EL-CRP: An Energy and Location Aware Clustering Routing Protocol in Large Scale Wireless Sensor Networks

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Abstract. With the development of Internet of Things (IoTs), large-scale wireless sensor networks (WSNs) are widely used in environment monitoring, industrial testing and intelligent transportation. In order to extend the lifetime of WSNs, it is necessary to reduce the energy consumption of sensors. To achieve the large-scale and flexible deployment, the wireless sensors are required to be low memory overhead. The existing WSN routing protocols are difficult to satisfy the requirements for low energy consumption and low memory overhead in those scenarios. This paper proposes an Energy and Location Aware Clustering Routing Protocol (EL-CRP) for large-scale WSN application scenarios. Using an adaptive clustering method, in which the location and energy of cluster members are considered simultaneously, the protocol reduces the energy consumption and memory overhead in the WSNs. Extensive simulations and hardware tests are conducted to evaluate the performance. Results finally verify the advantages of the protocol in large-scale network scenarios.

Keywords: Large-scale WSNs · Energy · Location · Routing protocol · Clustering

1 Introduction

In recent years, with the development of the Internet of Things, WSNs have been widely used. As indicated in [1], from 2019 to 2024, market of global WSNs equipments will maintain a growth rate of 17. 64%. By 2023, the global WSNs market is expected to reach $9.386 billion, including the fields of environment monitoring, industrial inspection, warehouse storage [2]. In the above scenarios, WSNs typically need to be deployed in a large-scale way.

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This work focuses on the design of routing protocols in WSNs, in order to meet the requirements of large-scale sensor nodes in low energy consumption with little memory overhead. On the one hand, in large-scale WSNs, sensor nodes have the characteristics of widespread, high deployment density and unknown location. Therefore, in order to establish a stable route, frequent data communications are required between nodes. Through analysis, it is observed that the energy of sensor nodes is mainly consumed in the process of wireless communications [3]. To design an energy-efficient route protocol in large WSNs is an important way to reduce the energy consumption of sensors by reducing the redundant data transmissions. On the other hand, nodes with large-scale deployment in practical scenarios should be low cost and miniaturization. The existing WSN routing protocols are difficult to balance the requirements in low energy consumption and low memory overhead. In response to the above problems in large-scale WSNs, this paper has made the following contributions: (1) Based on the envisaged large-scale WSN application scenarios, a network model and an energy model are constructed. (2) Based on the energy model, an energy and location aware routing protocol is proposed. Using an adaptive clustering method, both the energy consumption and memory overhead at each sensor node are reduced. (3) The performance of the proposed routing protocol is evaluated on a new simulation platform and tested by the developed hardware system.

The structure of this paper is as follows: Sect. 2 describes the system model, and Sect. 3 introduces the design idea of routing protocol with specific steps, including cluster establishment and route establishment. Section 4 evaluates the performance of the protocol through simulations and hardware test. Section 5 summarizes our research work.

2 System Model

In this section, we present the network and energy models of the application scenarios in large-scale WSNs.

2.1 Network Model

The application scenarios envisaged in this paper include environmental monitoring, industrial testing, etc. The network model should cover the following conditions: (1) A WSN consists of multiple normal nodes with routing capabilities and a sink node for data fusion. To simplify the network topology, we assume that the sink node is fixed and there is only one sink node in the network. (2) All the normal nodes are assumed to have identical properties, i.e., same data processing and communication capabilities. (3) Normal nodes are not fixed so that the network has no rigorous requirements in delay. (4) For the sink node, it is assumed that continuous power supply is available to ensure the function achievement. (5) The original location information of all nodes is unknown, there is no auxiliary facility in the network to help the node to obtain location information, and each node can only obtain the required information through communications with neighboring nodes. (6) The network scenario is assumed as sufficiently large so that the sink node can not communicate with all normal nodes directly. For simplicity, we assume that the sink node is located at the center of the scene.

