Energy-Efficient Coalition Formation in Sensor Networks: a Game-Theoretic Approach

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Abstract—The most important challenge in Wireless Sensor Networks (WSNs) is the energy constraint. Numerous solutions have been proposed to alleviate this problem, the most efficient of which is to cluster the sensor nodes. Although clustering in the realm of WSNs has widely been explored by researchers, a few effective mechanisms in grouping the nodes, including coalitional games, need more attention and research. This motivated us to employ cooperative games and to propose a Coalitional Game-Theoretic Clustering (CGTC) algorithm for WSNs. Basically two kinds of coalitions are formed regarding the location of sensor nodes, where local parameters play an important role in forming coalitions. Moreover, the Shapley value is adopted as the solution concept. The result of simulation confirms the effectiveness of CGTC in terms of energy efficiency.

Index Terms—Wireless Sensor Networks; Clustering; Game Theory; Cooperative Games.

I. INTRODUCTION

Recently, Wireless Sensor Networks (WSNs) have emerged as one of the most notable technologies. WSNs’ applications are widespread, ranging from military to health-care to smart cities. Since nodes are battery-operated, the most important challenge in WSNs is to conserve the energy. Accordingly, researchers have proposed plenty of solutions, trying to alleviate this challenge. One of the most popular solutions is clustering. Typically in clustering, the nodes are divided into some groups as clusters, and some nodes are elected to play the role of head of each cluster. Operations in clustering algorithms for WSNs are usually divided into three phases [1]: CH election, cluster formation, and data transmission. Clustering has many benefits for WSNs, including scalability, reduced routing delay, and topology management. Numerous techniques have been used in this respect, including heuristic algorithms and Fuzzy logic. Among them, Game Theory needs more attention, in light of its strong abilities in modeling distributed systems interactions.

Game theory is a strong framework with a set of mathematical tools to study the complex interactions among intelligent rational players [2]. Introduced by John von Neumann, modern game theory is broadly utilized in many sciences, including economics, politics, biology, and computer science. In game theory, each player has a set of choices, and it is assumed that each player plays rationally and selects the best strategy according to the outcome function (payoff or utility). In general, games could be divided into two groups: cooperative and non-cooperative. In non-cooperative games, each player plays individually and opts decisions to maximize its utility. On the other hand, cooperative games give this opportunity to players to create coalitions and prefer the network-wide utility to individual utility. Basically, it has been shown that coalitional games has a better performance in group formation than non-cooperative games [3].

In this paper, we adopt coalitional games for WSNs in order to form energy-efficient coalitions. Initially, the network area is divided into two regions: far and vicinity. In the far region, a set of nodes with the highest residual energy, called Coalition Head Nominees (CHNs), initiate cooperative games within their surroundings. Then, CHNs along with two other nodes shape final coalitions. On the other hand, in the vicinity region, some small coalitions are formed to tackle the energy-consuming data relaying task. The Shapley value is chosen as the solution concept for coalitional games. The remaining of this paper is outlined as follow. Section II provides a state-of-the-art survey on game-theoretic clustering algorithms for WSNs. Section III details preliminaries. Section IV describes proposed CGTC algorithm in detail. We present the simulation experiments in section Section V, and the paper is concluded in section VI.

II. RELATED WORK

Recently, a few clustering algorithms based on game theory have been developed and could generally be classified into: cooperative and non-cooperative clustering algorithms. DEGRA [4] is a non-cooperative clustering algorithm in which a finite complete and perfect information game is employed. The payoff of each player consists of three factors, namely the residual energy of the node, the consumed energy of the node’s neighbors, and the node density. In GTC [5], game theory is used in order to tune the cluster sizes. More precisely, operations in GTC is segmented into two phases: the load-balancing algorithm and cluster formation. Firstly, the network area is segmented into some squares. Then, the width of each square is determined via game theory in order to equalize the load among all CHs, considering the fact that there is exactly one CH in each square. In [6], the transmission load assignment in WSNs is modeled as a game. In the method, transmitting merely one packet to the base station (BS) suffices to trigger the response of surveillance system, and authors try to determine which sensor is going to do this, in order to fairly balance the load among all nodes. In general, since each node tries to individually achieve a better payoff, non-cooperative
games seem not to be the best match for group formation purposes.

