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An Energy-Efficient Clustering Algorithm Combined Game Theory and Dual-Cluster-Head Mechanism for WSNs

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ABSTRACT A novel energy-efficient clustering algorithm was proposed which aimed at improving the energy efficiency of WSNs via reducing and balancing energy consumption in this paper. The lemma concerning the dual-cluster-head mechanism which was designed to reduce the energy overhead during the process of rotation of Cluster Heads (CHs) was proposed and proven at first. In addition, a non-cooperative game model was presented with the purpose of balancing the energy consumption among the Cluster Heads. Besides, the Nash Equilibrium Point (NEP) of the game model was presented and the corresponding proof was provided. Subsequently, the Energy-efficient Clustering algorithm combined Game theory and Dual-cluster-head (ECGD) mechanism was detailed, which took the energy efficiency in both of the intra-cluster and inter-cluster communication into consideration. Finally, extensive experiments were conducted via simulation and the simulation results were compared with the existing Clustering strategies in terms of energy efficiency and network performance. The analyses of results have shown that the ECGD can improve energy efficiency and extend the network lifespan effectively.

INDEX TERMS Energy efficiency, dual-cluster-head mechanism, nash equilibrium point, non-cooperative game, network performance.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) is a kind of networks consisting of numerous tiny sensor nodes which are capable of sensing, processing and communicating [1], [2]. Owing to their low deployment cost, WSNs have gained extensive applications in recent years [3], such as environmental monitoring, military monitoring, medical caring, endangered species tracking, disaster relieving, and so on [1]–[3]. In general, most of the sensor nodes are powered by the battery, which means their energy supply is limited. Besides, the majority of the WSNs are deployed in the rugged environment and some of them are even out of human's reach. Therefore it is impossible or unpractical for them to be replenished [4]–[6]. When one or some of the sensor nodes lying in the crucial location exhaust their energy, the network partition occurs. It means the termination of the network lifespan. Since the purpose of WSNs is to acquire valid data as many as possible on a limited energy budget, it is vital to improve the energy efficiency.

Generally speaking, two aspects can be focused on to improve the energy efficiency, namely reducing and balancing energy consumption respectively. In general, the sensor node consumes its energy for data acquisition, process and communication. The portion of communication overhead accounts for the largest part of the total energy of each node [1], [2], [4]. According to the research results, the energy consumption for transmitting 100 meters per bit is equivalent to what is exhausted by the processing module to execute 3000 instructions [7]. Besides, Shih *et al.* pointed out at the Mobicom 2002 that most of the sensor's energy was consumed in the communicating module [8]. Therefore the energy efficiency can be markedly improved if the communication overhead is cut down largely. Since the data communication and the traffic flow depend on the routing protocol [9], the energy consumption can be reduced if the routing protocol

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takes the energy efficiency into consideration. On the other hand, the traffic flow pattern of WSNs is different from that of traditional wireless networks owing to the distinct logical topology. As for WSNs, all the data are transmitted to the Sink via "hop-by-hop" mode to the data server which is usually deployed out of the network area. As a result, the traffic flow follows the "convergecast" pattern [2], which leads to an inverted funnel-shaped distribution of the data flow and the "Hot Spot Problem" [10], [11]. The "Hot Spot Problem" results in the uneven energy distribution of WSNs, which has a deep influence on the energy efficiency and the lifespan.

Clustering strategy is a kind of schemes aimed at improving the energy efficiency of WSNs via balancing the energy consumption [2]. Specifically, Clustering strategy logically divides the network topology into hierarchical structure by organizing nodes which are geographically close to each other into independent clusters. In general, there are two kinds of different roles in the network, namely, Cluster Head (CH) and Cluster Member (CM). In each cluster, the intra-cluster data can be simply aggregated to reduce redundancy by CH. Figure 1 shown a schematic diagram of a wireless sensor network adopting the Clustering strategy, where the white circle represents CM (such as node d) and the black one denotes CH (such as node a). CM acquires the source data, and CH is responsible for dividing time slots according to the number of CMs in TDMA mode and forwarding the data received from the CMs to the Sink after a simple aggregation. CMs switch between working and sleeping modes according to their time slots allocated by the CH, which brings in the reduction of energy consumption. Generally speaking, Clustering strategy mainly includes two steps, namely, cluster formation phase and data transmission phase. In the cluster formation phase, CHs are selected and the CMs choose the appropriate CH to join in. Subsequently CH is mainly responsible for forwarding the data to the Sink during the data transmission phase. Specifically, after a simple process for the source data, CH forwards the data to the Sink via the upstream CHs in a "hop-by-hop" pattern. Overall, the Clustering strategy mainly aims at cutting down the energy depletion via reducing data redundancy and the duty cycle of CMs. Besides, it also balances the energy consumption by periodically rotating the roles of sensor nodes.

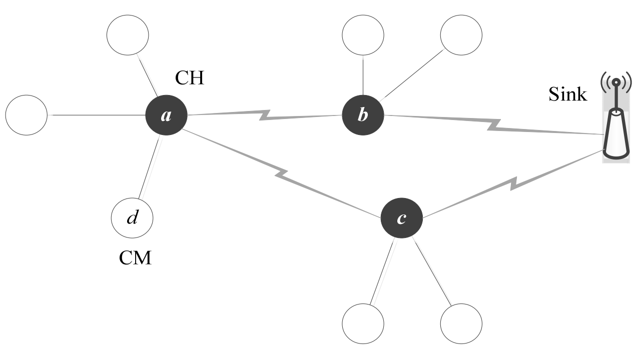

FIGURE 1. **Schematic diagram of clustering algorithm.**

A dual-cluster-head mechanism was proposed in this paper to reduce the energy consumption resulted from the rotation of the role of node. Besides, a non-cooperative game model to regulate the inter-cluster communication was presented and the corresponding Nash Equilibrium Point (NEP) was obtained and proven through the detailed theoretical analysis. Subsequently, a novel Energy-efficient Clustering algorithm combined Game theory and Dual-cluster-head (ECGD) was described in detail. Finally, extensive simulation experiments were conducted to verify the energy efficiency of ECGD in terms of lifetime and network performance of WSNs.

