Autonomous Clustering and Message Passing Protocol for Energy Efficiency in Wireless Sensor Networks

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Abstract*— Wireless sensor networks consist of a large number of nodes with limited battery power and sensing components, which can be used for sensing specified events and gather wanted or interesting information via wireless links. It will enable the reliable monitoring of a variety of environments for both civil and military applications. There is a need of energy-efficient message collection and power management methods to prolong the lifetime of the sensor network. Many methods, such as clustering algorithm, are investigated for power saving reason, however, they only consider reducing the amount of message deliveries by clustering but not the load balance of the clusters to extend the maximum lifetime of the network. Therefore, in this paper, we propose a fully distributed, randomized, and adaptable clustering mechanism named autonomous clustering and message passing (ACMP) protocol for improving energy efficiency in wireless sensor networks. ACMP enables sensor nodes cluster themselves autonomously according to their remaining energy and dynamically choose a corresponding cluster head (CH) to transfer the collected information with a minimum energy consumption route. Sensor nodes judge an appropriate power level to form clusters and use minimum energy to exchange messages. The network topology is changed dynamically depending on the CH's energy. Moreover, by maintaining the remaining energy of each node, the traffic load is distributed to all nodes and thus prolong the network lifetime efficiently. Simulation results show that ACMP can achieve a highly energy saving effect as well as prolong the network lifetime.

I. INTRODUCTION

A wireless sensor network consists of a lot of inexpensive, lower-power, and tiny sensor nodes, which has a wide range of potential applications including environment monitoring, target tracking, security, medical systems, health care, and robotic exploration, etc [5], [9], [13]. These sensor nodes can self-organize to form a network and can communicate with each other using their wireless interface. These sensor nodes are usually unreliable and inaccurate, but their size and cost enable applications to network hundreds or thousands of these tiny sensor nodes in order to achieve high quality, fault-tolerant sensing systems. Each node has one or more sensors, embedded processors and low-power radios, and is normally battery operated.

Because of the energy restriction of sensor nodes it needs an energy-efficient communication protocol for battery power saving so that prolongs the sensor network's lifetime. One major task of these sensor nodes is to gather wanted information and send them back to a coordinator called *sink* node for analyzing and monitoring specific matters. This action will consume a lot of energy if there is no efficient communication protocol. One potential solution of saving battery consumption is to reduce the number of messages to the sink node. One simple way to reduce the number of messages is to divide all sensor nodes into several clusters and gathers the information from nodes by cluster head. After accumulating a reasonable amount of messages, cluster heads transfer the aggregated information to the sink node in order to reduce the energy consumption [21]. Fig. 1 depicts an application where sensor nodes periodically transmit information to a remote observer (e.g., a sink node). It shows that the communication overhead can be reduced by separating sensor nodes into several clusters.

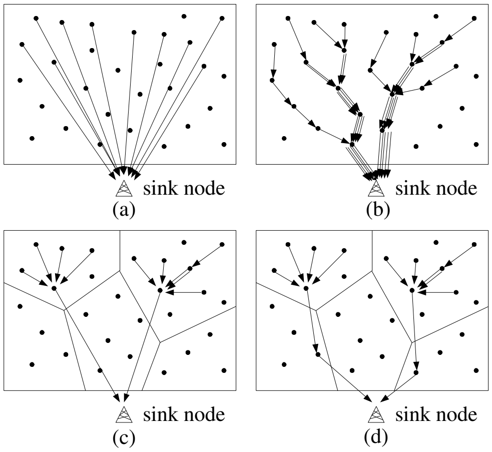


Fig. 1. An illustration of information gathering with and without clustering: (a) Single hop without clustering; (b) Multihop without clustering; (c) Single hop with clustering; and (d) Multihop with clustering.

Many clustering algorithms have been investigated and proposed in recent years [1], [2], [4], [7], [8], [11], [12], [19]. The Span [4] and geographic adaptive fidelity (GAF) [19] algorithms are geographic topology based clustering protocols that utilize location information to eliminate unnecessary links. However, they may not be feasible since the position of each node is often not provided in practice. The low-energy adaptive clustering hierarchy (LEACH) [11] utilizes randomized rotation of clusterheads (CHs) to evenly distribute the energy load among sensor nodes in the network. In fact, the rotation of CHs is not necessary and may waste more energy if there are few events in some areas. The clustering-based maximum lifetime data aggregation (CMLDA) [8] scheme is a data collection algorithm that focuses on how to find an efficient manner in which the data should be collected from all sensor nodes and transferred to the sink node, such that the network lifetime is maximized. Nevertheless, CMLDA does not considers the total energy usage and thus not achieve the global solutions. The Max-Min D-Cluster algorithm [1] generates d-hop clusters with a run-time of $O(d)$ rounds. Unfortunately, this algorithm does not ensure that the energy used in communicating information to the sink node is minimized.