On the other hand, quite few clustering algorithms based on cooperative games have been proposed in recent years. In CGC [7], a cooperative clustering algorithm is proposed for WSNs with the objective of maximizing the network lifetime. The wisdom behind CGC is to consider the trade-off between individual and network-wide costs. Formed coalitions consider the number of cluster members, the redundant energy, and the transmission energy. The Shapley value is chosen as the solution that assigns a single cost allocation to the cost sharing game. Nonetheless, initial candidate selection in CGC is partly random. Moreover, direct communication with the BS diminishes the scalability of CGC. We compare the performance of our algorithm with that of CGC in section IV. Similarly, CSGC [8] presents a bi-directional cooperative clustering model, where cluster members cooperate in inter-cluster and intra-cluster transmissions. Both methods use a cost-sharing game in order to select Coalition Heads (CHs). Moreover, [9] employs a coalitional game in heterogeneous WSNs. In the method, a small number of nodes with increased computing power and lifetime (called representatives) is employed as the controllers of coalitions. Besides, an adaptive clustering scheme is proposed in which neighbors of representatives form coalitions in order to increase energy efficiency at the cost of controllable data-accuracy reduction. However, supporting heterogeneity and strong nodes is not practical in all setups. Overall, none of above works solves the hot-spot problem, which is caused due to overloading nodes close to the BS.

III. Preliminaries

We consider a network of $n$ nodes that are deployed in an area of $m \times m$. The BS is located at a point far from the field. The nodes positions follow a uniform random distribution so that we have

$$n = \lambda |a| = \lambda m^2,$$

where $\lambda$ is the node density. Both the BS and nodes are stationary, and the nodes are not equipped with the GPS receivers. All sensor nodes have the same capabilities and can use different power levels to communicate with other nodes. The network operation is divided into rounds, at first of which coalitions are formed and then data is disseminated to the BS through multi-hop paths among CHs. In-network data aggregation is applied to eliminate redundant sensor reports. In CGTC architecture, the network area is divided into two general regions: far and vicinity. This division is adopted to solve the hot-spot problem, and we provide more details on this in section IV.

The model for energy dissipation is derived from the radio model proposed in [10]. Accordingly, the energy needed to transmit a $l$-bit packet to distance $d$ is,

$$e_t = \begin{cases} l(e_{el} + \epsilon_{fs}d^2) & d \leq d_0, \\ l(e_{el} + \epsilon_{mp}d^2) & d > d_0, \end{cases}$$

where $e_{el}$ is the electronics energy, $\epsilon_{fs}$ and $\epsilon_{mp}$ are the amplifier energy of free space and multi-path models, respectively, and $d_0 = \sqrt{\epsilon_{fs}/\epsilon_{mp}}$. Also, to receive a $l$-bit packet a node consumes

$$e_r = le_{el}.$$  

Considering $\mathcal{N}$ as the set of all players, any coalition $\mathcal{S} \subseteq \mathcal{N}$ stands for an agreement among players. Moreover, $v$ indicates the worth of a coalition in a game. Accordingly, a coalition game is defined as follows.

Definition 1. A coalitional game is defined by the pair $(\mathcal{N}, v)$, where $\mathcal{N}$ is the set of players, and $v$ is the mapping function that determines the payoffs of players.

The mapping function $v$, also called characteristic function, is defined as $v : 2^\mathcal{N} \rightarrow \mathbb{R}$ and satisfies $v(\emptyset) = 0$. Coalitional games have two popular solutions: the core and the Shapley value. In light of problems of the core solution [2], we use the Shapley value. Due to the low space, we suffice to give the alternative interpretation of the Shapley value and the curious reader is referred to [11] for more investigation.

$$\phi_i(v) = \sum_{S \subseteq \mathcal{N}\setminus\{i\}} \frac{|S|!(|\mathcal{N}|-|S|-1)!}{\mathcal{N}!}[v(S \cup \{i\}) - v(S)],$$

where $\phi$ is the payoff assigned in the game $(\mathcal{N}, v)$, $\phi_i(v)$ is the payoff assigned to player $i$, and $|S|$ is the cardinality of $S$. Since, in this paper, we mainly focus on the cost games, we use $c$ instead of $v$ and all concepts can easily be interchanged. The cost of each coalition is proportional to the amount of energy consumed by the coalition. The consumed energy at each node has a direct relationship with receiving a bunch of data and transmitting it over a distance. Depending on the location of nodes (i.e., located in the far or vicinity regions), the consumed energy is different. Accordingly, the cost of a coalition located in the far region is computed by