The remainders of the paper were organized as follow. The related works were detailed in section II. The preliminaries were presented in section III, which introduced the energy consumption model, the network topology, the related assumptions, as well as some notations in detail. Section IV presented the related lemmas and the corresponding proofs as well as the non-cooperative game model. Section V proposed the novel Energy-efficient Clustering algorithm combined Game theory and Dual-cluster-head (ECGD) mechanism. Subsequently, extensive simulation experiments were conducted and the simulation results were compared with the existing Clustering algorithm in detail in Section VI to evaluate its energy efficiency, followed by section VII which concluded the paper and pointed out some future research directions.

II. RELATED WORKS

Recent years have witnessed a lot of Clustering strategies aimed at improving the energy efficiency of WSNs. Generally speaking, most of the existing Clustering strategies mainly focus on the following three aspects to achieve the improvement of energy efficiency, namely, Cluster Formation Control, Cluster Size Control, and Data Transmission Control.

A. CLUSTER FORMATION CONTROL

In general, it focuses on controlling the process of CH selection so that the energy depletion among different clusters in the whole network topology can be equilibrium. At the same time, the residual energy difference between CH and CM is cut down as much as possible through periodic rotation of the role of Cluster Head. In addition, the energy overhead during the cluster formation phase can be also reduced through proper control over the rotation frequency.

As for existing strategies, most of them focus on controlling the selection of CHs. For instance, CHs are selected in a random- manner (Low-Energy Adaptive Clustering Hierarchy, LEACH [12]). Sometimes nodes take turns to act as CHs via forming the network to be a chain logical topology (Power-Efficient Gathering in Sensor Information Systems, PEGASIS [13]). In some scenarios, the CHs selection process is controlled on the basis of some predefined thresholds. For example, the similarities among nodes and the node degree are utilized as parameters for CH selection according to some specific scenario. In addition, a double-threshold mechanism, namely, the Hard Threshold (HT) and the Soft Threshold (ST), were adopted in TEEN (Threshold sensitive Energy Efficient sensor Network protocol) [14] which was applied in the hard real-time scenario. Similar strategies include APTxEEN (Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network) [15] which is an improved version for TEEN protocol using an adaptive algorithm to select CH, ELCH (Extending Lifetime of Clustering Head) [16] that selects CHs based on a neighbor voting mechanism, T-LEACH (Threshold-Based LEACH) [17] which rotates CHs according to a predefined threshold, DHAC (Distributed Hierarchy Aggregation Clustering) [18] selecting CHs according to the similarity matrix generated by the node's input, the algorithm which utilizes EDIT (Energy Delay Index for Trade-off) [19] to achieve a trade-off between energy consumption and network delay, and EEAOC (Energy-Efficient Adaptive Overlapping Clustering) [20] that adaptively selects CHs according to the residual energy of nodes. In addition, the network can be logically divided into multiple levels on the basis of the residual energy of nodes to form a multi-level architecture so as to achieve a high energy efficiency. For example, HHCA (Hybrid Hierarchical Clustering Approach) [21] classifies the nodes into layer-2 Grid head, layer-1 CH, and layer-0 normal nodes to form a three-level system, which adopts the distributed LEACH protocol and comprehensively considers the residual energy of nodes to have control over the cluster formation.

The Cluster Head selection can be also integrated with the optimization algorithm [22], such as the fuzzy logic, the game theory, the particle swarm optimization algorithm, and the simulated annealing algorithm, *etc*. Besides, combining with strategies which are related to the MAC and transport layers can also bring in the reduction of energy overhead and the equilibrium of energy consumption among clusters. Such strategies include LEACH-C [23] that centralizedly selects CHs through the simulated annealing algorithm, BCDCP (Base-Static Controlled Dynamic Clustering Protocol) [24] that realizes energy consumption balance among clusters by controlling the process of CH selection, OCCA (Optimal-Compression Clustering Algorithm) [25] which adopts the concept of Slepian-Wolf Coding to conduct Cluster Head selection, CC (Chessboard Clustering scheme) [26] based on the chessboard Clustering strategy for the heterogeneous sensor networks, DISD (Distributed Independence Set Discovery) [27] adopting sleep management mechanism, LEACH-ERE [28] introducing the concept of Expected Residual Energy (ERE) level which is established by the fuzzy logic as well as the T2FL model adopted for Cluster Head decision-making through a two-level fuzzy logic [29], *etc*. Related strategies also include FLEEC (Fuzzy-Logic based Energy-Efficient Clustering Algorithm) [30] and FCM [31] that can be applied to practical applications, the dynamic Clustering strategy EAERP (Energy-aware Evolutionary Routing Protocol) [32], GEEC (Game Theory Based Energy Efficient Clustering Protocol for WSNs) [33] and EEREG (Energy Efficient Routing protocol based on Evolutionary Game) [34] which are all based on the game theory, and PSO-C [35] which adopts the particle swarm optimization to conduct Cluster Head selection with the purpose of minimizing energy consumption for communication in the cluster.

B. CLUSTER SIZE CONTROL

The scheme controlling the cluster size concentrates on the balance of the inter-cluster energy consumption via properly regulating the number of CMs. It achieves the improvement of energy efficiency and extension of network lifespan by balancing the energy consumption. By controlling the cluster size in a way that the size of the cluster close to the Sink is smaller than that of the cluster in the edge area, the "Hot Spot Problem" can be alleviated effectively. For example, the large network topology can be divided into fan-shaped clusters to solve the "Hot Spot Problem" (Fan-Shaped Clustering, FSC [36]). In addition, the relevant characteristics of the network topology, such as the hop count (such as EC [37]), the distance from the location of nodes to the Sink, connection density (Balanced Clustering Algorithm with Distributed Self-Organization for Wireless Sensor Networks, DSBCA [38]) and the coverage, *etc*., can be adopted to optimize the cluster size for randomly-deployed WSN [39]. Related algorithms include EDFCM (Energy Dislocation Forecast and Clustering Management) [40] which belongs to a kind of LEACH-improved protocols and determines the cluster size according to the residual energy and the energy dissipation rate, EBCAG (Energy-Balancing Cluster Approach for Gradient-Based Routing) [41], LLBC (Localized and Load-Balanced Clustering protocol) [42] which is integrated with ICHR (Improved Cluster Head Rotation) and MSC (Modified Static Clustering) mechanism. In addition to the strategies listed above, the fuzzy logic theory, the optimization algorithm, the game theory and other intelligent algorithms can be also utilized to control the cluster size so as to achieve the energy balance among clusters [43]–[46].

