Dynamic Clustering for Coverage-Time Maximization in Two-Tiered Hierarchical Sensor Network Architectures *

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Abstract. This paper proposes dynamic clustering for coverage-time maximization (DC-CTM) in sensor networks. The coverage-time is defined as the time until one of cluster heads (CHs) runs out of energy in clustering-based sensor networks. DC-CTM regulates cluster radii for balanced energy consumption among CHs for coverage-time maximization. By using DC-CTM, three advantages can be achieved. The first one is balanced energy consumption among CHs. The second one is minimized energy consumption in each CH. The last one is the consideration of mobility on CHs. The novelty of proposed scheme, DC-CTM scheme, is shown by various simulation-based performance analyses.

1 Introduction

In recent years, many research efforts on sensor networks have become one of the most active research topics in wireless networking technologies [1]. Due to the limited power source of sensor nodes, energy consumption has been concerned as the most critical factor when designing sensor network protocols. Facing these challenges, several schemes, i.e., clustering-based topology control, have been investigated [2]- [7]. In topology control schemes of wireless sensor networks, clustering-based topology control schemes are widely used. By the advantages of clustering-based topology control, many clustering-based sensor networks protocols are proposed. In this paper, we consider the non-homogeneous clustering-based sensor networks as a reference network model. In non-homogeneous clustering-based sensor networks [2] [5] [6], different types of sensor nodes are used in the aspect of computing power, energy status, and

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Table 1. PARAMETERS USED FOR MODELING OF ENERGY CONSUMPTION

Parameters	Descriptions
E_{CH_k}	The energy consumed in a CH named k
$E_{communicate_k}$	The energy consumption of data communication in a CH named k
$E_{process_k}$	The energy consumption of data processing in a CH named k
α_{t_k}	The energy/bit consumed by transmitter electronics in a CH named k
α_{r_k}	The energy/bit consumed by receiver electronics in a CH named k
α_{amp_k}	The energy/bit consumed in the transmit op-amp in a CH named k
d	The distance that the message traverses. i.e., distance between two CHs
E_{tx_k}	The energy consumed to send b bits in the node named k
E_{rx_k}	The energy consumed to receive b bits in the node named k

etc. In two-tiered hierarchical sensor network architecture, we use the concept of coverage-time as a measurement index of network lifetime. The coverage-time is defined as the time until one of CHs runs out of energy, resulting in an incomplete coverage of the sensing region [7]. In this paper, a dynamic clustering for coverage-time maximization scheme (DC-CTM) is proposed. DC-CTM scheme can achieve balanced energy consumption among CHs by regulating cluster region. Also for more adaptability in practical applications, the consideration of mobility on CHs is required. Therefore DC-CTM scheme is designed under the consideration of a CH is a mobile device. The remainder of this paper is organized as follows. In Section 2, we investigate the energy model of mobile device. Section 3 describes the proposed dynamic clustering scheme for coverage-time maximization. Section 4 shows the simulation-based performance evaluation of the proposed scheme. In section 5, we show the related work. Finally, section 6 concludes this paper.

2 Energy Model of a Cluster Head

A CH has a circuit for signal conditioning and conversion, digital signal processor, and wireless radio link [8]. Therefore the energy consumption of a CH is summation of the energy consumption on data communication ($E_{communicate_k}$) and the energy consumption on data processing ($E_{process_k}$). That is,

$$E_{CH_k} = E_{communicate_k} + E_{process_k} \tag{1}$$

All parameters used in this section are explained in Table 1.
1) Energy consumption on data communicating: The energy consumption on data communicating is as follows:

$$E_{tx_k} = (\alpha_{t_k} + \alpha_{amp_k} \times d^2) \times b \tag{2}$$

$$E_{rx_k} = \alpha_{r_k} \times b \tag{3}$$

Therefore, the total energy consumption on data communication in a CH named k is as follows:

$$E_{communicate_k} = E_{tx_k} + E_{rx_k} \tag{4}$$

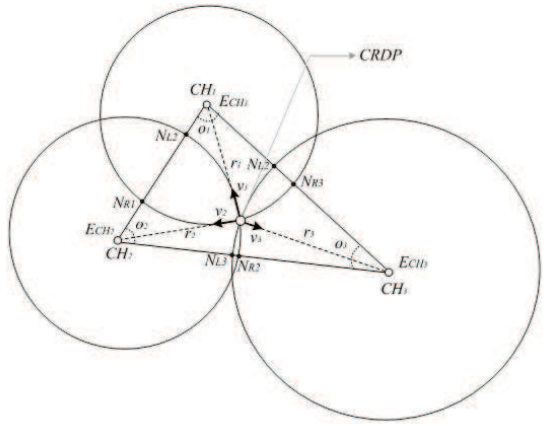

Fig. 1. System model for upper tier in two-tiered hierarchical sensor network architecture

