Lifetime Constrained Relay Node Placement in WSNs: A Cluster-based Approximation Algorithm

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***Abstract*—The lifetime of Wireless Sensor Networks (WSNs) is significantly shortened by the energy hole problem that is caused by the many-to-one communication pattern adopted by most WSNs. Various approaches have been designed to solve the energy hole problem, and this paper considers improving the energy efficiency by deploying additional relays, which is called the Lifetime Constrained Relay Node Placement (LCRNP) problem. To address the NP-hardness of the LCRNP problem, this paper proposes a Cluster-based Approximation Algorithm (CAA) that first groups the sensors into different clusters in which the lifetime constraint can be ignored and sensors are close to each other, and then builds network connectivity for each cluster. Next, the Augmented CAA is designed based on the CAA to further improve network lifetime by building addition paths for the relays prone to suffer heavy traffic loads. Unlike existing works, we prove that the proposed algorithms can guarantee polynomial time complexities and explicit approximation ratios. Finally, the efficiency of the proposed algorithms is verified through extensive simulations.**

I. Introduction

The great majority of Wireless Sensor Networks (WSNs) work in the many-to-one pattern, in which sensors transmit their sensed information to a data collector, referred to as the sink, via multi-hop paths. To forward the data transmitted from outside nodes, the nodes closer to the sink suffer much more traffic loads, and as a result their batteries will drain away more quickly, which is called the energy hole around the sink. The extremely unbalanced traffic load leads to the disconnection of whole WSNs with the energy of most sensors left unused. The experiments conducted by Wadaa et al. [1] [2] show that when the WSNs consisting of uniformly distributed nodes run out their lifetime, up to 90% of the initial energy of the networks remains unused.

Numerous approaches have been proposed to mitigate the energy hole problem. This paper focuses on the approach of deploying additional relays to balance the traffic load of the whole network. One important branch of this approach is to utilize the density control method [3] [4], i.e., the deployment area is first divided into multiple ring areas (or so-called coronas) centered at the sink, and then the density of nodes in each corona is adjusted by deploying additional relays such that the traffic load is balanced. Nevertheless, the deployment cost of this density control method is high and another drawback of the density control method is the high probability of data collisions within the high-density areas [5].

Recently, the two-tiered WSNs have been introduced to improve the energy efficiency and scalability [6]. Wang et al. [7] attempted to solve the energy hole problem based on the two-tiered architecture and modeled this as the Lifetime Constrained Relay Node Placement (LCRNP) problem, which is NP-hard since the traditional Relay Node Placement (RNP) problem without lifetime constraint is NP-hard [8]. They proposed three heuristic algorithms to solve this problem. However, neither time complexities nor approximation ratios of their algorithms are provided in [7].

Thus, this paper aims to approximately solve the LCRNP problem with a polynomial time complexity and an explicit approximation ratio. To this end, a Cluster-based Approximation Algorithm (CAA) is proposed to solve the LCRNP problem in two steps. A drawback of the CAA is that the lifetime constraint is satisfied only when the multi-hop routes are determined by the CAA. Therefore, in order to prolong the network lifetime when the routes cannot be determined by the CAA, an Augmented CAA (ACAA), whose main idea is to save the relays prone to suffer more traffic loads by building additional paths, is proposed based on the CAA.

The main contributions of this paper are listed as follows:

- A CAA with time complexity O(n^6) and approximation ratio O(n) is proposed based on a well-designed clustering approach, where n is the number of sensors. To the best of our knowledge, this is the first approximation algorithm that guarantees an explicit approximation ratio to the LCRNP problem.
- An ACAA is proposed based on the CAA to improve the lifetime when the routes cannot be determined by the CAA, and the time complexity and approximation ratio of the ACAA are proved O(n^6) and O(n), respectively.
- Extensive simulations are conducted to evaluate the performance of the proposed algorithms. Simulation results show that the proposed CAA can save up to 49.81% of the deployed relays in comparison to existing algorithms, and ACAA can effectively prolong lifetime of the networks built by CAA.

II. Preliminaries

A. Network Model

As in [7], some reasonable assumptions are introduced to facilitate analysis and listed as follows:

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- The considered WSNs are clock-based many-to-one networks, in which each sensor generates a constant bit rate. The data generated by sensors can only be sent to their 1-hop neighbor relays, and sensors cannot relay any data.
- The transmission scheduling and congestion control are perfect such that no collisions and congestions occur in the considered WSNs.
- The packets generated by sensors have an identical length. No data aggregation is performed in relays, i.e., the incoming traffic of a relay is equal to its outgoing traffic.

B. Problem Formulation

As in [7], only the energy consumption for packet transmission and reception is considered and the lifetime of a node is measured by the maximal number of packets that can be transmitted by this node. The maximal number of packets that can be received and forwarded by relay r is calculated as

$$F_c(r) = \frac{E(r)}{I_{tx}(r) + I_{rx}(r)}, \tag{1}$$

where $E(\bullet)$ denotes the initial energy of a node, $I_{rx}(\bullet)$ and $I_{tx}(\bullet)$ denote the energy consumption for data reception and data transmission of a node, respectively.