C. DATA TRANSMISSION CONTROL

According to the first-order radio model [29]–[31], the amount of energy consumption for communication is directly proportional to the amount of the data transmitted when the communication distance is constant. Therefore, energy consumption can be cut down by reducing the data amount involved in transmission. For example, in some scenarios where the data are collected in burst mode, the energy can be conserved via reducing the frequency at which the sensor nodes transmit the source data to the corresponding CHs [14]. Besides, the data correlation existing in source data can be also utilized to reduce the amount of redundant data originated from the CMs via performing some simple aggregations at the corresponding CH, which cuts down the amount of data traffic among clusters. Such strategies include VGA (Virtual Grid Architecture routing) [47] in which the CH acts as LA (Local Aggregation) to conduct data aggregation and a MA (Master Aggregator) is selected from the LA set for global data aggregation to reduce energy consumption further after clustering. In addition, EIRNG was proposed which takes the energy balance among clusters into consideration frist [48]. However, it ignored the energy overhead resulted from the selection and rotation of CH. In addition to the schemes listed above, the mobile Sink or Relay [49], [50] was also utilized by the Clustering strategy to balance the energy consumption via changing the distribution of the "Hot Spot Area".

Although the energy efficiency can be improved through the Clustering strategies listed above to some extent, however, the energy overhead resulted from the process of CH rotation was not taken into account. On the other hand, almost all of them only focused on the mechanism of Cluster Head selection and the energy consumption within the cluster. In fact, the energy balance among different clusters also needs to be considered due to the fact that the overuse of an optimal routing results in fast energy depletion of nodes involved in the path. Therefore the energy efficiency can be improved further if the above problems are taken into consideration. The energy overhead for the rotation of CHs was reduced by adopting the dual-cluster-head mechanism in our proposal. Besides, the energy efficiency in inter-cluster communication was also considered in this paper and the energy balance among the Cluster Heads was improved via the non-cooperative game. Therefore our proposal aims to improve the energy efficiency via the reduction and balance of energy consumption simultaneously.

III. PRELIMINARIES

In this section, the energy consumption model and the network topology adopted in this paper were introduced firstly. Subsequently, some related assumptions and notations were presented.

A. ENERGY CONSUMPTION MODEL

In this paper, the first-order radio model [11], [12], [29]–[31] was adopted to describe the energy consumption for the propagation of a sensor node. Specifically, the energy consumption for a sensor node to transmit a k-bit packet to another over distance d equals

$$e_{tx} = k(E_{elec} + \varepsilon_{amp} \cdot d^{\alpha}), \tag{1}$$

where E_{elec} is the energy consumed in the transmitter circuit, ε_{amp} the transmitter amplifier and α $(2 \leq \alpha \leq 4)$ the propagation loss exponent whose value depends on the propagation model. Specifically, α is 2 for the free space model and increases to 4 for the multipath model respectively. On the other hand, to receive a k-bit message, the corresponding energy dissipation was shown as the following Expression (2)

$$e_{rx} = kE_{elec}, \tag{2}$$

where E_{elec} denotes the energy consumption of the receiver circuit.

B. NETWORK TOPOLOGY

In this paper, a sector-shaped network was adopted which is similar to what was adopted in Reference [51]. The Sink was deployed at the center and each layer was in ring shape with constant width, just as shown in figure 2. Without loss of generality, the sector region can be either an absolute monitor area or just a part of a larger general region. Therefore, the conclusions on the optimal distribution of the Cluster Head and the game model in section IV can be also applied to the region of any shape, such as rectangle, square, triangle, and so on.

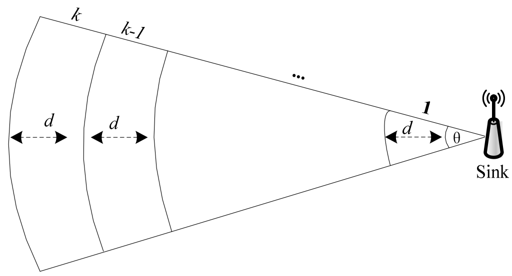

FIGURE 2. The network topology adopted in the paper.

C. RELATED ASSUMPTIONS AND NOTATIONS

For the sake of simplicity, some assumptions and notations were presented as follow.

The radius of the network topology is set to be R and central angle is θ. Besides, the network topology is divided into k ring-shaped layers with d in depth.

All the nodes keep stationary once deployed. Besides, they possess the same amount of initial energy. In addition, each sensor node is free to adjust its transmission range via changing the transmission power.

As shown in figure 2, the value of the parameter d is set to be 87m. The transmission range of each sensor node is also kept to be no larger than 87m to make sure that the data propagation follow the free space model [8].

The Sink is infinite in computing capability, storage capacity and energy supply compared with the sensor node. Besides, it has the full knowledge of the whole network topology, such as the parameters θ, k, R, d, and so on.

The data generation follows the uniform distribution. In addition, suppose the data packet is able to be divided into fragments as small as possible so that the traffic flow can be regarded as a continuous variable.

IV. RELATED LEMMAS AND CORRSPONDING FROOFS

In this section, the lemmas concerning the dual-cluster-head mechanism as well as the NEP of the non-cooperative game model for inter-cluster communication and the corresponding proofs were presented in detail.

A. DUAL-CLUSTER-HEAD MECHANISM

In this section, the dual-cluster-head mechanism was introduced which consists of the optimal distribution of CH, the ratio of energy to distance, and the role of Backup Cluster Head (BCH). Specifically, the Lemma concerning the optimal distribution of Cluster Head and the corresponding proof were presented firstly. Subsequently, the concept of the ratio of the residual energy to the distance from the sensor node to CH was proposed. The scheme to select the Backup Cluster Head was introduced finally.

1) OPTIMAL DISTRIBUTION OF THE CLUSTER HEAD

Lemma 1: Let d_n denote the distance from the Cluster Head lying in the nth ($1 \leq n \leq k$) layer to the Sink. The energy consumption of each cluster is minimized if condition $d_n = (2n-1)\sin\frac{\theta}{2}d/\theta$ is met, then d_n is called as the optimal distribution of the Cluster Head.

