    Reserve    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                              ADDR                             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 3. Clustering confirmation information message.

D. DESIGN AND PROCESS FOR CLUSTERING CONFIRMATION INFORMATION MESSAGE

The clustering confirmation information message is mainly used when the waited node unicasts DAO_CLUSER_ACK to the cluster head node after receiving the clustering information announcement message. The three-way handshake mechanism (similar to TCP protocol) is adopted to ensure the correct reception of cluster joining confirmation information and to avoid the interference of any malicious message during the message sending process. The clustering structure confirmation information message is illustrated in Fig.3.

- Type: Extensible message, defined as 0x0b.
- Option Length: Length of extensible message type, 6 bytes.
- SYN/ACK: Request/acknowledgement mark. The node sending the cluster joining request is SYN; the cluster head node confirms as ACK and value is computed as SYN+ACK.
- ADDR: Node address, or sending node address information.

The node receives clustering information announcement message DIO_CLUSER sent by the cluster head node from the above clustering confirmation information message sending process and thus decides whether or not to join the cluster based on the objective function. If the node chooses to join in the cluster, it sends a clustering confirmation information message including SYN and node address and applies to the cluster head node, where the computer expects SYN+ACK. When the cluster head node receives the application, it judges whether to accept the node request or not based on the clusters current state. If the cluster head node agrees, it sends a DAO_CLUSER_ACK message including SYN+ACK. The waiting node then compares the received SYN+ACK with its own expectation after receiving this message, and successfully joins the cluster and sends data packets if they are equal. If these expectations are unequal, the node discards the message and continues to wait. The node quits joining a cluster during a timeout period and receives the clustering information announcement message from other cluster head nodes.

V. E2HRC ROUTING ALGORITHM

A. ALGORITHM DESCRIPTION

We established backbone network type routing mechanism based on optimal direction angle (DA), node residual energy (EN), and hop difference (HC). When selecting relay nodes, the nodes in the backbone network consider the optimal direction angle, the residual energy, and the minimum number of hops to reduce network energy consumption and balance network energy.

Definition 13 (Optimal Direction Angle, DA): We joined the sink to the relay node in a straight line and joined the relay node to source node in another straight line. If the included angle between those two lines is less than or equal to 180° *and greater than or equal °, this included angle is the optimal direction angle.*

Theorem 1: Communication between node m and sink node by relay node n with optimal direction angle can reduce energy consumption (compared with direct communication with sink node.) as shown in Fig.4.

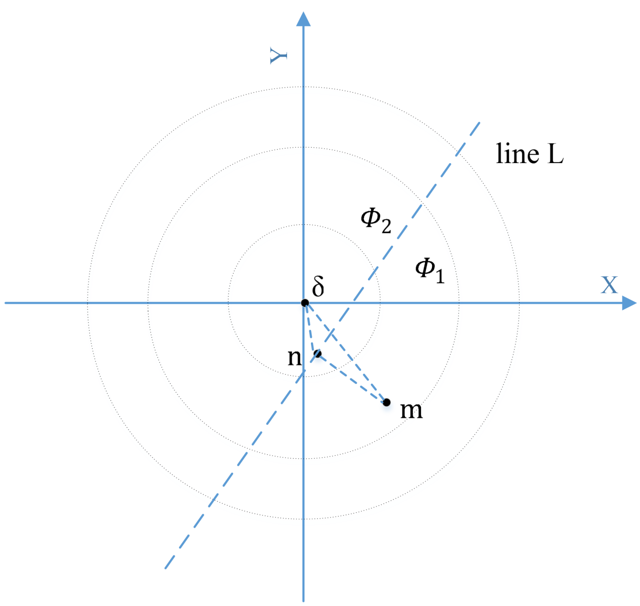

FIGURE 4. **Diagram of communication area.**

Proof: Connect points m, n, , to $\triangle mn\delta$, using the trigonometric function theorem:

$$d^2(m,\delta)=d^2(m,n)+d^2(n,\delta)-2d(m,n)d(n,\delta)\cos\alpha \quad (2)$$

Given that $mn \perp L$, $\alpha = \angle mn\delta > 90°$, $\cos\alpha < 0$, which is $-2d(m,n)d(n,\delta)\cos\alpha > 0$. Then, from per Eq.(2)

$$d^2(m,\delta) > d^2(m,n) + d^2(n,\delta) \quad (3)$$

The following shows that node energy loss is proportional to the square of the communication distance [33].