In [2] and [7], the authors propose a distributed algorithm for organizing sensors into a hierarchy of clusters with the objective of minimizing the total energy spent in the system to communicate the information gathered by these sensors to the sink node. However, they do not consider the network lifetime, which is defined as the time from nodes deployment to the time when the first node is run out of function due to energy depletion. The energy consumption is defined as the total energy consumed by all nodes in the sensor network during the whole data processing procedure. In [12], the authors propose a dynamic cluster-based structure to track the movement of boundaries and facilitate the fusion and dissemination of boundary information in a sensor network. It is suitable for tracking special events like fire but is not for tracking one or more individual objects, such as people, animals, and vehicles.

To avoid above mentioned drawbacks, this paper proposes an autonomous clustering and message passing (ACMP) protocol for wireless sensor networks. The ACMP has five unique characteristics:

- ACMP is a fully distributed and autonomous sensor communication protocol.
- Each node can join C clusters at most simultaneously.
- The cluster topology is changed dynamically depending on the remaining energy of CHs.
- The load balance of each cluster is considered in this scheme.
- ACMP supports local re-clustering.

Sensor nodes will dynamically decide to pass the data to a CH which has more remaining energy. It will dynamic re-cluster locally, if have no need to re-cluster globally. We will simulate it to demonstrate that the energy consumption is fewer and the network lifetime will longer than other clustering protocols. ACMP is a protocol for self-organized and autonomous distributed sensor systems.

The remainder of this paper is organized as follows. Section II describes the system model of ACMP. Section III discribes the detail of ACMP. In Section IV, shows ACMP effectiveness via simulations and compares it to other clustering techniques. we perform a series of simulations to evaluate the performance of ACMP. Finally, we give some conclusions in Section V.

II. SYSTEM MODEL

ACMP uses the carrier sense multiple access (CSMA) medium access control (MAC) protocol to form clusters. Once the clusters are created, the CH receives all messages from its members of the cluster. According to the number of its members, the CH creates a time schedule time based on division multiple access (TDMA) protocol [6], [14], [17] to tell its members when it can wake up to transmit or receive. The radio of each member can be turned off until the node's allocated transmission time, thus it can minimize energy consumption. The CH must keep its receiver on to receive all the data from the nodes in the cluster. When all the data has been received, the CH compresses the data into a single message and transmit the aggregated information to the sink node.

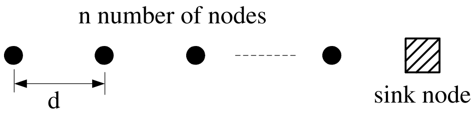


Fig. 2. A simple linear network.

A typical sensor node consists mainly of a sensing circuit for signal conditioning and conversion, a digital signal processor, and radio links [3], [10], [15]. The energy consumption model [11], [16] for each sensor are given as below.

A. Communication Energy Dissipation

The key energy parameters for communication in this model are the energy/bit consumed by the transmitter electronics (α_t), energy dissipated in the transmit op-amp (α_a), and energy/bit consumed by the receiver electronics (α_r). Taking Fig. 2, assume a d^2 energy loss due to channel transmission. Thus, to transmit a r-bit message a distance d using the radio model, the radio expends:

- $E_{Tx}(r,d) = \alpha_t r + \alpha_a r d^2$, where E_{Tx} is the energy consumed to send a r-bit message.
- $E_{Rx}(r,d) = \alpha_r r$, where E_{Rx} is the energy consumed to receive a r-bit message.
- α_t, α_r, energy dissipated in transmitter and receiver electronics per bit (Taken to be 50 nJ/bit).
- α_a, energy dissipated in transmitter amplifier (Taken to be 100 pJ/bit/m^2).
- r, number of bits in the message.
- d, message transmission distance.

B. Computation Energy Dissipation

We assume the leakage current model of [15], [18]. The model depends on the total capacitance switched and the number of cycles in the program.

III. AUTONOMOUS CLUSTERING AND MESSAGE PASSING

Consider a sensor network consisting of hundreds or thousands of sensor devices, which are fairly distributed in an area, with the same hardware specification. Each sensor node has k kinds of power level $E = \{e_1, e_2, \ldots, e_k\}$ and its corresponding transmission distances are $d_1, d_2, \ldots, d_k$. Assume $e_1 < e_2 < \ldots < e_k$ then we have $d_1 < d_2 < \ldots < d_k$. Taking Fig. 2, in minimum-transmission-energy (MTE), each

Type	Destination	Source	CH	Remaining Energy	TTL	Hop_Count

Fig. 3. The ACMP control message format.

node sends a message to the closest node on the way to the sink node. The node located at distance nd from the sink node would require n transmits a distance r and $n-1$ receives. From the literature [11], it shows that the direct communication to the sink node requires less total energy than MTE routing protocol if:

$$\frac{\alpha_t}{\alpha_a} > \frac{d^2 n}{2}. \tag{1}$$

According to this criterion, ACMP can choose a minimum energy consumption route to the CH to form the cluster. In the following, we will describe ACMP in detail.