Proof: Assume the area of the nth layer equals to the size of a cluster for the sake of convenience. As shown in figure 3, the Cluster Head lies in the location which is x far away from the Sink. Besides, suppose an arbitrary node is randomly distributed at the coordinate which is a far away from the Cluster Head. It acts as a Cluster Member. Obviously the position of CH makes the energy consumption minimal when the sum of the square of distances from all the CMs to the CH are kept smallest. In figure 3, the square of the distance from the Cluster Member to its corresponding Cluster Head is denoted as

$$a^2 = x^2 + y^2 - 2xy\cos\alpha, \tag{3}$$

where y denotes the distance from the CM to the Sink and α the angle between line CH-Sink and line CM-Sink respectively.

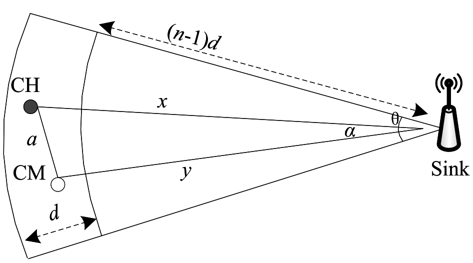

FIGURE 3. The optimal distribution of CH.

Hence, the sum of the square of the distance from all the CMs to their corresponding CH within one cluster can be established as follow,

$$\sum a^2 = \int_{-\theta/2}^{\theta/2}\int_{(n-1)d}^{nd}(x^2+y^2-2xy\cos\alpha)d\alpha dy. \tag{4}$$

Finally, the following Expression (5) can be obtained,

$$\sum a^2 = \theta dx^2 - 2(2n-1)d^2\sin\frac{\theta}{2}x + 3\theta(3n^2-3n-1)d^3. \tag{5}$$

Therefore the conclusion that $\sum a^2$ is minimal when condition $x = (2n-1)\sin\frac{\theta}{2}d/\theta$ is met can be drawn. According to the energy consumption model in section III, the energy overhead can be minimized when Expression (5) is established. Therefore the optimal distribution of CH is obtained.

2) RATIO OF ENERGY TO DISTANCE

In order to reduce the energy consumption resulted from the Cluster Head selection and rotation, the concept of the ratio of energy to distance was proposed in this paper. Specifically, it represents the ratio of a node's residual energy to the distance from itself to its corresponding Cluster Head. For the sake of briefness, it was denoted as R_{E-d}. In this paper, its mathematical definition was presented as

$$R_{E-d} = E_{re}/d_{s-CH}, \tag{6}$$

where E_{re} and d_{s-CH} represented the residual energy of the sensor node and the distance from itself to the corresponding Cluster Head respectively.

3) BACKUP CLUSTER HEAD

As for the Clustering strategy, the Cluster Head bears much heavier traffic burden than the Cluster Member. Therefore a CH dissipates energy much faster than its corresponding CMs. In order to achieve the energy consumption balance, the mechanism of rotating the role of the sensor node is adopted. Specifically, there are two roles for sensor nodes, namely CH and CM. The role of the Cluster Head is rotated periodically to alleviate the "Hot Spot Problem". To this end, the candidate exchanges message with each other to run for CH via broadcast. Apparently, the large amount of the broadcast leads to a waste of energy and the decline of energy efficiency.

In order to reduce the energy consumption resulted from CH rotation further, a third role which is called the Backup Cluster Head (BCH) was presented in this paper in addition to the roles of CH and CM. With the help of BCH, the rotation of CH happens between the Cluster Head and the Backup Cluster Head, which brings in the reduction of energy overhead resulted from the selection broadcast. In the initial phase, the node is designated as the Cluster Head if the value of R_{E-d} is the largest. Subsequently, the node with the second largest value of R_{E-d} is selected as the Backup Cluster Head by the present Cluster Head. The ratio and ID of the Backup Cluster Head are kept in the present Cluster Head's memory. Then the Backup Cluster Head is informed of its role by the present Cluster Head via a unicast. After fixed intervals, the present CH needs to check if it is necessary to hand over the role of CH to BCH.

B. NON-COOPERATIVE GAME MODEL FOR THE INTER-CLUSTER COMMUNICATION

In this section, the non-cooperative game model for the inter-cluster communication was presented firstly. Subsequently, the nep of the game model was pointed out and proven.

1) NON-COOPERATIVE GAME MODEL

As shown in figure 4(a), without any regulations made for WSNs, each player prefers to take the action which makes its own energy expenditure lowest during the process of forwarding determination. Specifically, each node tends to choose the

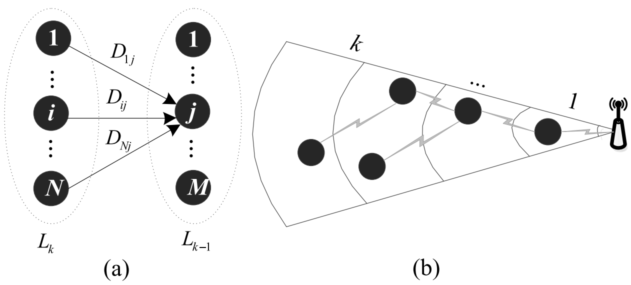

FIGURE 4. Non-cooperative game model.

node whose location is closest to itself as the next hop on account of the energy constraint. Therefore a node has a high probability to be selected as the next hop if it has relatively small distances to several nodes, which leads to its quick energy depletion. As a result, the node exhausts its energy ahead of time. If the proportion of exhausted nodes reaches a threshold, the network partition will occur. To this end, some regulations need to be made to avoid the problem and the non-cooperative game model was adopted in this section. Just as shown in figure 4(b), the network topology was divided into k layers. All the nodes lying in the same layer constitute the player set. The strategy set consists of nodes' amount of data towards to nodes at the adjacent upstream layer. Through the proper regulations made via the non-cooperative game model, the traffic load between two adjacent layers is more equilibrium, thus the energy consumption balance can be achieved. Each Cluster Head makes independent decision about data forwarding towards the next hop via the non-cooperative game model. The strategy of the game brings in energy consumption balance among the Cluster Heads laying in the adjacent layers.