$$E_{Tx}(u,v) = \begin{cases} qE_{elec} + q\varepsilon_{fs}d(u,v)^2 & d(u,v) < d_0 \\ qE_{elec} + q\varepsilon_{mp}d(u,v)^4 & d(u,v) \geq d_0 \end{cases} \quad (4)$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (5)$$

where E_{elec} is consumed energy for circuit transmission unit data, the threshold value d_0 is a constant, ε is a constant, and when $d(u,v) < d_0$, ε is ε_{fs}, power amplifiers use the free-space transmission mode. When $d(u,v) \geq d_0$, ε is ε_{mp} and power amplifiers use the multi-path fading channel transfer mode. α is the path loss exponent in outdoor radio propagation models, where usually $\alpha \geq 2$ (in this study, α is either 2 or 4), thus: $P(m,\delta) > P(m,n) + P(n,\delta)$ and

$$P(m,\delta) > P(m,n,\delta) \quad (6)$$

where relay node n is located on line segment $m\delta$, $d(m,\delta) = d(m,n) + d(n,\delta)$, on both sides of Eq.(4) defines the square, so, $P(m,\delta) > P(m,n,\delta)$.

The proposed routing algorithm is a stepwise process.

- The sink sends a DIO message received by cluster head nodes on the first communication ring domain, which then unconditionally selects the sink as a parent node and sends the DAO message downward. The nodes in the other communication loop domains do not touch the DIO message. If the node in the first communication loop domain does not receive the DIO message sent by the sink, the node sends a DIS message to the sink.
- The DIO router messages containing the distance between the node and the sink, node rank value, the residual energy of nodes, and other parameters are sent when selecting the optimal parent node to provide reference selection for the nodes in the lower loop domain.
- The energy optimization network model is first applied to calculate the DA among current inter-nodes, relay nodes, and the sink when the cluster head nodes of the other layer domains receive a DIO message. The node is discarded when DA is less than 90°.
- The formula $\theta = \alpha * \frac{DA}{\pi} + \beta * \frac{EN}{E_{init}} + \gamma * \frac{HC}{10}$ is used to identify the node with maximum routing metric value of θ as the optimal parent node, and is then sent in the DAO message to form a downward route.
- The node sends a DIS message to judge whether rank value is greater than the receiving nodes own rank value if no optimal parent node has been identified when the backbone network times out. If the rank value is greater, the node sends a DIO route notification message and yields the optimal angle of the judgment according to the formula $\theta' = \beta * \frac{EN}{E_{init}} + \gamma * \frac{HC}{10}$, thus selecting the optimal parent node to receive the DAO message.

The backbone network in the communication loop domain is formed through this routing network algorithm. The backbone is similarly routed to the original RPL routing protocol, which supports point-to-multipoint routing, point-to-point routing, and multipoint-to-point routing. The algorithm is improved by optimal parent node selection after introducing two parameters, optimal direction angle and energy, to reduce and balance overall network energy consumption. Communication within the cluster includes point-to-multipoint communication between ordinary nodes and cluster head nodes, point-to-point communication between cluster head nodes and ordinary or among ordinary nodes, and multipoint-to-point communication between ordinary nodes and cluster head nodes.

B. DESIGN AND IMPLEMENTATION FOR ROUTING SCHEME IN THE NETWORK

The node is in the announcing state during the clustering stage. The node saves the candidate neighbor node information when receiving DIO_CLUSER messages from other nodes in different ring region ranks in the same state. Collecting the neighbor node information during the clustering stage enables the neighbor node to collect as much information as possible by taking advantage of the broadcasting of the DIO_CLUSER message, thus improving message utilization. However, the node only needs to unicast the targeted routing announcement information to candidate neighbor nodes to establish the corresponding routing information and avoid broadcasting the messages in this stage in the routing establishment stage, relieving network pressure and reducing network total energy consumption.

Here, we propose a message notification message for route establishment that functions via the message sending and receiving process. Combined with the objective function, we thus establish the upward routing, downward routing, and point-to-point routing processes. The routing message notification message DIO_RAI is sent along with the DIO message in terms of the extension head as shown in Fig.5.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x0c   | Option Length |  Prefix Length |   RSSILoss    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Source  Address                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Target  Address                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 5. Route message notification message (DIO_RAI).

Each field in the message is defined as follows.