A. Clustering and Power Control

Assume each node has the same probability P to become a CH in the network. Initially, every node decides itself whether to be a CH or not according to the probability P. The node will advertise a control message via broadcast to its neighbors within its radio transmission range with the lowest power level e_1 once it decides to be a CH. The control message format is shown in Fig. 3 and described as follows:

- The "TYPE" field indicates the type of the message which represents REQUEST, REPLY, REFRESH, or RESET, respectively. The REQUEST message is sent by an unclustered node which wishes to form a cluster; the REPLY message is used to reply to the REQUEST; the REFRESH message is used by CHs to announce its members to update their CH table. The RESET message is sent by CHs to announce its members to exit their cluster and delete the records of CHs that announce the message.
- The "Destination" is the destination address.
- The "Source" is the sender's address.
- The "CH" field indicates the message belongs to which CH.
- The "Remaining Energy" is the remaining energy of CH.

An unclustered node wishes to form a cluster, it sends the REQUEST message. Before sending the REQUEST message, the sensor node should proceed a backoff procedure to avoid more than one node serving as a CH at the same time. We let $B(E_r)$ represent the backoff function and is given by

$$B(E_r) = \frac{2m}{E_r} \tag{2}$$

where m is the number of neighbors of the sender and E_r is the remaining energy of the node. This strategy is to ensure that the node with a higher remaining energy would serve a CH first.

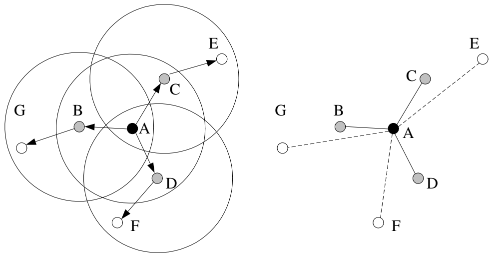
Nodes which receive the REQUEST message will become a cluster member automatically and check the TTL field (time-to-life) to determine whether forward this message or not. When the TTL is bigger than 1, it subtracts 1 from TTL and forwards this message with minimum transmit energy e_1 via broadcast to its neighbors. The forwarding process will be terminated until the value of TTL reaches 1. The Hop_count field will be increased by 1 when forward is performed. This field is provided for sensor node to estimate itself how far from the CH. We note that each node can join c clusters at most simultaneously. A detailed description of the clustering algorithm is shown in Fig. 4.

```
INPUT: $P$, $E$, $R$
//$P$ is the probability to become a CH, and $E$ is the set of power level
//$R$ is the set of remaining energy level
BEGIN
if node $p_i \leq P$ then
    waits a backoff time $B(Er)$
    if does not receive REQUEST from other nodes then
        sends REQUEST with power level $e_1$ and $R_i$
        node $i \leftarrow$ CH
    else
        if $CH\_number < c$ then
            $CH\_number$++ and node $i \leftarrow$ cluster member
            if TTL $> 1$ then
                TTL := TTL $- 1$
                Hop_count := Hop_count $+ 1$
                forward the REQUEST
else
    waits a specified time $2m$
    if receives REQUEST from other nodes then
        if $CH\_number < c$ then
            $CH\_number$++ and node $i \leftarrow$ cluster member
            if TTL $> 1$ then
                TTL := TTL $- 1$
                Hop_count := Hop_count $+ 1$
                forward the REQUEST
    else
        waits a backoff time $B(Er)$
        if does not receive REQUEST from other nodes then
            sends REQUEST with power level $e_1$ and $R_i$
            node $i \leftarrow$ CH
        else
            if $CH\_number < c$ then
                $CH\_number$++ and node $i \leftarrow$ cluster member
                if TTL $> 1$ then
                    TTL := TTL $- 1$
                    Hop_count := Hop_count $+ 1$
                    forwards REQUEST
END
```

Fig. 4. The clustering algorithm.

Fig. 5 illustrates an example of the cluster forming process. Initially, node A wishes to be a CH and broadcasts a REQUEST message to its 1-hop neighbors with power level e_1 and the value of TTL field is 2. If it's 2-hop neighbors do not join any cluster or the number of joined clusters less than c, it will join the cluster. At first, nodes B, C, and D receive the REQUEST message, and check TTL field. The TTL is 2, nodes B, C, and D subtract 1 from TTL and the Hop_count field be increased by 1 and estimate an appropriate power level to send REPLAY message to the CH according to the Hop_count and the criterion (1).

Nodes B, C, and D forward this message with power level e_1 via broadcast to their neighbors. Node E, F, and G receive the forward REQUEST message, and check TTL field. The TTL is 1, they estimate an appropriate power level to send REPLY message to the CH and do not forward the message.



(a) (b)

Fig. 5. The initial clustering, node A uses minimum power level e_1 to broadcast the REQUEST message to form cluster. The solid node indicates the CH and the gray and white nodes use power level e_1 and e_2 to pass massage, respectively.