The inter-cluster communication problem is modeled as a non-cooperative game which was denoted as follow

$$(P, S, U). \tag{7}$$

In the game model, all the nodes at an arbitrary layer n $(1 \leq n \leq k)$ of the network topology constitute the game player set. Suppose the number of the nodes lying in the nth layer is N, then the player set can be denoted as follow,

$$P = \{P_i | 1 \leq i \leq N\}. \tag{8}$$

Each player chooses his own action independently according to the corresponding utility function without needing to know any other players' strategies. In this paper, the strategy of a player i $(1 \leq i \leq N)$ at the nth layer is to determine the amount of traffic flow towards the adjacent node j $(1 \leq j \leq M)$ which locates at the $(n\text{-}1)$th layer. As shown in figure 4(b), M denotes the number of nodes at the $(n\text{-}1)$th layer. For the sake of convenience, the strategy set of the players denotes as

$$S = (s_1, s_2, \ldots, s_N), \tag{9}$$

where the strategy of node i is

$$s_i = D_{ij}. \tag{10}$$

D_{ij} denotes the data amount from node i to node j. Besides, the capacity of node j is defined as

$$C_j = \frac{E_j}{e_{rx}}, \tag{11}$$

where E_j is the energy budget for node j to receive data.

To improve the energy balance between two adjacent layers, a concept of balance factor is defined as follow

$$\theta_i = \frac{d_{\min}}{d_{ij}}, \tag{12}$$

where $d_{\min}$ denotes the minimum distance of nodes between the nth and the $(n\text{-}1)$th layers, and d_{ij} is the distance from node i to node j respectively.

Finally, the utility function of node i (denoted as player P_i in the following) is denoted as

$$U_i(s_i, s_{-i}) = D_{ij}^{\theta_i}(C_j - \sum_{i=1}^{N} D_{ij}), \tag{13}$$

where s_{-i} denotes the strategy set of other players except P_i. According to Expression (13), not only the energy consumption of the transmitter i but also that of the receiver j is taken into consideration through parameters θ_i and C_j, which brings in a better energy balance. Therefore the energy efficiency can be improved largely if appropriate strategies of the game players are designed.

2) NASH EQUILIBRIUM POINT

Definition 1: (Nash Equilibrium Point, NEP): Let $U_i(s_i, s_{-i})$ denote the utility function of player P_i, then $(D_{1j}^*, D_{2j}^*, \ldots, D_{ij}^*, \ldots, D_{Nj}^*)$ is the Nash Equilibrium Point (NEP) of the game iff $\forall i \in N, D_{ij} \in s_i, 0 \leq D_{ij} \leq C_j$, the condition $U_i(D_{ij}^*, D_{-ij}^*) > U_i(D_{ij}^*, D_{-ij})$ is always established, where s_i is the set of data amount determined by the player P_i to the nodes at the upstream layer.

Lemma 2: It is obvious that the Nash Equilibrium Point (NEP) of the non-cooperative game $(D_{1j}^*, D_{2j}^*, \ldots, D_{ij}^*, \ldots, D_{Nj}^*)$ exists. When the following Expression (14) is established

$$D_{ij}^* = \frac{\theta_i \cdot C_j}{1 + \theta_1 + \theta_2 + \cdots + \theta_N} = \frac{\theta_i \cdot C_j}{1 + \sum_{i=1}^{N} \theta_i}, \tag{14}$$

the value of utility function $U_i(D_{ij}, D_{-ij})$ is maximum.

Proof: For the sake of convenience, $U_i(D_{ij}, D_{-ij})$ is simply denoted as $U_i(\cdot)$. According to the differential theory, when $\frac{\partial U_i(\cdot)}{\partial D_{ij}} = 0$ is met, the value of $U_i(\cdot)$ is maximum. Therefore, when Expression (15) holds

$$\frac{\partial U_i(\cdot)}{\partial D_{ij}} = \theta^i D_{ij}^{\theta_i - 1}(C_j - \sum_{i=1}^{n} D_{ij}) - D_{ij}^{\theta_i} = 0, \tag{15}$$

the following Expression can be obtained

$$\theta_i C_j - \theta_i \sum_{i=1}^{n} D_{ij} = D_{ij}. \quad (16)$$

Let i in Expression (16) equal any possible values from 1 to N, we can obtain the following Expression (17) after several iterations

$$\sum_{i=1}^{n} D_{ij} = \frac{C_j(\theta_1 + \theta_2 + \cdots + \theta_N)}{1 + \theta_1 + \theta_2 + \cdots + \theta_N}. \quad (17)$$

Substituting Expression (17) into Expression (16), the following Expression (18) can be established

$$D_{ij} = \frac{\theta_i \cdot C_j}{1 + \theta_1 + \theta_2 + \cdots + \theta_N} = \frac{\theta_i \cdot C_j}{1 + \sum_{i=1}^{N} \theta_i}, \quad (18)$$

it is the Nash Equilibrium Point of the game model.

Lemma 3: The amount of data transmitted by the players locating at the nth layer to the upstream node j which lies in the (n-1)th layer depends on the energy budget for the communication between them. When the energy allocated for all the nodes laying in the nth layer to communicate with node j is equivalent, the data amount of each node at the nth layer to node j is NEP of the inter-cluster communication game.

Proof: Expression (1) indicates that the energy consumption for communication is in proportion to the square of transmission distance. Besides, it is easily concluded from Expression (12) that the value of balance factor θ_i is related to the transmission distance. Finally, Expression (18) shows that NEP of the game model is determined by the balance factor θ_i. Therefore the optimal amount of traffic flow of each game player is related to the energy budget for communication. Specifically, when all the players consume the same amount of energy for transmission, equation $\theta_1 = \theta_2 = \cdots = \theta_N$ holds, which means all the nodes at the nth layer transmit the same amount of data to node j.

It can be obtained from Lemmas 2 and 3 that the Nash Equilibrium Point of the non-cooperative game model exists. Both the energy allocated for the sender to transmit and that for the receiver to receive are taken into account during the process of inter-cluster communication. Specifically, the optimal strategy is determined by both of the balance factor θ_i and the capacity C_j. Obviously, the balance factor θ_i reflects the energy consumption for transmission and the capacity C_j stands for the energy consumption for reception. Thereby, the non-cooperative game model can alleviate the energy consumption imbalance problem among the Cluster Heads. When all of the CHs schedule their data amount according to Lemma 2, the energy consumption balance can be improved largely.