Considering the requirements of low memory overhead, it is necessary to reduce extra function. The traditional methods, i.e., multi-channel communication protocols and adjustment of transmission power require additional hardware overhead, we thus assume that the nodes communicate under a single channel, and the transmission and reception distance of the information is constant.

2.2 Energy Model

The linear energy model is typical method to characterize energy consumption in sensor networks, which is also adopted in our work by referring to [4]. The total energy consumption of a node is denoted as E_i, which is consist of transmission energy consumption E_{Tx}, reception energy consumption E_{Rx}, energy consumption caused in listening state E_l, and energy consumption in sleep state E_s. Specifically, E_i is denoted as:

$$E_i = E_{Tx} + E_{Rx} + E_l + E_s, \tag{1}$$

$$E_{Tx} = lE_{elec} + l, \tag{2}$$

$$E_{Rx} = lE_{elec}, \tag{3}$$

$$E_l = P_l T_l, \tag{4}$$

$$E_s = P_s T_s, \tag{5}$$

where l is the length of the transmitted packet, and the unit is bit. E_{elec} is the energy consumed to process 1 bit of data, and the unit is J/bit. P_l is the power of the node in the listening state. T_l is the time the node is listening. P_s indicates the power of the node in the sleep state. T_s is the time at which the node sleeps.

3 Protocol Design

In large-scale WSNs, the central routing protocol represented by Sensor Protocols for Information via Negotiation (SPIN) [5] can establish routing without excessive memory overhead, but easily causes information congestion in large-scale scenarios, which lead to the deterioration of network performance. The idea to solve this problem is to divide the nodes in the network into different clusters, and select one or more nodes in each cluster as cluster heads. The cluster head undertakes the information interaction of nodes within the cluster and the communications with the sink nodes. The cluster heads are periodically rotated to balance energy consumption. Using the clustering method, the communication efficiency among sensor nodes can be improved so that the network performance could be enhanced.

The routing algorithms using clustering ideas in WSN mainly include Low Energy Adaptive Clustering Hierarchy (LEACH) [6], Power-Efficient GAthering in Sensor Information Systems (PEGASIS) [7], Hybrid Energy-Efficient Reactive protocol (HEER) [8] and Threshold sensitive Energy Efficient sensor Network (TEEN) [9]. LEACH protocol selects the cluster heads based on the random number, which need a sink node control the periodic cluster heads rotation in the network. PEGASIS is a distance-based chain routing algorithm that solves the problem that the LEACH protocol cannot perform multi-hop communications, but in large-scale WSNs, this approach increase the data delay. HEER dynamically selects the cluster head through the information interaction between nodes, and considers the residual energy of the node. TEEN algorithm improves LEACH by adding the hard threshold and the soft threshold to control the time when the node uploads the information data. However, the clustering algorithm of the above protocols relies on the control of a sink node, which increase the data interaction in WSN.

Compared with the clustering process in other WSN routing protocols, the clustering process proposed in EL-CRP does not need to exchange location information with surrounding nodes, which saves the storage space of hardware devices. The self-organizing, adaptive clustering algorithm can flexibly cover the entire network. Since the judgment of whether a node becomes a cluster head depends on the distribution of surrounding nodes, the formed network topology tends to be uniform distribution. Because the application scenario of this paper has low latency requirements, the establishment of routing links refers to PEGASIS. It also provides a route establishment method similar to SPIN for high priority services. The specific processes include cluster establishment and route establishment.

3.1 Cluster Establishment

The cluster establishment algorithm is shown in Algorithm 1. The specific steps are as follows:

Step 1: Node A is powered on, set a random listening time T_{listen}. This step is to avoid network congestion caused by multiple nodes starting and sending broadcasts in close time.
Step 2: Node A enters listening state.
Step 3: If node A hears the beacon frame sent from cluster head B within the time T_{listen}, the node A sends a cluster request to the cluster head B, and waits for the time T_w. If the node A does not receive the reply sent by the cluster head B within the time T_w, step 2 is re-executed. If the node A receives the reply sent by the cluster head B, the node joins the cluster where the cluster head B is located, and sends the interest message to the cluster head B through time division multiple access according to the application requirement. If the node A does not receive the beacon frame within the time T_{listen}, node A itself becomes the cluster head and periodically sends the beacon frame.