In this example, we assume the transmit range of e_1 and e_2 are $d_1 = 10$m and $d_2 = 20$m, respectively. After forming the cluster, nodes B, C, and D use e_1 to pass message to the CH and nodes E, F, and G use e_2 to pass message to the CH. The result of clustering as shown in Fig. 5(b).

Every node should maintain a CH table, which records the joined CH's address, the transmit power level to the CH, and the remaining energy of the CH. Each CH maintains a participation table records the information of the participating nodes in the cluster and the transmit power level to its members.

B. The analysis model

Assume all sensor nodes are distributed uniformly in a Lm $\times$ Lm square area and the diameter of the cluster is represented as h-hop. The total energy consumption of the sensor network is the energy consumed by all member nodes sending data to their CHs and all CHs sending aggregate data to the sink node. Let N, N_C, and N_M represent the total number of sensor nodes, CHs, and members in a sensor network, respectively, and $N = N_C + N_M$. The $N_M(i)$ is denoted as the number of members within the i-hop distance from CHs.

Let Δ_1 be the total energy spent by all sensors communicating r bits of data to their respective CHs. Denote N_M^{ij} being the number of members, which is i hops distance from its corresponding CH, belong to the CH j. Thus, the total energy spent by all sensors is given by

$$\Delta_1 = \sum_{i=1}^{h}\sum_{j=1}^{N_C} N_M^{ij}\big(E_{Tx}(r, d_i) + E_{Rx}(r, d_i)\big), \tag{3}$$

where d_i represents the distance of i hops to the CH. Since sensor nodes are distributed uniformly in the Lm $\times$ Lm square area and the sink node is placed in the center of the area, then the average distance $\overline{D}$ from CHs to sink node will be

$$\begin{aligned}\overline{D} &= \sum_{x=0}^{L}\sum_{y=0}^{L} P_{xy} D_{xy} \\ &= \sum_{x=0}^{L}\sum_{y=0}^{L} \frac{1}{(L+1)^2}\sqrt{(\frac{L}{2}-x)^2 + (\frac{L}{2}-y)^2},\end{aligned} \tag{4}$$

where P_{xy} is the probability of CHs distributed in the location (x, y), and D_{xy} is the distance from CHs at (x, y) to the sink node.

Let Δ_2 be the total energy spent by all CHs communicating r bits of data to the sink node. From (1), the energy consumption can benefit from direct transmission than multihop transmission if the transmission distance d satisfies

$$d < \sqrt{\frac{2\alpha_t}{n\alpha_a}}. \tag{5}$$

Since each transmission includes the energy consumptions of both the transmitter and the receiver, thus the more intermediate nodes is involved in forwarding the more energy is consumed. Therefore, the minimum energy consumption is achieved when $n = 2$ in a given distance. Thus the maximum transmission distance $d_{\max}$ of each CH that will benefit from using direct communication than MTE routing protocol if and only if $d_{\max} \leqslant nd$. From (5), we have

$$d_{\max} \leqslant \sqrt{\frac{2n\alpha_t}{\alpha_a}}. \tag{6}$$

For example, in the energy consumption model [11], [16], if $n = 2$, $\alpha_t = 50$ nJ/bit, and $\alpha_a = 100$ pJ/bit/m^2, the $d_{\max} \approx 44.72$m.

In the worst-case, CHs use $d_{\max}$ transmission range to transmit their aggregate data to sink by one hop or multiple hops. Thus, the average number of hops $\overline{h}_s$ from CHs to the sink node is equal to $\overline{D}/d_{\max}$. The total energy spent by all CHs communicating r bits of data to the sink node can be obtained by

$$\Delta_2 = N_C\Big[E_{Tx}(r, d_{\max})\overline{h}_s + E_{Rx}(r, d_{\max})(\overline{h}_s - 1)\Big]. \tag{7}$$

Assume each CH's cover area can be divided into h concentric circles and the width of each section is d_1. Then the area of the i-th concentric circle A_i can be calculated as $(d_i)^2\pi$. Thus the area of the i-th section denoted as S_i is given by

$$\begin{aligned} S_i &= A_i - A_{i-1} \\ &= d_i^2\pi - d_{i-1}^2\pi \\ &= i^2\pi d_1^2 - (i-1)^2\pi d_1^2 \\ &= (2i-1)\pi d_1^2. \end{aligned} \tag{8}$$