2) Energy consumption on data processing: The model depends on the cycles in the program. In general, the energy consumption on data processing is significantly smaller than data communication.
3) Concluding remarks: By from Eq. (1) to Eq. (4), the energy model of a CH can be derived as follows:

$$E_{CH_k} = E_{communicate_k} + E_{process_k} \cong (\alpha_{t_k} + \alpha_{r_k} + \alpha_{amp_k} \times d^2) \times b \qquad (5)$$

3 Dynamic Clustering For Coverage-Time Maximization (DC-CTM) Scheme

A DC-CTM scheme aims to cover the entire network with the balanced energy consumption of each CH by regulating the cluster range. DC-CTM scheme consists of two phases and one iteration policy. In this algorithm, we assume that a sink node knows the position of each CH.

3.1 Initial Phase

In initial phase, the CHs deployed at random to construct a triangle for determining 'Cluster Radius Decision Points (CRDPs)' that can lead balanced energy consumption among CHs and minimize energy consumptions of CHs while covering the entire network field as shown in Fig. 1. Delaunay triangulation [9], which guarantees the construction of an approximate equilateral triangle, is used for constructing a triangle.

3.2 Dynamic Cluster Control (DCC) Phase

After initial phase is over, DC-CTM scheme goes to 'dynamic cluster control (DCC) phase'. The design rationale of DCC phase is as shown follows: The clus-

Table 2. Parameters Used For Description of DC-CTM Scheme

Parameters	**Descriptions**
CH_k	Cluster head, named k
S_{CH_k}	The area of in a CH named k
$\lvert CH_k \rvert$	The number of cluster head
$CRDP$	Cluster Radius Decision Point
v_k	Vector from $CRDP$ to CH_k
θ_k	The angle between neighbor cluster heads
r_k	The distance between $CRDP$ and CH_k
ϕ_k	Weight factor of CH_k
m	The number of weight functions

ter radii of three CHs including the construction of a triangle can be dynamically controlled by using a CRDP as a pivot. The each distance between each CH and CRDP becomes radius of

each cluster. As shown in Fig. 1, the triangle which is composed by three CHs. To find the optimal CRDP, we make two scenarios. One scenario is for the all CHs have same functionality. The other scenario is for the all CHs have different functionality.

1) DCC phase for homogeneous CHs: The DCC phase of DC-CTM scheme in all CHs are same functionality is described in this subsection. The size of overlapping area, the solution of objective function which is proposed in this section, can be obtained by extracting the size of triangle from the summation of three sectors in Fig. 1. By this basic concept, we can derive the objective function to find the CRDP for minimizing the overlapping areas of each sector. Because main purpose of this phase is minimized energy consumption, if we can consider energy status in this phase, more efficient result can be derived. As considering energy factor, two kinds of approach are possible. First one is nonlinear programming based approach (NLP-based approach) and the other one is vector computation based approach (VC-based approach). The objective function of NLP-based approach is as shown follows:

$$\textbf{minimize: } f(r_1, r_2, r_3, \theta_1, \theta_2, \theta_3, E_{CH_1}, E_{CH_2}, E_{CH_3})$$

$$= \frac{1}{2}\sum_{i=1}^{3} \theta_i \cdot r_i^2 \frac{E_{CH_i}}{\frac{1}{3}\sum_{j=1}^{3} E_{CH_j}} - S_{triangle} \tag{6}$$

$$\textbf{s.t. } r_i^2 = (x_{CRDP} - x_i)^2 + (y_{CRDP} - y_i)^2$$

The notations used in Eq. (6) is shown in Table II. By using energy factors as a weight factors in Eq. (6), we can find the position of CRDPs under the consideration of energy status of CHs. By applying Eq. (5) into Eq. (6),

$$\textbf{minimize: } f_{Homo\_NLP}(r_1, r_2, r_3, \theta_1, \theta_2, \theta_3, E_{CH_1}, E_{CH_2}, E_{CH_3})$$

$$= \frac{1}{2}\sum_{i=1}^{3}\theta_i \cdot r_i^2 \frac{(\alpha_{t_i} + \alpha_{r_i} + \alpha_{amp_i} \times d^2)}{\frac{1}{3}\sum_{j=1}^{3}(\alpha_{t_j} + \alpha_{r_j} + \alpha_{amp_j} \times d^2)} - S_{triangle} \quad (7)$$

$$\textbf{s.t. } r_i^2 = (x_{CRDP} - x_i)^2 + (y_{CRDP} - y_i)^2$$

In NLP-based approach, it may generate additional computation overheads due to an iterative NLP method. We thus consider another method based on vector computation (VC-based approach) to reduce computation overheads. In VC-based approach, the objective function does not consider energy factor as shown in Eq. (8). The energy factor is considered in iterative vector calculus as shown in Eq. (9).