$$c(S^f) = \sum_{i \in S^f} c_{ch_i} + \sum_{j \in S^f} c_{nch_j},$$

where $c_{ch_i}(S^f)$ is the consumed energy by a CH in coalition $S^f$ and is

$$c_{ch_i}(S^f) = lk(e_{el} + e_{da} + \mu(e_{el} + \epsilon_{fs}d^2)),$$

where $e_{da}$ indicates the energy dissipated for data aggregation, $k$ is the number of coalition members assigned to CH, and $\mu$ is the aggregation coefficient. Note that here $d$ is the distance between a CH and its next-hop CH and could be $d^f$ if the distance is greater than $d_0$, based on Eq. [2]. Moreover, $c_{nch_j}$ is the energy consumed by a non-CH node in coalition $S^f$ and is achieved by

$$c_{nch_j}(S^f) = l(e_{el} + \epsilon_{fs}d^2).$$

On the other hand, the cost of a coalition in the vicinity region is proportional to the amount of energy all ordinary nodes located within the same coalition spend to relay the received data. Thus,

$$c(S^v) = \sum_{i \in S^v} c_{on_i},$$
and
\[ c_{on/(S)} = \eta (e_{el} + e_{cl} + \epsilon_s d^2) = l(2 e_{el} + \epsilon_s d^2), \]  

(9)

where \( \eta \) denotes the number of far coalitions select this coalition as their next-hop.

IV. DETAILED CGTC ALGORITHM

In this section, we elaborate CGTC algorithm. Basically, coalition formation in the far region is performed with the objective of data gathering and transmitting to the BS. On the other hand, in the vicinity region, coalitions are formed in order to appropriately handle the data relying task imposed by farther coalitions. Note that the area division is performed once at first of the network deployment by the BS through broadcasting a REG-DEC message throughout the network. We first explain coalition formation in the far region.

A. Far Region Coalition Formation

Our main objective of coalition formation is energy efficiency so the remaining energy plays a crucial role in selecting CHs. At the beginning of each round, nodes broadcast a CHN-INF packet containing some information, including the residual energy (\( E_{res} \)), the number of neighbors (node degree, \( D_n \)), and the proximity to the BS (\( d_{i,bs} \)), within their coalition range (\( R_c \)) and wait for a predefined time (\( T_c \)), which is a function of \( R_c \). Having waited for \( T_c \) and received the packets from neighbors, each node either selects itself as the CHN based on the highest residual energy or remains the ordinary node, noting that ties are randomly broken in the first round.

When CHNs are elected, they select at most two other nodes in order to constitute their coalitions. CHNs select two nodes with the highest \( D_n \) or smallest \( d_{i,bs} \) as other head of each coalition. To do so, the CHN unicasts a CH-REC packet to potential CHs. The condition for cooperation is that the initial cost of the CHN should be reduced. In other words, if there is a node, e.g., \( A \), in the \( R_c \) of the CHN, it cooperates with \( A \) if \( \phi_{CHN} + \phi_A < c(CHN) \), where \( c(CHN) \) is the cost of coalition when \( S = \{CHN\} \) and is computed by Eq. (5). Note that each node computes its share by Eq. (4). Therefore, the final successful coalition in this example has three CHs, i.e., \( S = \{CHN, A, B\} \) (see Fig. 1).

Elected as CHs, head nodes broadcast an advertisement message CH-ADV within their \( R_c \) and invite ordinary nodes to become their coalition members. On receiving this message, each non-head node sends a JOIN-REQ message to the nearest head node based on RSSI. After this, CHs establish a TDMA protocol and send time schedules to their members.

Once coalitions are formed, data should be transmitted to the BS periodically. To do this, multi-hop paths should be established among CHs. Unlike traditional clustering algorithms, there are up to three CHs within each coalition so that the routing latency significantly diminishes. The routing task in our scheme is so easy. Within each coalition, each CH transmits its data to the CH that has a smaller \( d_{i,bs} \). Then, last CHs of each coalition transmit their data to the closest CHs of the next coalition toward the BS. Lastly, the data reaches the vicinity region and is relayed to the BS. Fig. 1 illustrates this context.