For example, the area of $S_2 = (2 \times 2 - 1)\pi d_1^2 = 3\pi d_1^2$ and $S_3 = 5\pi d_1^2$. Thus, the ratio of the number of nodes in the i-th section to the overall number of nodes in the h-hop cluster is equal to $S_i/\pi(hd_1)^2 = (2i-1)/h^2$. From (3) and (7), the total energy consumption of the overall network will be

$$\begin{aligned}\Delta_1 + \Delta_2 &= \sum_{i=1}^{h}\sum_{j=1}^{N_C} N_M^{ij}\big(E_{Tx}(r, d_i) + E_{Rx}(r, d_i)\big) \\ &\quad + N_C\Big[E_{Tx}(r, d_{\max})\overline{h}_s + E_{Rx}(r, d_{\max})(\overline{h}_s - 1)\Big] \\ &= \sum_{i=1}^{h}\Big[(N - N_C)(\frac{2i-1}{h^2})(E_{Tx}(r, d_i) + E_{Rx}(r, d_i))\Big] \\ &\quad + N_C\Big[E_{Tx}(r, d_{\max})\overline{h}_s + E_{Rx}(r, d_{\max})(\overline{h}_s - 1)\Big].\end{aligned} \tag{9}$$

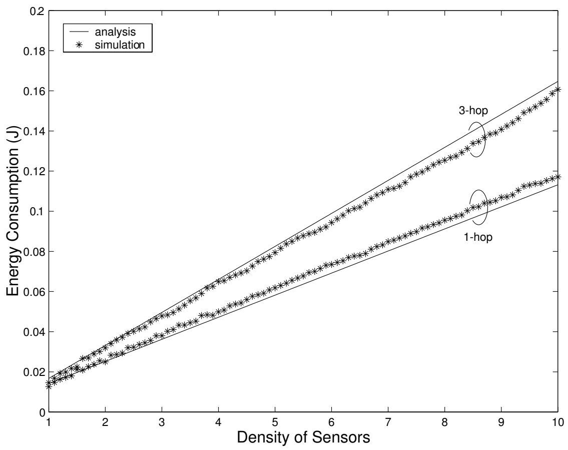


Fig. 6. The results of analysis and simulation of ACMP when $h = 1$ and $h = 3$.

Now we have to solve the value of N_C. Assume the radius of a cluster is h-hop and denoted as d_h ($d_h = hd_1$), the minimum number of CHs $N_{C,\min}$ that can cover a Lm × Lm square area can be calculated by

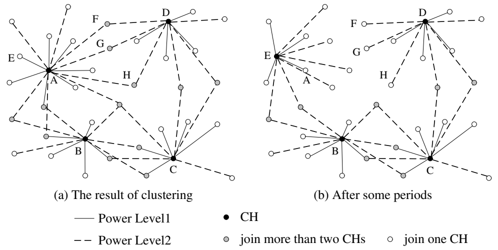
$$N_{C,\min} = \frac{L^2}{\pi {d_h}^2} = \frac{L^2}{\pi h {d_1}^2}. \tag{10}$$

Fig. 6 shows the results of analysis and simulation of ACMP in detail. All nodes are distributed uniformly in 100m × 100m when $h = 1$ and $h = 3$. We vary the density of sensors from 1 to 10 (100 to 1000 nodes) to investigate the energy consumptions in the result of (9) and ACMP. Assume every node transmit 1 bit of data to their CHs and after all CHs aggregate all of the data from member nodes, they send the data to the sink node. We can see that the simulation results are close to our analysis.

C. Load Balance of CHs

Clustering enables the network scalability to large number of sensors, reduce the communication overhead and extends the network life. CHs are responsible for coordination among the nodes within their clusters and collection of data information (inter-cluster communication) and sent these data to the sink node. However, the CH energy will run out quickly if many events occur frequently in its dominated area or it has to coordinate many members in its cluster. We, therefore, propose a load distribution mechanism for load balance of CHs in ACMP. Assume each CH has j thresholds of remaining energy $R = \{r_1, r_2, \ldots, r_j\}$ and $r_1 > r_2 > \ldots > r_j$.

When the remaining energy of the CH is less than one of thresholds, it will select the maximum transmit power level recorded in the participation table to broadcast the REFRESH message to announce all of its members. The member nodes will update their CH table after they receive the REFRESH message. Each cluster member chooses a CH with a maximum remaining energy according to the CH table to report data. If there are more than one candidate CHs, i.e., their remaining energy are equal, the cluster members choose the closest CH to report data.



(a) The result of clustering
(b) After some periods

Fig. 7. An example of clustering process of ACMP where cluster size is 20m, $h_1 = 10$m and $h_2 = 20$m. (a) The initial clustering topology. (b) The result of the local re-clustering by node A.

D. Local Re-clustering

When the remaining energy of CHs reaches the lowest energy threshold r_j, it will choose the maximum transmit power level recorded in the participation table to broadcast the RESET message to all of it cluster members. Each member will join another cluster immediately after receives the message. If nodes do not have any alternative CH for join and its remaining energy is higher than r_j, it will form a new cluster with probability P. Otherwise, it will serve as a slaver and join its previous CH again. After local re-clustering, every cluster member will update its CH table.