$$\textbf{minimize: } f_{VC}(r_1, r_2, r_3, \theta_1, \theta_2, \theta_3)$$

$$= \frac{1}{2}\sum_{i=1}^{3}\theta_i \cdot r_i^2 - S_{triangle} \quad (8)$$

$$\textbf{s.t. } r_i^2 = (x_{CRDP} - x_i)^2 + (y_{CRDP} - y_i)^2$$

To consider the energy status in iterative calculus, we compute the following equation iteratively.

$CRDP^{n+1} = CRDP^n$

$$-\sum_{i=1}^{3}\theta_i \cdot r_i^2 \frac{(\alpha_{t_i} + \alpha_{r_i} + \alpha_{amp_i} \times d^2)}{\frac{1}{3}\sum_{j=1}^{3}(\alpha_{t_j} + \alpha_{r_j} + \alpha_{amp_j} \times d^2)} \times \frac{CRDP^n - CH_i}{||CRDP^n - CH_i||} \quad (9)$$

$$\textbf{s.t. } CRDP^n = (x_{CRDP}, y_{CRDP})$$
$$CH_i = (x_{CH_i}, y_{CH_i})$$

In VC-based approach, we just have to update the coordination of CRDP in previous step. Therefore, the repeated vector computation is much simpler than NLP computation at the aspect of algorithm complexity.

2) DCC phase for heterogeneous CHs: In previous subsection, we consider that all CHs have same functionality and hardware constraint. However if any CHs have more computing power and the CHs takes more member nodes than assigned, the coverage-time can be extended. Therefore the objective functions can be re-designed as follows. The descriptions of notations are in Table 2.

$$\textbf{minimize: } f(r_1, r_2, r_3, \theta_1, \theta_2, \theta_3, \phi_{CH_1}, \phi_{CH_2}, \phi_{CH_3})$$

$$= \frac{1}{2}\sum_{i=1}^{3}\theta_i \cdot r_i^2 \frac{\phi_{CH_i}}{\frac{1}{3}\sum_{j=1}^{3}\phi_{CH_j}} - S_{triangle} \quad (10)$$

$$\textbf{s.t. } r_i^2 = (x_{CRDP} - x_i)^2 + (y_{CRDP} - y_i)^2$$

Eq. (11) is the modified CRDP repositioning formula for heterogeneous CHs by VC-based approach.

$$CRDP^{n+1} = CRDP^{n} - \sum_{i=1}^{3} \theta_i \cdot r_i^2 \frac{\phi_{CH_i}}{\frac{1}{3}\sum_{j=1}^{3} \phi_{CH_j}} \times \frac{CRDP^{n} - CH_i}{||CRDP^{n} - CH_i||} \quad (11)$$

$$\textbf{s.t. } CRDP^{n} = (x_{CRDP}, y_{CRDP})$$
$$CH_i = (x_{CH_i}, y_{CH_i})$$

3.3 Iteration Policy

When event frequently occur in some specific areas where a certain CH consumes its energy a lot. In this situation, the CHs in the target region will consume more energy and the operation will be relatively more important than the other CHs in the other area of the network of lower tier. Then a sink has to change the radius of clusters to balance energy consumption of each CH and to preserve the energy of the CH which has higher priority than the other CHs.

4 Performance Evaluation

The novelty of DC-CTM scheme is shown by performance evaluation. Based on the predefined simulation environment, the evaluation of DC-CTM scheme is performed.

4.1 Simulation Environment

In this section, the simulation environment for performance evaluation of DC-CTM scheme is described. There are two types of DC-CTM scheme in this simulation evaluation. The first one is 'DC-CTM: homo' and the second one is 'DC-CTM: hetero'. The 'DC-CTM: homo' is a scheme where all CHs have same functionalities and system architecture. On the other hand, 'DC-CTM: hetero' considers the difference of functionalities and system architecture in each CH. We compare DC-CTM scheme against the method that has a fixed cluster radius. The cluster radius is fixed, but it has to be extended to the distance to allow communication among all CHs. We define such a method as Fixed Radius (FR).