V. ENERGY-EFFICIENT CLUSTERING ALGORITHM COMBINED GAME THEORY AND DUAL-CLUSTER-HEAD MECHANISM

In this section, the novel Energy-efficient Clustering algorithm combined Game theory and Dual-cluster-head (ECGD) mechanism was presented in detail. Overall, the ECGD algorithm is executed round by round. Each round consists of three phases, namely, the optimal cluster head selection phase, the data acquisition phase and the dual-cluster-head mechanism respectively.

A. OPTIMAL CLUSTER HEAD SELECTION

The Sink determines the optimal distribution of the Cluster Head according to the parameters of the network topology, such as θ, d, R, and k. Subsequently, it floods a broadcast which contains $d_n(1 \leq n \leq k)$ and the corresponding layer number n to notify all the sensor nodes of the information concerning the optimal distribution of Cluster Head at each layer.

Once obtaining the optimal distribution of Cluster Head d_n, the sensor node calculates the corresponding distance d_{s-CH} from itself to the optimal distribution and then obtains the ratio of energy to distance R_{E-d} according to Expression (6). Subsequently, the sensor node keeps the ratio in its memory and then broadcasts a Cluster Head Election message which contains the parameters n, ID, and R_{E-d}. On receiving the broadcast from other nodes, each node compares its own ratio R_{E-d} with that contained in the broadcast to determine whether to accept the Cluster Head role which is recommended by the broadcast or not. To be specific, if its own ratio is higher, the sensor node discards the broadcast and generates a new Cluster Head Election message to recommend itself as the Cluster Head. Otherwise, it simply forwards the broadcast to other nodes. Finally, the node with the highest ratio is selected as the Cluster Head. Then the others act as Cluster Members. The Cluster Head broadcasts an Advertisement (ADV) message to inform others of the role as the Cluster Head.

The Cluster Member selects the appropriate CH to join in via replying with a join message (JOIN) once receiving the ADV messages. In general, the JOIN message contains the information such as the ratio, the ID of the sender, the layer number, and so on. As for the node who has not received any ADV messages, it selects itself as the CH and forms an Isolated Cluster which contains only one node.

The Cluster Head selects the second highest R_{E-d} via sorting all the ratios included in the JOIN messages. Subsequently, it assigns the Backup Cluster Head (BCH) role to the Cluster Member with the second highest ratio. Specifically, the present Cluster Head notifies the Cluster Member with the second highest ratio of the role of Backup Cluster Head via a unicast.

B. DATA ACQUISITION PHASE

In general, data acquisition phase consists of intra-cluster data acquisition and inter-cluster data transmission. In our proposal, the inter-cluster data transmission is regulated via the non-cooperative game model.

1) INTEA-CLUSTER DATA ACQUISITION

Once the cluster formation phase is finished, the Cluster Head divides the time slot based on TDMA mode according to the number of its Cluster Members. Subsequently, it allocates the time slot to all the CMs. The Cluster Member in the designated slot is supposed to acquire the source data, and the others turn to the SLEEP mode to save energy as much as possible.

2) INTER-CLUSTER DATA TRANSMISSION BASED ON NON-COOPERATIVE GAME

On the basis of the non-cooperative game model as well as Lemmas 2 and 3, the inter-cluster data transmission was proposed as follow.

Once the cluster formation is finished and the Cluster Heads are selected, an arbitrary Cluster Head (take node j $(1 \leq j \leq M)$ for example for the sake of convenience) of the (n-1)th $(1 \leq n \leq k-1)$ layer first calculates its maximum data capacity C_j which it can bear for data reception according to Expression (11). Subsequently it notifies all the Cluster Heads lying in its downstream level, namely, the nth layer of C_j in the form of broadcast. When all the Cluster Heads at the nth layer obtain the value of C_j, they calculate their corresponding distance to the Cluster Head j respectively according to the Received Signal Strength Indication (RSSI) [22]. In addition, each CH lying in the nth layer obtains the value of balance factor θ_i based on Expression (12) and informs other CHs at the same layer of its balance factor via broadcast. When the Cluster Head has the full knowledge of others' balance factor, it establishes the optimal amount of data towards node j at the (n-1)th layer according to Expression (14).

The above process repeats till an arbitrary node i $(1 \leq i \leq N)$ obtains the optimal data amount D^*_{ij} $(1 \leq j \leq M)$ to nodes at the (n-1)th layer. Finally, it regulates the amount of data towards CHs lying in its upstream layer according to the value of D^*_{ij} $(1 \leq j \leq M)$.

C. DUAL-CLUSTER-HEAD MECHANISM

To reduce the energy overhead resulted from the rotation of the Cluster Head, the dual-cluster-head mechanism which rotates the role of CH between the Cluster Head and the Backup Cluster Head was presented in this section.

At the end of each round, the present Cluster Head compares its ratio R_{E-d} with that of the Backup Cluster Head. If its own ratio is lower, it sends out a HAND OVER message to the Backup Cluster Head via a unicast. On receiving the HAND OVER message, the Backup Cluster Head updates its own ratio based on Expression (6) firstly since its residual energy has changed resulted from the communication last round. Subsequently it decides whether to take over the role or not according to its new ratio.

If the Backup Cluster Head decides to be CH, it broadcasts an Advertisement (ADV) and waits for the JOIN message from the Cluster Member. Subsequently it selects a new Backup Cluster Head and keeps a record of the information on the new BCH. Besides, it also informs the new Backup Cluster Head of its role of BCH in the form of unicast. On the contrary, if BCH's ratio is lower than the present CH's ratio, the Backup Cluster Head simply discards the HAND OVER message and continues to be BCH.

VI. SIMULATIONS

To evaluate the energy efficiency of ECGD, extensive experiments were conducted via simulation on the NS2 simulator in the paper. One hundred sensor nodes were independently and uniformly deployed in a circle area with the radius $R = 100m$. The initial energy of each sensor node was set to $2J$. The energy for receiving or transmitting one bit message was $50nJ$. Besides, the value of ε_{amp} was set to $13pJ/bit/m^2$. In this section, the network topology was divided into three layers, which means the value of k was equal to 3. Besides, the Sink located at the center of the network topology. In order to evaluate the energy efficiency of ECGD comprehensively, some metrics were defined firstly for comparison.