- Type: Extension head type, denoted as 0x0c.
- Option Length: Extension head length, denoted as 10 bytes.
- Prefix Length: The prefix in the network always represents a co-owned node part in a cluster, using the same prefix for the nodes in the same cluster. When the node joins the cluster, the cluster head allocates an address for the node according to its prefix.
- Source Address: Node address sending data packets.
- Target Address: Node address either in the higher ring region or lower ring region.
- RSSILoss: Strength loss of received signal.
- Upward routing: The routing that the data packets are sent in the sink. To form this routing, the node with a lower rank value sends the upper level node routing message to the lower level node with higher rank value. After receiving the routing notification message, the lower level node calls the objective function to judge if it is the optimal forwarding node.
- Downward routing: The opposite direction of upper routing, where the node sends a notification message including the routing information of lower level node to upper node. After receiving the message, the upper level node calls the objective function to judge if it is the optimal forwarding node.
- Point to point routing: The forwarding route of node data packets in the same ring region. This data packet forwarding is realized by first choosing upper routing to find the common ancestor node, and then downward routing to forward. (We do not specifically deal with this type of routing in the routing establishment stage.)

The routing information directed by the optimal direction angle objective function based on energy optimization is formed in a backbone network through the above sending and receiving routing information message processes. After routing is established, the node dynamically adjusts to the transmitting power by the next hop node in the routing information when forwarding the data packets, thus reducing node energy consumption when sending data packets.

C. DESIGN AND IMPLEMENTATION FOR NETWORK REPAIR MESSAGE

The network is inevitably plagued by node unreachability due to the characteristics of the inner areas (such as the energy of nodes or software problems) or external factors (such as changes of external environment) as network running time is prolonged. When this occurs, corresponding repair measures are started up to repair the network.

In the cluster head rotation scheme, the packets involved include the cluster head rotation message notification packet (DIO_CH_POISONING), cluster head rotation message notification confirmation packet (DIO_CH_POISONIG_ACK), cluster head appointment packet (DIO_CH_APP), and cluster head lost contact message notification packet (DIO_CH_LOSE).

The cluster head rotation message notification packet is a kind of information notification packet that is actively sent by the cluster head node to the cluster members. The goal of packet sending is to enable cluster members to send a cluster head rotation message notification confirmation packet after receiving this message, thus enabling the cluster head node to select a new cluster head node. The packet structure is shown in Fig.6.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x0d   | Option Length |           reserved             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 6. Cluster head rotation message.

- Type: Extensible head type, the value is 0x0d.
- Option Length: Extensible head length, the value is 2 bytes.
- Reserved: The reserved field.

The node sends the parameters (e.g., remaining energy) to the cluster head node through the cluster head rotation message notification confirmation packet. The node then becomes a waiting node. The packet structure is shown in Fig.7.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x0e   | Option Length |  Left Power   |    reserve    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 7. Cluster head rotation message notification confirmation.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x0f   | Option Length | Prefix Length |    reserve    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                          Old  Address                         +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                                                               +
|                          New  Address                         |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 8. Cluster head data message packet.

- Type: Extensible head type, the value is 0x0e.
- Option Length: Extensible head length, the value is 2 bytes.
- Left Power: The remaining energy of the node.
- Reserved: The reserved field.

The new cluster head node has been determined when the old cluster head node sends the cluster head appointment packet. The cluster head appointment packet is sent to the nodes in the original cluster and the cluster head nodes in other ring regions among the old cluster head nodes. After receiving this packet, the cluster members judge if the node becomes the cluster head node or joins a new cluster. The cluster head nodes in other ring regions will send the routing establishment related packets to the new cluster head node and repair the routing in the backbone network. The packet structure is shown in Fig.8.

- Type: Extensible head type, the value is 0x0f.
- Option Length: Extensible head length, the value is 34 bytes.
- Prefix Length: The prefix length of the new cluster head node address.
- Reserved: The reserved field.
- Old Address: The original address information. The node will judge by itself whether the new cluster uses it or not.
- New Address: The address information of the new cluster node.

The cluster head lost contact message notification packet (DIO_CH_LOSE) is used to announce to the cluster head that a node has been lost. The packet structure is shown in Fig.9.

- Type: Extensible head type, the value is 0x10.
- Option Length: Extensible head length, the value is 18 bytes.
- Prefix Length: The prefix length of the cluster head node address.
- Reserved: The reserved field.
- CLUSTER Address: The address information of cluster head node.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Type=0x10   | Option Length | Prefix Length |    reserve    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                        CLUSER  Address                        +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

FIGURE 9. Cluster head lost contact message.