4.2 The Accumulated Number of Collide Packets

The accumulated number of collided packets is a very important measurement index in designing high-performance protocols. As shown in Fig. 2, we measured number of collided packets. 'DC-CTM: homo' and 'DC-CTM: hetero' have similar performance. Because the weight functions assigned to each CH are not related to the clustering area. The number of collided packets depends on the

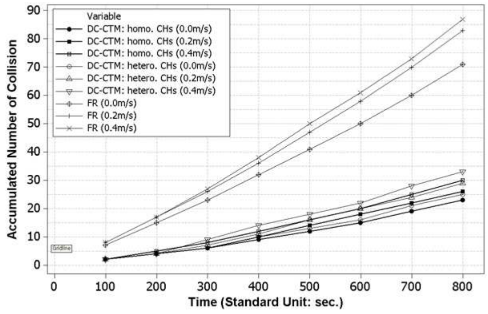

Fig. 2. Accumulated Number of Packets

clustering area. Therefore the weight factors that not related to the clustering area have no effects. Therefore the performance between 'DC-CTM: homo' and 'DC-CTM: hetero' is almost same, but DC-CTM: homo' has a slightly better performance than 'DC-CTM: hetero'. The reason is that the energy factor which is considered in 'DC-CTM: homo' is related to the clustering area.

4.3 Coverage-Time

The coverage-time is defined as the time until one of cluster heads (CHs) runs out of energy resulting in an incomplete coverage of the sensing region as mentioned in previous section [7]. Therefore the coverage-time is a critical factor when measuring network lifetime of clustering-based networks. Fig. 3 shows the coverage-time when all CHs are same. Fig. 4 shows the coverage-time when CHs do not have the same functionalities and system architecture. In this case, it is important for heterogeneous CHs to consider the characteristics of network environment. As shown in Fig. 4, 'DC-CTM: hetero' has longer coverage-time than 'DC-CTM: homo' and FR because of the consideration of the characteristics of network environment. As described in Fig. 3 and Fig. 4, as the velocity of mobile

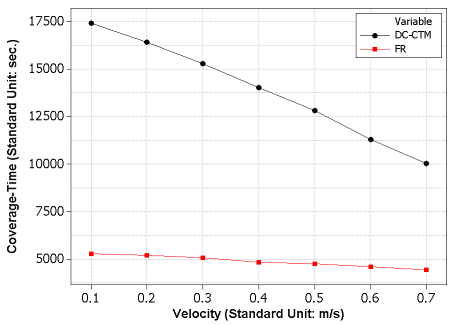

Fig. 3. Coverage-Time: Homogeneous CHs

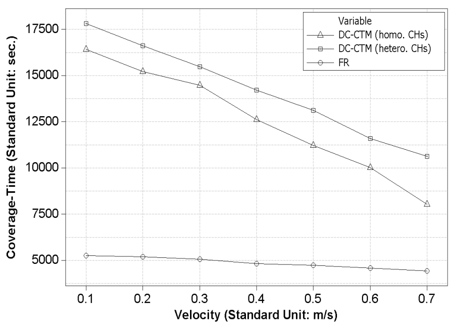

Fig. 4. Coverage-Time: Heterogeneous CHs

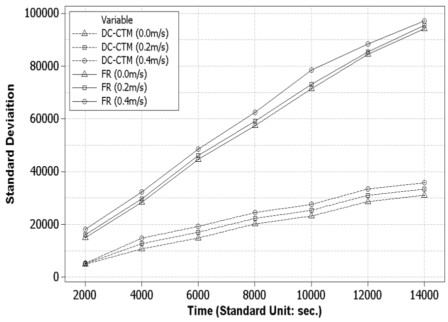

Fig. 5. Std. Dev. of Residual Energy of Each CH: Homogeneous CHs

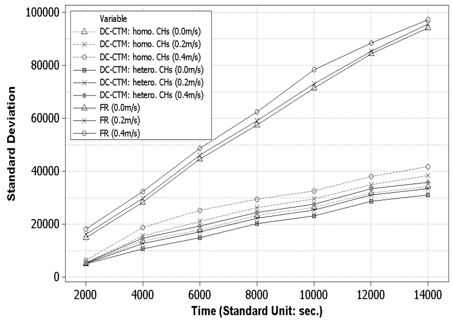

Fig. 6. Std. Dev. of Residual Energy of Each CH: Heterogeneous CHs

CHs increases, the coverage-time becomes increasingly smaller. Therefore, high mobility on CHs can lead to less coverage-time.