Algorithm 1. Cluster Establishment Process.

Require: T_{Min}, T_{Max},T_w,M,$NodeA$
Ensure: $Cluster_i$
Node A power on
T_{listen} = random(T_{Min},T_{Max}), $Timer_1 = T_{listen}$
while $Timer_1$!= 0 **do**
    $Timer_1 = Timer_1$ - 1
    if Node A receives the beacon frame sent by the cluster head B nearby **then**
        Node A joins the cluster B
    end if
end while
if $Timer_1 = 0$ **and** Node A does not join any cluster **then**
    Node A becomes the cluster head, Node A broadcasts the beacon frame
end if
if Node A is cluster head **and** $E_A < Th_{power}$ **then**
    for i is member id in Cluster A **do**
        if $E_i > Th_c$ **and** $Node_i$ is the last node communicating with Node A **and** there is no other cluster head around **then**
            select $Node_i$ as new cluster head
        end if
    end for
end if

Step 4: If the node A is a cluster head, when the clustering request sent by the node C is detected, determine whether the number of nodes n_c in the current cluster meets the equation: $n_c \leq M - 1$, Where M is the cluster capacity, it means the maximum number of member nodes that a cluster can contain. If equation is met, the reply is sent to the node C, and the cluster head A records the cluster node id; if the condition is not met, no processing will be done.

Step 5: When the energy of cluster head A is lower than the threshold Th_{power} set by us, cluster head A select a member node C as new cluster head. Node C satisfy that the energy of node C is higher than the energy threshold Th_c and node C is the last node to communicated with cluster head A. After that, cluster head A inform all members change the cluster head.

In the above process, the value of T_{Max} depends on the total number of nodes in the network and the transmission delay between adjacent nodes T_{td}, it can be described as: $T_{Max} > NT_{td}$. To ensure that the node can hear at least one beacon frame during the listening period, the following relationships should be met: $T_{Min} > T_{beacon}$, the waiting time meets the relationship $T_w \propto T_{beacon}$. The value of cluster capacity M is related to the density of nodes in the cluster. According to the conclusion of [10], when the cluster capacity M satisfies:

$$M = \sqrt[4]{\frac{3\pi N^2 \varepsilon_{fs}}{2\varepsilon_{amp} L^2}} \tag{6}$$

the network has the least communications, the total energy consumption of the network is minimum, where L is the length of the area, $\varepsilon_{fs} = 10\,\text{pJ/bit/m}^2$, $\varepsilon_{amp} = 0.0013\,\text{pJ/bit/m}^4$ [11].

3.2 Route Establishment

Since the clustering process proposed in this paper may cause too long communication distance between sensor nodes, which make the direct communications be hard. In order to ensure the communication link work normally, it is necessary to introduce some new routing nodes from the cluster head to sink nodes. The selection of the routing nodes refers to the selection of the cluster head by the LEACH protocol. First, we set a threshold Th_r, the node with routing function generates a random number r after power on, if $r < Th_r$, the node becomes a routing node. The process of establishing route is shown in Algorithm 2. The specific steps are as follows:

Step 1: The sink node A periodically broadcasts routing information to perform routing maintenance.
Step 2: The routing node B which receives the routing broadcast records the address as the parent node. Node B continues to forward the routing broadcast. The routing node C that receives the broadcast and does not have the parent node records the node B as the parent node. This step is repeated until all of the routing nodes in the network have the records of its parent node.
Step 3: The cluster head periodically sends the interest message in the cluster to the parent node according to the application requirements.
The advantage of the route establishment process in EL-CRP is that each routing node only needs to save its own address of parent node, which saves memory overhead. By means of broadcasting, the establishment of a communication link can be realized rapidly in a wide range.