E. An Example

Fig. 7 illustrates an example of clustering process in a sensor network by using ACMP in detail. Initially, all nodes do not join any cluster and each node will form clusters with a given probability P to become a CH in the network. Assume each node can join 2 clusters at most simultaneously, and the maximum number of hops of each cluster is 2 hops. Fig. 7(a) is the first result of clustering, nodes A, B, C, and D become CHs, each member according the Hop_count to use appropriate power level to communicates with their CHs. After some periods, A's remaining energy lower than r_1, it broadcasts a RESET message to reset the cluster, and local re-cluster. The result is shown as Fig. 7(b).

IV. SIMULATION MODEL AND RESULTS

In order to evaluate the performance of proposed ACMP, a detailed simulation model is developed. First, different numbers of sensor nodes N are uniformly distributed in a 100m×100m square. These different numbers of sensor nodes 500, 1000, 1500, 2000, 2500, and 3000 are used to represent different network densities D_e (see Table I). For example, the $D_e = 5$ represents the number of sensor nodes is 500. The size of each cluster is measured by d_1 (the distance of minimum transmission power) and represented as hops or called TTL. Please notice that, for example, the term "ACMP with 3-hop" implies that the radius of the cluster is 3 hops long and all members within this cluster will use "one hop" to transmit messages to the CH, i.e., direct transmission. Each sensor node can join different number of clusters C simultaneously.

This implies that a sensor node can join C clusters around its neighboring nodes at most if any.

TABLE I

SYSTEM PARAMETERS IN SIMULATIONS

Number of Sensors (N)	Density (D_e)	Probability (P)	Maximum Number of Hops (TTL)
500	5	0.1012	5
1000	10	0.0792	4
1500	15	0.0688	3
2000	20	0.0622	3
2500	25	0.0576	3
3000	30	0.0541	3

The event occurring model in all simulations is generated by a given probability P_e. The simulated area is divided into many 2m×2m squares and each of them has the same event occurring probability P_e. The event is triggered every one round and the round is defined as a specific time unit. Once an event occurs, the sensor nodes around the event will generate messages to transfer to the corresponding CHs. Each sensor node has ten kinds of power levels e_1, e_2,..., and e_{10}, and their corresponding transmission distances are 10m, 20m,..., and 100m, respectively. The sensing range of each sensor is set 2m long and the initial energy of each node is one Joule. There are nine threshold levels of remaining energy $R = \{9/10, 8/10, \ldots, 1/10\}$. When the remaining energy of the CH reaches any threshold of R, the CH will announce this status to its members. Members after receiving this message will choose another CH for passing collected data if any. The CH performs the re-clustering procedure locally only when the remaining energy reaches $1/10$.

In the simulations, ACMP is compared with the energy efficient hierarchical clustering (EEHC) algorithm [7] and LEACH [11] scheme, to evaluate the performance of power consumption and network lifetime. We refer to the optimal energy minimization parameters of the EEHC algorithm in [7], which is shown in Table I. For comparison, ACMP adopts the same parameters as in EEHC, excepting the parameters TTL $= 3$ and TTL $= 1$. The data length of each sensed information is represented as 2000 bits long and reports to the CH per each event. Each simulation run lasts 50,000 rounds and each simulation result is obtained by averaging the results from ten independent simulation runs.

A. Simulation Results

In the experiments, we investigate two major metrics as the performance of the protocols:

- Network Lifetime: The time from nodes deployment to the time when the first node is run out of function due to energy depletion. It is measured in rounds.
- Energy Consumption: The total energy consumed by all nodes in the sensor network during the whole data processing procedure.

The first simulation evaluates the network lifetime of the ACMP by varying the parameter C. The simulation is terminated immediately when any node runs out of its energy.

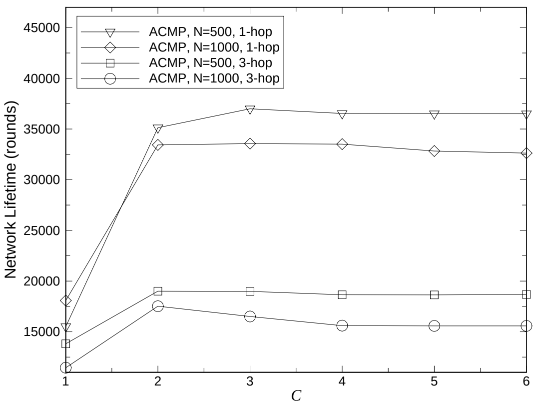


Fig. 8. The network lifetime vs. Max. joinable CHs (C) when $P_e = 0.1$.

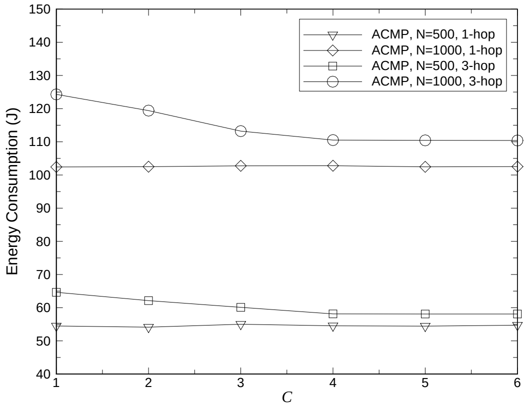


Fig. 9. The energy consumption vs. Max. joinable CHs (C) when $P_e = 0.1$ and the simulation time is 15000 rounds.