There are many various packet types among nodes during the rotating cluster head, though the procedural process of these packets is relatively simple. This range is mainly used to realize communication negotiation among nodes through messages. Here, we display various packets processing procedures based on flowcharts between various nodes. When the cluster head node rotates, the routing information of the backbone network also changes because the backbone network nodes are composed of cluster head nodes. Cluster head rotation is executed via local autonomy to minimize energy consumption and network message congestion. Thus, the repair and reestablishment of routing information updates local information as well. Repair routing and reestablishment are triggered by two different events: The routing repair scheme actively triggered by routing nodes and the routing repair scheme triggered by proxy nodes. The difference between these two schemes is the trigger event; the process of each node is essentially the same. The packets in need of routing repair are the same as the clustering confirmation information messages.

TABLE 1. Simulation parameters.

Attribute Parameter	Value
Number of the Nodes	120
Simulation time(s)	3600
Simulation area	500*500 m^2
Simulator	Cooja
Mote Type	Sky mote
Operating System	Contiki 2.7
Radio medium	UDGRM(Unit Disk Graph Medium):Distance Loss
Mote startup delay (ms)	1000
Transmission range (m)	50

VI. SIMULATION AND ANALYSIS

We set region size to $500m * 500m$ with 120 nodes (one sink node and 119 route notes) randomly distributed throughout. The network topology was formed based on the most common sink topology (radial distribution around the network). A list of specific simulation environment parameters is provided in Table 1.

Fig.10 displays where nodes in the network vary over time. Original RPL and E2HRC routing protocol energy consumption is also varied. The data acquisition start time during simulation was open for all nodes, and the end time for each non-sink node was 1 min to successfully send 10 packets.

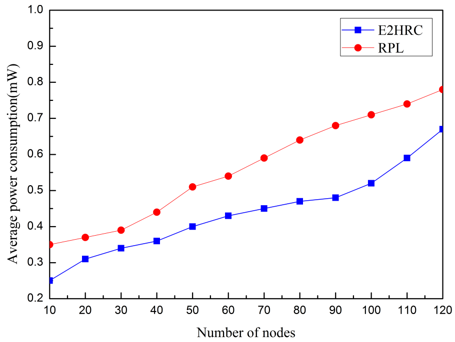

FIGURE 10. Comparison of average network energy consumption.

The x-axis in the figure is number of different nodes in the network and the y-axis is average energy consumption of the network, as defined by Eq.(2), which yields average network power consumption $P_{average}$. P_{sum} is the total network energy consumption, and C_{node} is the number of network nodes. We conducted replicate experiments to ensure accurate simulation results. The lower end of each nodes data in the y-axis direction is the minimum value among multiple simulation runs.

$$P_{average} = \frac{P_{sum}}{C_{node}} \tag{7}$$

Energy balance is very important for the wireless sensor when this network is working. The experimental results for energy balance tests are shown in Fig. 11, where the x-axis marks nodes that participated in the experiment and the y-axis is the average energy consumption of nodes.

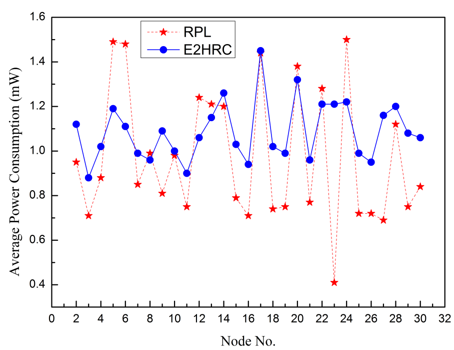

FIGURE 11. Comparison of average energy consumption of nodes.

As shown in Fig.11, the fluctuating range of the node energy consumption curve in the wireless sensor network when original RPL was used was higher than that when the E2HRC routing protocol proposed in this paper was used. Per our analysis, some energy-balanced steps followed the E2HRC routing protocol such as by establishing ring domain communication, calculating cluster head ratio, and determining the probability factor. Accordingly, cluster head election and the probability factor adjustment mechanism were adopted to guarantee uniformity in the cluster head distribution in the rings. The energy consumption of wireless sensor network was effectively balanced and the lifespan was extended.

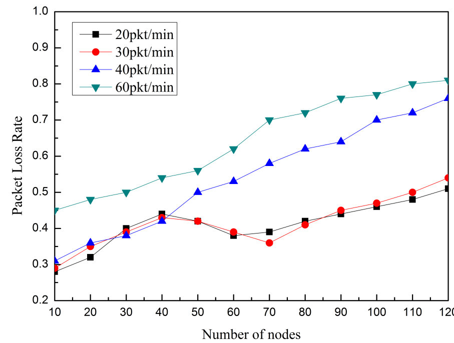

FIGURE 12. Packet loss ratio of original RPL.