Depending on the application requirements, we design two different modes for this protocol: active mode (EL-CRP/Active) and passive mode (EL-CRP/Passive). In EL-CRP/Active, when there is a message to be sent in the routing node and the parent node is lost, the routing node actively sends a route broadcast within one hop range, and the other routing node that receives the broadcast sends an ACK frame to establish a connection with the routing node. This mode is suitable for scenarios where there is information that needs to be sent urgently. In EL-CRP/Passive, the routing node without parent node does not actively send routing broadcasts, which is suitable for scenarios that do not contain emergency messages.

Algorithm 2. Route Establishment Process.

Require: Th_r
Ensure: $ParentID$
$Node_i$ = Sink Node
label: $Node_i$ send routing broadcast
for j Within the communication range of $Node_i$ **do**
    if $ParentID_j$ == Null **then**
        $ParentID_j$ = i
        i=j
        goto **label**
    end if
end for

4 Simulations and Hardware Tests

Simulations. In order to evaluate the performance of the protocol, we design a simulate platform based on C++. Considering the requirements of the application scenarios, We built a hardware system based on *TI*'s *cc2530* chip [12] for actual testing, for the reason that the performance indicators of the sensor in the simulations refer to the *cc2530* chip. The simulation setting are shown in Table 1.

Table 1. Simulation parameter setting

Parameter	Value
Scene size	40 m × 40 m
Number of nodes	1000–10000
Transmission rate	250 kbps
Packet size	1024 bit
Cluster capacity	10–200
Beacon cycle	10 s
Business cycle	10 s
Total simulation time	360 s
Receive power consumption	24 mA × 3.6 V × 4 ms
Transmit power consumption	29 mA × 3.6 V × 4 ms
Monitor power consumption	0.2 mA × 3.6 V × t
Sleep power consumption	0.1 mA × 3.6 V × t

We first test the effect of cluster capacity on energy and delivery rate through simulations, as shown in Fig. 1. The x-axis represents the maximum number of each cluster in the network model, and the y-axis represents the average power P_a of each node in the network, the value of P_a is

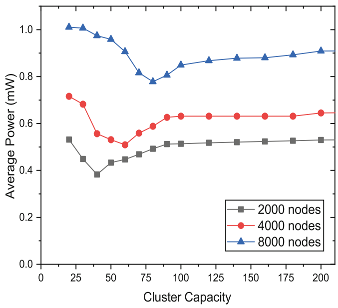

Fig. 1. Relationship between node average power and cluster capacity.

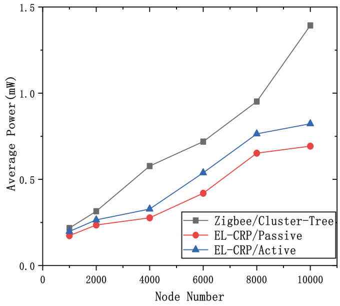

Fig. 2. Relationship between node average power and number of nodes under different protocols.

$$p_a = \frac{E_N}{N \cdot t} \tag{7}$$

E_N is the sum of energy consumption of all nodes in the network during simulations, N is the total number of nodes in the network, and t is the simulation time. It is obvious in Fig. 1 that there is an optimal value for the cluster capacity in the network, and the optimal value is approximately equal to the result calculated by Eq. 6.