From the simulation results, shown in Fig. 8, the network lifetime will be longer than that the members can only join one CH. This is because that ACMP can benefit from two main mechanisms: (i) autonomous clustering (dynamic load balance of CHs) and (ii) autonomous message passing, and, hence, extends the network lifetime efficiently. The first mechanism enables CHs to re-cluster itself automatically as their remaining energy is lower than each threshold of R. This mechanism can prevent the CH from running out of its energy quickly by taking turns to be the CH with its neighboring nodes. The second mechanism is a dynamic load balance scheme to alleviate the message forwarding load of CHs. This mechanism is achieved by each sensor node dynamically choosing one of its neighboring CHs, which has the largest remaining energy, to pass the message if the sensor node can join more than one CH simultaneously.

From Fig. 8, we can see that the network lifetime of $C = 1$ is lower than that can join more than one CH both in 1-hop (TTL $= 1$) and 3-hop cases. ¿From this result, we can know that the network lifetime can be prolonged efficiently when the sensor nodes can choose more than one CH. Moreover, from the results, we can see another interesting remarkable results that the network lifetime will be shorter when the cluster size is larger. This is because that the CHs' energy will be run out rapidly due to the cluster size is larger, the CHs must coordinate more sensors as well as lead to more overheads of the CHs. This strategy will waste more energies and degrade the network lifetime. One the other hand, when the cluster size is smaller, there are fewer sensors in the clusters and the overheads of the CHs is lower. Thereby if the cluster size is smaller, the network lifetime is longer than the cluster size is larger.

Following above experiment, Fig. 9 shows the energy consumption of the sensor nodes under different C. We can see that the energy consumption of $N = 1000$ is higher than that of $N = 500$. But the energy consumption of 1-hop cases ($N = 500$ and $N = 1000$) in different C are quite equal. This is because that no matter how the sensor node chooses the CH for passing messages, the energy consumption is same since the sensor node sends messages to the CH with power level e_1. However, in the case of 3-hop, the total energy consumption will decrease when the C increases. Under the case of $C = 1$, if the distance between the member and the CH is far, it has to use higher power level to send messages. This will cost a lot of energy consumptions. On the contrary, when $C > 1$, the members can send message to their CHs according to the remaining energies of CHs alternately. If the remaining energies of CHs are equal, the member will randomly choose one CH to transmit. Because the traffic load is dispersed to each sensor nodes, the network lifetime is prolonged efficiently.

In Fig. 10 and Fig. 11, we vary the D_e from 5 to 30 to investigate the energy consumption and network lifetime of ACMP, EEHC, and LEACH. The event occurring probability is set as $P_e = 0.1$. We observe that, from Fig. 10, EEHC consumes more energies than ACMP 1-hop and 3-hop since ACMP computes a minimum energy consumption route by (1) to report sensed information to the CH. However, EEHC always uses the minimum power to report data to the CH and involves many intermediate nodes for data forwarding. Meanwhile, LEACH also consumes more energies than ACMP 1-hop and 3-hop since LEACH utilizes randomized rotation of CHs to evenly distribute the energy consumptions among sensor nodes in the network. Since the rotation of CHs is periodically performed by EEHC, it will cause more energy consumptions when P_e is low. We also note that the gap of energy consumption among ACMP, EEHC, and LEACH gets bigger as D_e increases since, in higher density network, more sensor nodes will be involved to forward data and thus consume more energies.

In Fig. 11, the network lifetime of ACMP, EEHC, and LEACH decreases following the increment of the D_e (from 5 to 30). This is because that more nodes will sense events and generate the messages to transfer to the sink node in higher density. This outcome lead to shorter network lifetime. However, ACMP uses the load balance to alleviate the traffic overhead of CHs and expend the lifetime of each node by local re-clustering when its energy is low. Therefore, ACMP can get a longer network lifetime than EEHC. From Fig. 6, we can know ACMP 3-hop spends more energy consumption than ACMP 1-hop, in other words, ACMP 1-hop will have more network lifetime than ACMP 3-hop. The network lifetime of ACMP 1-hop is also longer than LEACH since LEACH utilizes randomly rotation of CHs. This will waste more energies.

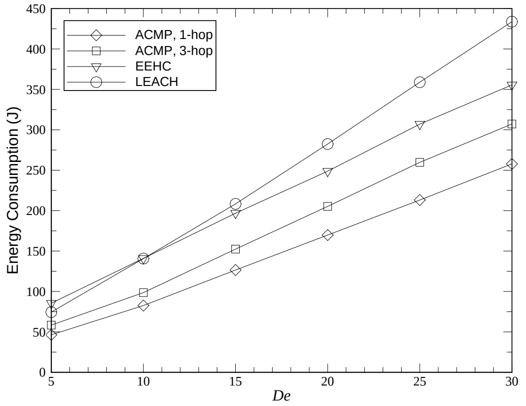


Fig. 10. Density of sensors vs. energy consumption when $P_e = 0.1$ and the simulation time is 15000 rounds.