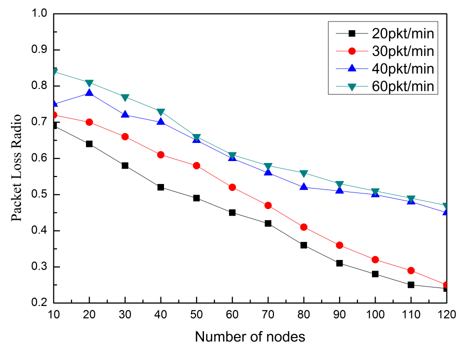

FIGURE 13. Packet loss ratio of E2HRC routing protocol.

Packet loss ratio is an important index to measure network performance. If the wireless sensor networks packet loss ratio is too high, the transmission performance of the network will be too low to use. As shown in Figs.12 and 13, the bandwidth is wider in E2HRC compared to RPL resulting in a higher packet loss ratio in certain wireless sensor networks and in the case of the same number of nodes.

Further analysis showed that as the number of nodes increases in the wireless sensor network where the original RPL is used, packet loss ratio gradually increases as well. However, the packet loss ratio gradually decreases as number of nodes increases in wireless sensor networks where the E2HRC routing protocol is used. Further, the greater the number of nodes, the better the wireless sensor network with the E2HRC routing protocol compared to the original RPL in terms of packet loss ratio. These results were obtained before the best father node was selected, and considering optimal direction angle and residual energy. In effect, the proposed method could effectively reduce signal attenuation for long-distance communication.

Figs.14 shows the packet delivery ratio gradually decreases as number of nodes increases in wireless sensor networks where the E2HRC routing protocol is used. However, E2HRC has higher packet delivery ratio compared to original RPL. This can be explained by the fact that in E2HRC the relay node with optimal direction angle is selected. Thanks to the proposed routing algorithm and routing protocol that the

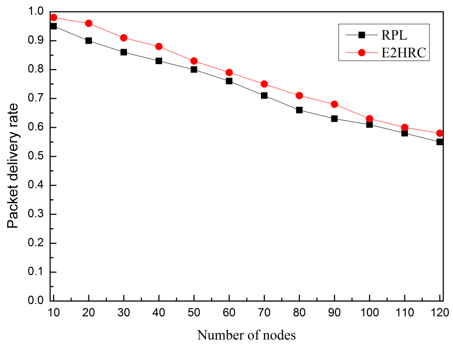

FIGURE 14. Comparison of Packet delivery ratio.

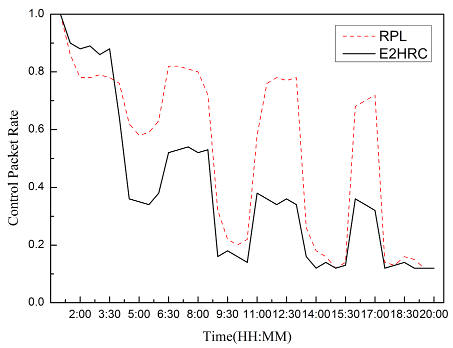

FIGURE 15. Control packet ratio of RPL and E2HRC routing protocol.

proposed method could effectively reduce signal attenuation for long-distance communication and decreased the packet loss ratio.

Control packets are very important for topology establishment and maintenance as well as wireless sensor network route repair. Data packets are not forwarded to their destination nodes if control packets are more congested than the wireless sensor network. Additionally, excessive control packets consume more node energy when they are sent or received, truncating the lifespan of the wireless sensor network. The control packet monitoring data numbers in the wireless sensor network from 1:00 to 20:00 is shown in Fig.15. Compared to the original RPL, the E2HRC routing protocol effectively decreased the number of control packets as time progressed. The proposed clustering algorithm and cluster rotation mechanism also achieved distributed cluster rotation to prevent an energy hole, and effectively decreased the number of control packets during cluster rotation, thus balancing the network load and improving network performance.

VII. CONCLUSION

We established a heterogeneous ring communication topology, proposed a related clustering algorithm for this topology, and built the E2HRC routing protocol to improve original RPL performance in this study. The proposed method yields better average energy consumption and overall performance than original RPL while balancing the energy consumption of the whole wireless sensor network. We also designed a messaging structure for clustering and routing and verified that both protocols are efficient and effective.

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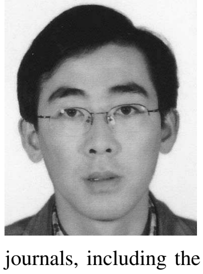

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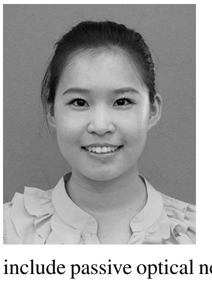

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