4.4 The Standard Deviation of Residual Energy on Each CH

CH Under the definition of coverage-time, the balanced energy consumption of each CH is important to maximize network lifetime. To show balanced energy consumption in each CH, we measure and show the standard deviation of residual energy in CHs. For more detailed performance evaluation, Fig. 5 shows results when all CHs have the same functionalities and Fig. 6 shows the results when each CH has different functionalities. As shown in Fig. 5, DC-CTM takes balanced energy consumption. Also when we measure the performance of DC-CTM, we consider the mobility of CHs. Since a higher mobility leads to an unstable network topology, when mobility becomes higher, the performance of DC-CTM becomes lower. Fig. 6 shows the standard deviation of residual energy of each CH. Also in Fig. 6, we show the novelty of the DC-CTM.

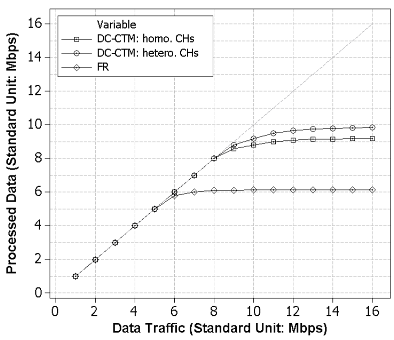

Fig. 7. Processed Data per Data Traffic

4.5 The Tolerance against Traffic Load

If one CH takes too much data from sensor nodes in lower tier, the traffic load from the sensor nodes becomes larger. If balanced data processing cannot be achieved, one CH can have enlarged ability for processing data from the lower tier. This phenomenon leads to the early energy exhaustion of the CH. In Fig. 7, we can observe that 'DC-CTM: hetero' takes the highest tolerance against traffic load. The CH which is operated by 'DC-CTM: hetero' can take until the traffic load becomes almost 10 Mbps.

5 Related Work

As mentioned in section 1, clustering-based sensor network architecture can be classified into two types [2]. In homogeneous clustering-based sensor networks, the algorithm for cluster head election is required because the CH must be chosen among sensor nodes. In this structure, therefore, sensor nodes must have the functionalities for clustering and controlling their clusters. On the other hand, in non-homogeneous clustering-based sensor networks [2] [5] [6]. In this structure, CHs have more computing power, less energy constraint, and less hardware constraint than a sensor node. In homogeneous clustering-based sensor networks [3], all the sensor nodes are identical in terms of battery energy and hardware constraint. Therefore, the cluster head selection algorithm is required. There are many clustering-based topology control schemes in homogeneous clustering-based sensor networks. Among the schemes, LEACH [3] is the notable clustering schemes. LEACH constructs its clusters with a distance-based approach. A distance-based scheme, however, cannot consider the energy status of each CH. The property can lead energy inefficiency in power-constrained sensor nodes. For more efficiency, therefore, hierarchical network architecture is required. Then, the sensor nodes can save their energy and make more energy efficient network architecture than homogeneous clustering-based sensor networks. There are numerous topology control algorithms for non-homogeneous clustering-based sensor networks [2] [4]- [6]. In [5], base on the operation which has the concept of balanced energy consumption. However [5] must totally share information to operate proposed algorithm. Maintaining global information to operate proposed algorithm can be a burden to CHs. Therefore decentralized scheme is required. The proposed scheme in [4] has a two-tiered sensor network architecture. By using this hierarchical clustering-based sensor networks, the proposed scheme in [4] can achieve more energy efficiency. In [4], however, the radii of clusters are fixed. In this system, the performance of scheme depends on each radius of the cluster. That is to say, it can be a waste of energy when a cluster has a larger radius than its requirement. Therefore maintaining the optimal cluster radius is important in the aspect of energy efficient. However [4] is impossible to regulate the cluster radius. Therefore LLC [6] is proposed. However in LLC we cannot consider mobility on CHs. Therefore, for more applicability, we design DC-CTM scheme.

6 Conclusion

In this paper, a dynamic clustering scheme for coverage-time maximization (DC-CTM) has been proposed. DC-CTM scheme can regulate the cluster radius for balanced energy consumption for coverage-time maximization while the entire lower sensor network field is still being covered totally by clusters. Low-Energy Localized Clustering (LLC) in [6] makes the first trial in this approach. However LLC did not consider the mobility on CHs. To accomplish these objectives, DC-CTM scheme dynamically regulates the radius of each cluster. There exist three kinds of main contributions in DC-CTM proposed in this paper. The first one and the second one are balanced energy consumption for coverage-time maximization and minimized energy consumption in each CH. We show 'balanced energy consumption among CHs' and 'minimized energy consumption among CHs' by simulation based performance evaluation. The last one is the consideration of mobility on CHs. By basic design rationale of DC-CTM scheme, the mobility on CHs can be shown. Our ongoing work includes the exploration of the applicability of DC-CTM to practical network environments such as RFID networks [10] was one of preliminary products of such efforts.

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