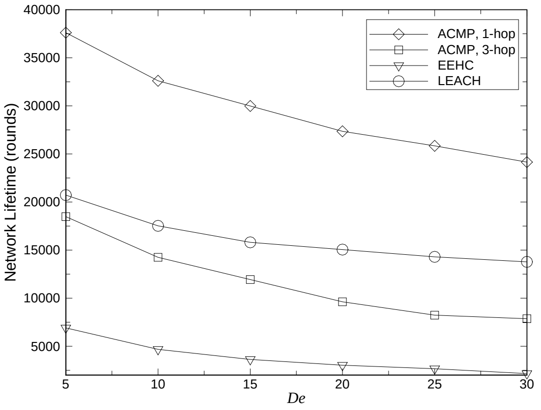


Fig. 11. Density of sensors vs. network lifetime when $P_e = 0.1$.

To investigate the influence of P_e on energy consumption and network lifetime, we perform a detailed experiment by varying P_e to observe the results obtained by ACMP, EEHC, and LEACH as shown in Fig. 12 and Fig. 13. We can see that energy consumptions of ACMP, EEHC, and LEACH increase as P_e increases. ACMP both in 1-hop and 3-hop can get lower energy consumption than LEACH and EEHC since either LEACH or EEHC will re-cluster themselves periodically. On the contrary, ACMP re-clusters depending on the remaining energy of CHs and thus saves more energies than LEACH and EEHC. Notice that the gap of energy consumption between ACMP 1-hop and EEHC gets bigger and bigger when P_e increases since ACMP utilizes autonomous clustering/re-clustering and message passing mechanisms to reduce the probability of one sensor node running out its energy rapidly.

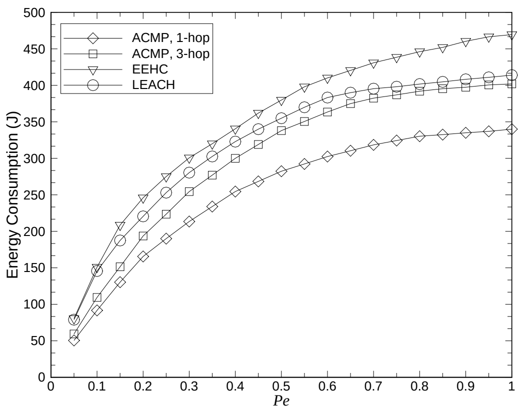


Fig. 12. The P_e vs. energy consumption when N = 1000 and the simulation time is 15000 rounds.

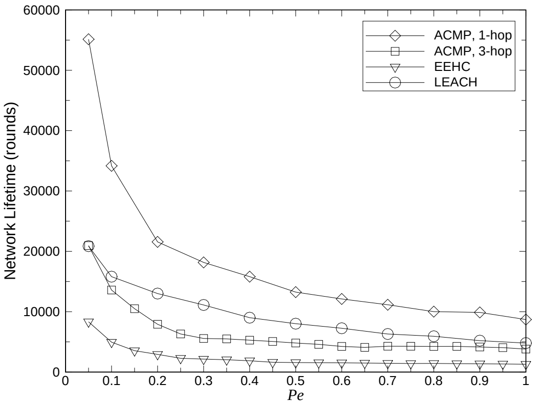


Fig. 13. The P_e vs. network lifetime when N = 1000.

This result encourages us to use ACMP especially in the area of frequent event appearance.

Fig. 13 shows that when the probability P_e is low, the network lifetime of ACMP is long. This is because that, ACMP can distribute the traffic load in the network and balance the energy consumption well. However, the network lifetime of ACMP, EEHC, and LEACH are getting lower as P_e increases higher. The ACMP 1-hop can obtain a longer network lifetime than EEHC's and LEACH's in higher network density due to local re-clustering scheme to prolong the network lifetime. From these results, we can conclude that a lower energy consumption can be obtained by decreasing the sensor density accordingly.

V. CONCLUSION

This paper presents an autonomous clustering and message passing (ACMP) protocol for energy efficiency in wireless sensor networks. The lifetime of the sensor network can be prolonged further by adopting an efficient traffic balance scheme. ACMP provides the load distribution scheme by maintaining the remaining energy to extend the network life time. Meanwhile, ACMP also provides a local re-clustering to avoid a node runs out of its energy when its remaining energy is low. Besides, ACMP uses the minimum energy consumption route (direct transmission) rather than uses multihop minimum distance route to form the cluster. Simulation results show that ACMP can achieve a highly energy saving effect as well as prolong the network lifetime.

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