A. EVALUATION METRICS

Since the algorithm ECGD aims at improving the energy efficiency and extending the lifetime of WSNs, the network lifespan is one of the main metrics needed to be evaluated. In general, the definition of network lifespan varies with the type of applications. As for this paper, the following three definitions in terms of the network lifespan were predefined.

The time until the First Node Dies (FND). It denotes the simulation time until the first node has used up its energy. For some applications with high reliability requirements, such as the military monitoring and endangered species tracking, *etc.*, which have a strict demand on the reliability of data, it is vital to evaluate the value of FND.

The time until Half of the Nodes Die (HND). It denotes the time period until half of the sensor nodes have exhausted their energy.

The time until the Last Node Dies (LND). It reflects the duration until the last sensor node of WSNs has exhausted its energy. It means all the nodes have exhausted their energy already.

Average residual energy of WSNs. It denotes the mean residual energy of all the sensor nodes in the network topology. Since the algorithm ECGD was proposed with the purpose of improving the energy efficiency, it can reflect the energy dissipation rate of WSNs directly.

The total throughput of the Sink. It denotes the total amount of data received by the Sink during the simulation. Because the significance of WSNs can be achieved only if enough valid data are collected for the external server, it is critical to measure the throughput to evaluate the performance of ECGD. Besides, it also belongs to an important metric which is often adopted to evaluate the network performance.

The throughput against energy consumed. It denotes the throughput of the Sink at the instant when a certain percentage of the total network energy has been used up. Obviously, it takes both of the amount of data received and the energy consumed into consideration, so it reflects the energy efficiency intuitively.

ECGD is dedicated to improving the energy efficiency in term of reduction and equilibrium of energy consumption. Overall, it belongs to the Clustering strategy and takes the energy consumption in both of the intra-cluster and inter-cluster transmission into consideration. Therefore it needs to be compared with some existing Clustering strategies to evaluate its energy efficiency. In this section, some classical Clustering strategies, such as TEEN [14] and PEGASIS [13] were adopted for comparison. In addition, EIRNG [48] also considered the inter-cluster transmission as discussed in section II, therefore it was compared with ECGD in this paper. Finally, to evaluate its energy efficiency objectively, the LEACH-ERE [28], which is a fuzzy-logic-based Clustering algorithm with many citations recently was also compared.

B. RESULTS ANALYSIS

Figure 5 shown the comparisons among the five kinds of Clustering strategies in terms of the number of nodes alive during the simulation. As shown in figure 5, the number of nodes alive of ECGD is obviously much larger than those of the others. Noting that ECGD took the energy consumption in both of the intra-cluster and inter-cluster data transmission into consideration, the energy efficiency can be improved to a large extent and the lifespan can be extended markedly. Therefore the curve of ECGD lasts until the end as shown in figure 5. In addition, according to section VI(A), the network lifespan is also measured by the values of FND, HND, and LND. In this paper, ECGD was also compared with the other four algorithms in terms of the above three metrics. The following figure 6 shown the comparisons of network lifetime among the five algorithms. It indicated that the value of FND of ECGD was 75.3% and 7.0% larger than those of

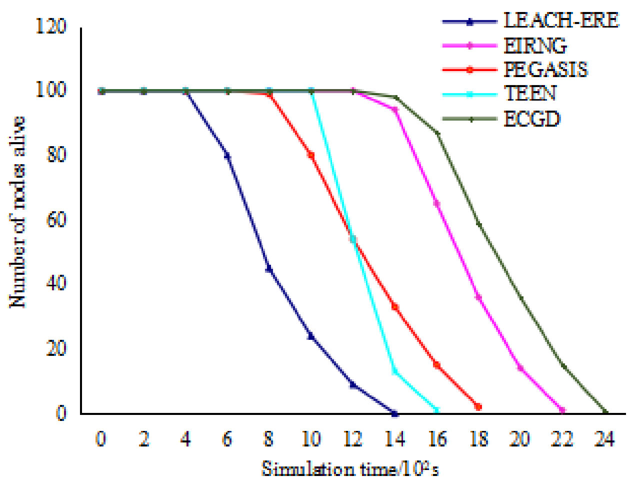

FIGURE 5. The number of nodes alive.

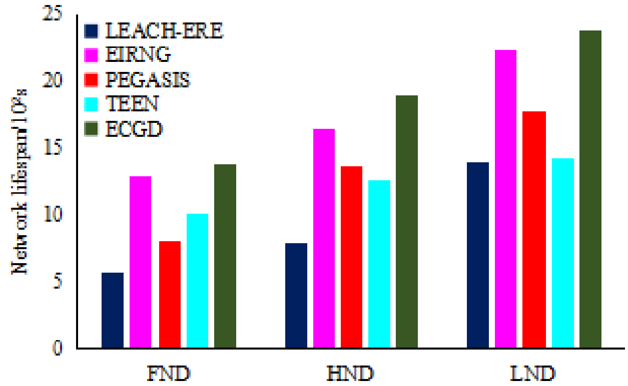

FIGURE 6. The comparison of network lifetime.

PEGASIS and EIRNG respectively. As for the value of HND, ECGD was 31.7% and 15.9% larger than TEEN and EIRNG respectively. Finally, the value of LND of ECGD has been improved compared with TEEN and EIRNG by 51.4% and 6.7% respectively.

Figure 7 shown the change of average residual energy of the network with the simulation time for the five different algorithms. It is obvious that the mean residual energy of ECGD was larger than those of other four algorithms at the same instant. For example, it was improved by 13.3%, 8.7%, 23.9%, and 31.2% compared with LEACH-ERE, EIRNG, PEGASIS, and TEEN in the 800th second respectively. Besides, it can be easily obtained from figure 8 that the slope of ECGD was the smallest among the five curves. It means that the energy dissipation rate of ECGD is the lowest. Therefore it directly reflects that ECGD processes a higher energy efficiency than others.