B. Vicinity Region Coalition Formation

In the vicinity region, there is no CH and boundary nodes usually start the game. When boundary nodes receive data from far coalitions, they calculate the cost of direct transmission to the BS. Then, they select up to three nodes, preferably with high \( E_{res} \), and check the condition of cooperation, explained in the previous subsection. Note that since the defined cost is in fact the energy consumed by a coalition, if nodes that join the coalition has a higher \( E_{res} \) than the node starting the game, this extra energy is subtracted from the coalition cost, which is computed by Eq. (9). Note also that nodes’ priority in the vicinity region is data relaying task. This decided in order to compensate the imposed data overhead and to solve the hot-spot problem.

V. PERFORMANCE EVALUATION

In this section, the results of our experiments through extensive simulation are given.

A. Simulation Setup

CGTC is simulated using MATLAB. Two different node densities are studied: \( \lambda_1 = 0.01 \) \((n = m = 100)\) and \( \lambda_2 = 0.005 \) \((n = m = 200)\), based on Eq. (1). The BS is located at \((m + 50, m/2)\) and the node positions follow a uniform random distribution. We take the duration of each round to be equal to five data gathering epoch. Also, we do not consider packet losses and we assume that all messages are successfully received by their destinations.

We compare CGTC with two baseline clustering algorithms, namely LEACH [10] and CGC [7]. LEACH is the popular clustering protocol that utilizes random CH election. Generally, we have picked the parameter settings that yield the best performance for baseline algorithms. In particular, for both competing algorithms, depending on the node density, we have the CH election probability \( p \in [0.05, 0.1] \). Other simulation parameters are summarized in Table 1. The individual results are the average over 20 runs and the length of each run is 6000 rounds. When subjected to 95% confidence interval the results stayed within 6-10% of the sample mean.
B. Simulation Results

In this subsection, we report the results of simulation. Fig. 2(a) compares the network lifetime of the three algorithms for $\lambda_1$. As shown in the figure, CGTC significantly outperforms the two competing algorithms in terms of the network lifetime. While in CGTC there are more than 80% of nodes alive until round 3000, the majority of nodes (around 60%) die before rounds 1500 and 2500 in LEACH and CGC, respectively. This is mainly because CGTC forms suitable coalitions, picks nodes with appropriate parameters values as heads, as well as solves the hot-spot problem. Among baseline algorithms, CGC has a better condition due to employing coalitional games and taking residual energy into account for CH election; however, the algorithm still suffers from random candidate election. Moreover, it adopts direct communication between CHs and the BS so energy consumption climbs.

Fig. 2(b) illustrates the energy-efficiency for $\lambda_2$, which significantly affects the performance of the two baseline algorithms. As shown, the number of alive nodes in LEACH quickly drops to less than 20, and all nodes die before round 2000. In CGC, after a dramatic decrease in the number of alive nodes, it experiences a less sharp decline and reaches zero before round 2500. In contrast, more than half of the nodes are alive in CGTC until round 3500. Overall, yet the network scales grow, CGTC has a good performance, in terms of energy efficiency, and significantly outperforms two baseline algorithms.

VI. Conclusion

We have proposed CGTC, a Coalitional Game-Theoretic Clustering algorithm for sensor networks, whose main objective is energy-efficiency. Initially, the network area is divided into the far and vicinity regions. Then, depending on the location of nodes, different coalitions are formed. Basically, the residual energy plays a significant role in shaping coalitions. The Shapley value is used as the solution of coalitional games. The results of simulation shown that CGTC considerably outperforms competing algorithms CGC and LEACH.

| Parameter | Scenario 1 | Scenario 2 |
|-----------|------------|------------|
| $n$       | 100        | 200        |
| $m$       | 100        | 200        |
| $\lambda$ | 0.01       | 0.005      |
| BS        | (150,30)   | (250,100)  |
| $e_{f}$   | 10pJ/bit/m$^2$ | 10pJ/bit/m$^2$ |
| $e_{c}$   | 0.0013pJ/bit/m$^2$ | 0.0013pJ/bit/m$^2$ |
| $e_{a}$   | 50nJ/bit   | 50nJ/bit   |
| $e_{s}$   | 5nJ/bit/signal | 5nJ/bit/signal |
| $H_c$     | 20m        | 20m        |
| $\mu$    | 0.5        | 0.5        |
| Initial Energy | 1 J | 1 J |
| Data Payload | 100 Byte | 100 Byte |
| Header     | 2 Byte    | 2 Byte    |
| Trailer    | 1 Byte    | 1 Byte    |

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Fig. 2. Network lifetime comparison among three protocols.