The existing communication technologies widely used in WSNs, mainly include Narrow Band Internet of Things (NB-IoT) [13], LoRaWAN [14] and Zigbee [15]. Since the network construction of NB-IoT or LoRaWAN relies on the establishment of cellular base station or LoRa gateway, the conditions of deployment are demanding. Therefore, NB-IoT and LoRaWAN are not suitable for the application scenario of this paper. We choose Zigbee technology for comparison and testing. Since there is no communication requirement between the terminal nodes in the network model proposed in this paper, the tree topology from the sink node to the terminal node is the most efficient. The Zigbee protocol usually uses the Cluster-Tree routing algorithm [16] to establish a communication link in tree topology. The basic idea of the algorithm is: (1) After receiving the data, the routing node first determines whether the destination address is a child of itself. (2) If the destination node is a child node of the current node, the routing node forwards the data directly to the target node; If the destination node is not a child node of the current node, the data will be send to its parent node for processing. We evaluate the delivery rate and power consumption of EL-CRP/Active, EL-CRP/Passive and Zigbee/Cluster-tree through simulations. The comparison results are shown in Figs. 2 and 3. Obviously, with the increase in the number of nodes in the network, EL-CRP has obvious advantages in energy consumption and delivery rate.

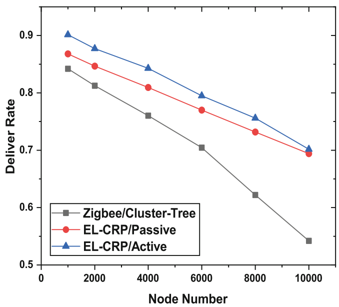

Fig. 3. Relationship between delivery rate and number of nodes under different routing protocols.

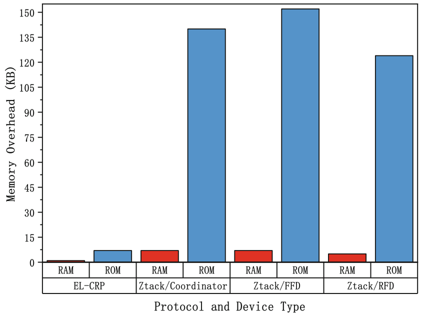

Fig. 4. The RAM and ROM overhead of the EL-CRP and Z-stack running on *cc2530* chip.

Hardware Tests. We choose *TI*'s product *cc2530* chip for testing, because the product has the advantages of low power consumption, low cost and supports software programming. *cc2530* chip integrates *TI*'s Z-stack protocol stack to perform basic Zigbee networking and communication. There are three types of devices in the Zigbee protocol, including the coordinator that acts as a sink node, the Full-Function Device (FFD) with routing capabilities, and the Reduce-Fuction Device (RFD) that does not have routing capabilities. We test the memory overhead of running the above three types of nodes in a Zigbee network. At the same time, we replace the original routing protocol in *cc2530* chip with EL-CRP and test the memory overhead under the same conditions. We evaluate the performance of the protocol in memory overhead by the random access memory (RAM) and read only memory (ROM) overhead of the device. By comparing the memory overhead occupied by the z-stack protocol stack and the EL-CRP in actual scenario tests, as shown in Fig. 4. It is obvious that the memory overhead of EL-CRP has significant advantages compared with the Zigbee route protocol, which means that in the same application scenario, devices using the EL-CRP can reduce the size, weight and cost. This result verifies the contribution of EL-CRP on memory overhead.

5 Conclusion

At present, researches on large-scale WSNs mainly focus on reducing energy consumption and extending the lifetime of the network. There is a lack of adequate consideration about how to reduce the memory overhead of sensors in WSNs. This paper designs a energy-efficient WSN routing protocol EL-CRP to meet the requirements of low-energy consumption of nodes and low memory overhead of sensors in large-scale WSN networks. Different from existing routing protocols, our routing protocol is based on a novel clustering scheme, in which clusters are formed by considering both the location and energy of sensor nodes. We first build a network model and an energy model for the application scenarios. Then we divide the routing protocol into cluster establishment and route establishment. Each process is described in detail. Finally, We evaluate protocol performance of EL-CRP on energy consumption and delivery rate in large-scale scenarios through a self-designed software simulation platform, and the performance in memory overhead is achieved through hardware testing. The results show that our protocol has good performance on energy consumption, delivery rate and memory overhead in the scenarios of large number of nodes and high node density, which provides a reference for large-scale WSN application scenarios.

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