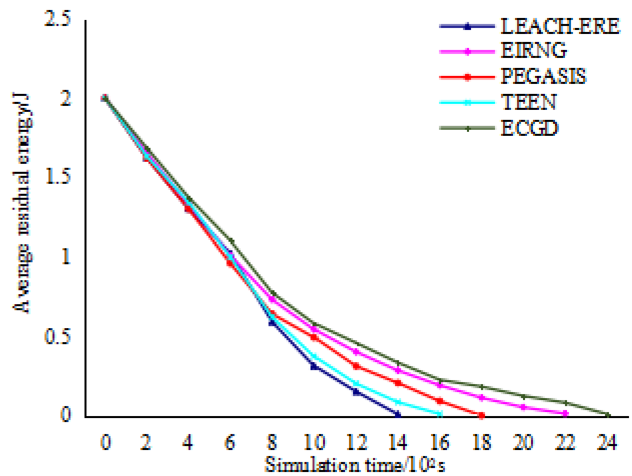

FIGURE 7. The average residual energy of nodes.

Figure 8 shown the change of data amount received by the Sink with respect to the simulation time for the five algorithms. It is apparent that the throughput of ECGD was the largest compared with the other four algorithms at the

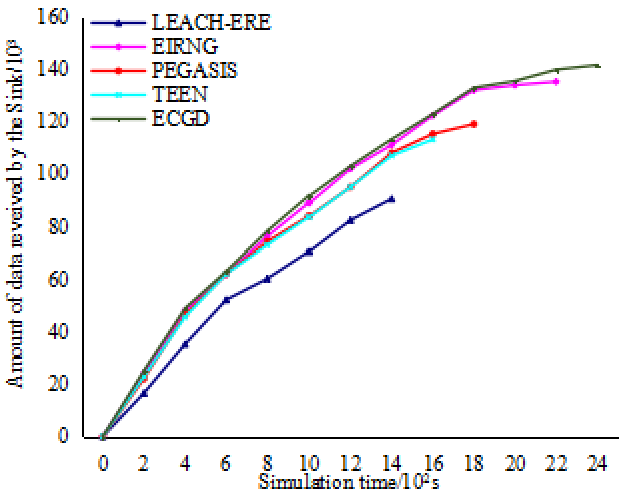

FIGURE 8. The amount of data received by the Sink.

same instant. Since the energy overhead resulted from the process of Cluster Head selection and rotation as well as the inter-cluster energy consumption imbalance were simultaneously considered in ECGD, the energy efficiency was improved. Besides, the time for Cluster Head rotation was cut down owing to the Dual-cluster-head mechanism, therefore the throughput of ECGD was relatively larger than others at the same instant. For example, at the 1400th second, the value of throughput of ECGD increased by 25.2%, 1.9%, 4.8%, and 5.9% compared with LEACH-ERE, EIRNG, PEGASIS, and TEEN respectively. In addition, the lifetime of WSNs for ECGD was prolonged, as a result, the total throughput of WSNs rose up. Therefore, the curve of ECGD lasts until the end among all the five curves as shown in figure 8.

Figure 9 shown the amount of data received by the Sink at the instant when a contain percentage of energy was consumed for each protocol. This metric directly reflects the energy efficiency owing to the fact that it takes both of the energy consumption and network capacity into consideration. As shown in figure 9, it indicated that the amount of data of ECGD under the given energy budget was the largest compared with the others. In addition, the data amount of ECGD increased markedly compared with the others when more than half of the network's energy has exhausted. Specifically, when seventy percent of the total energy of the network was used up, the amount of data of ECGD was 22.4%, 2.7%, 7.6%, and 12.5%, more than those of LEACH-ERE, EIRNG, PEGASIS and TEEN respectively.

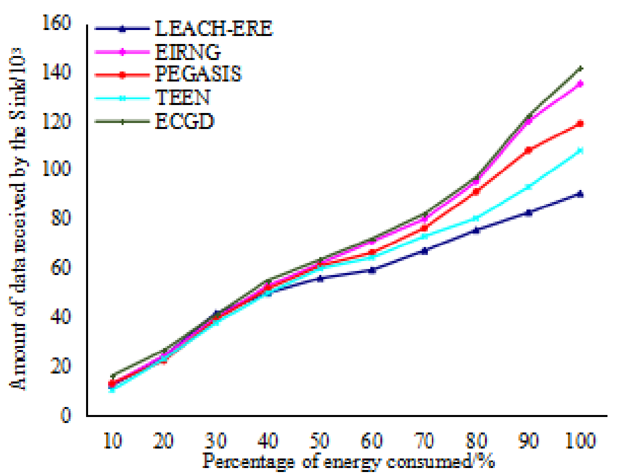

FIGURE 9. The amount of data at the instant when a certain percentage of energy exhausted.

VII. CONCLUSIONS AND FUTURE DIRECTIONS

In this section, the conclusions were drawn firstly to sum up what has been achieved in this paper. Subsequently, some future research directions were pointed out.

A. CONCLUSIONS

WSNs have the feature of limited energy and computing capacity. Besides, it is impossible or unpractical for the sensor node to be replenished owing to the constraint of the application occasion and the environment. It makes energy constraint become one of the main challenges facing WSNs. This paper focused on the following two aspects to improve the energy efficiency: reducing energy consumption and balancing energy consumption. Specifically, the paper proposed a novel Energy-efficient Clustering algorithm combined Game theory and Dual-cluster-head mechanism (ECGD) to improve the energy efficiency further. ECGD aimed at reducing the energy overhead resulted from cluster formation as well as CH rotation and alleviating the energy imbalance via Dual-cluster-head mechanism and non-cooperative game model respectively. Finally, extensive simulations were conducted and the results comparisons have verified its energy efficiency.

B. FUTURE RESEARCH DIRECTIONS

Although the Clustering strategies can improve the energy efficiency to some extent, almost all of them are subject to the demand of Nyquist's Theorem that the sample frequency should be at least twice as much as the largest frequency of the source signal to recover it precisely. It leads to the phenomenon that the collected data exhibit high Spatial-temporal correlation, which means the data redundancy exists in WSNs. It results in a waste of energy somewhat. Therefore, in the future research, the Compressive Sensing (CS) theory and the predictive coding theory can be adopted to reduce the energy consumption resulted from the Spatial-temporal correlation [52], [53].

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