Let $S = \{s_1, s_2, ..., s_n\}$ and K be the set of sensors and the sink, respectively. After the deployment of a set of relays $R = \{r_1, r_2, ..., r_m\}$, a directed graph $G = (V, A)$ can be built, where $V = S \bigcup R \bigcup \{K\}$ is the node set and A is the arc set. Let $\mathcal{R}(u)$ and $\|u - v\|$ denote the communication radius of node u and the Euclidean distance between nodes u and v, respectively. Then, any $(u, v) \in A$ should satisfy that $\|u - v\| \leq \min(\mathcal{R}(u), \mathcal{R}(v))$, where (u, v) denotes an arc from u to v. In G, each arc (u, v) is associated with a nonnegative value $f(u, v)$, which is called the flow from u to v and indicates the number of packets transmitted from u to v. To prolong network lifetime, a relay r should meet that $f(u, r) \leq F_c(r)$ in the built network, which is termed as the lifetime constraint. Thus, the LCRNP problem is defined as: placing a minimum number of relays to build network connectivity while complying with the lifetime constraint.

III. Cluster-based Approximation Algorithm

A. Description of CAA

The main methodology lying in the CAA is to decompose the LCRNP problem into a group of small subproblems which can be solved without the consideration of the lifetime constraint. To be specific, at each step, the CAA first searches a cluster of sensors that are close to each other and assigns part of their packets (that are no more than the total packets can be received and forwarded by a relay, i.e., the lifetime constraint is satisfied) to be transmitted via the paths built for this cluster, and then deploys relays to build connectivity for this cluster ignoring lifetime constraint. This step repeats until all the packets generated by the sensors can be sent to the sink via the paths built previously.

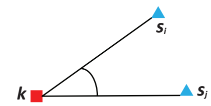


Fig. 1. An illustration to the angle between two sensors.

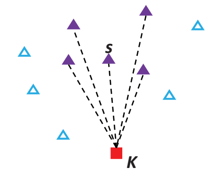


Fig. 2. An example to show how to select the sensors in a cluster.

Some definitions are first given to facilitate the description of the approach for clustering sensors. As illustrated in Fig. 1, the angle between two sensors s_i and s_j (i.e., $\angle s_i K s_j$) is defined as the angle between the two line segments (i.e., Ks_i and Ks_j) connecting the sink and these two sensors. Given a sensor s, we search a cluster of sensors and call these sensors (including s) the cluster centered at s, denoted by $\mathcal{C}(s)$. In order to save the relays deployed to build the connectivity of a cluster, the CAA tries to make the sensors in a cluster as close to each other as possible. For this purpose, we allocate the sensors with smallest angles between them and s into $\mathcal{C}(s)$, as shown in Fig. 2, where the purple sensors in the shaded area form a cluster.

For each sensor u in $\mathcal{C}(s)$, we assign part of its packets to be transmitted to the sink via the paths built for this cluster, and this part of packets is denoted by $\mathcal{F}_{\mathcal{C}(s)}(u)$. Then, we stipulate that the total packets, which are to be transmitted via the paths built for this cluster, should satisfy $\sum_{u \in \mathcal{C}(s)} \mathcal{F}_{\mathcal{C}(s)}(u) \leq F_c(r)$. This means that the lifetime constraint can be ignored during the process of building paths for this cluster. The clustering approach is explicitly detailed in Algorithm 1, where $F_r(u)$ ($u \in \mathcal{C}(s)$) denotes the packets (of u) that are not assigned to be transmitted via any path.

Algorithm 1: The algorithm to find the cluster centered at s.

Input: Sensor set $\bar{S}$ and a sensor s ($s \in \bar{S}$).
Output: A sensor set $\mathcal{C}(s)$ ($\mathcal{C}(s) \subseteq \bar{S}$).
begin
  $\forall u \in \bar{S}$, calculate the value of $\angle sKu$;
  sort $\bar{S}$ in an ascending order according to the value of angle (for the sensors having the same value of angle, sort them according to their distance to the sink.);
  $\mathcal{C}(s) = \{s\}$, $\bar{S} = \bar{S} - \{s\}$, $\mathcal{F}_{\mathcal{C}(s)}(s) = F_r(s)$;
  while $\left(x = F_c(r) - \sum_{u \in \mathcal{C}(s)} \mathcal{F}_{\mathcal{C}(s)}(u) > 0\right)$ && $(\bar{S} \neq \varnothing)$ **do**
    u =the first sensor in $\bar{S}$;
    `%the following steps assign packets to be transmitted via the paths built for this cluster.`
    if $x > F_r(u)$ **then**
      $\mathcal{F}_{\mathcal{C}(s)}(u) = F_r(u)$;
    else
      $\mathcal{F}_{\mathcal{C}(s)}(u) = x$;
    $\mathcal{C}(s) = \mathcal{C}(s) \bigcup \{u\}$, $\bar{S} = \bar{S} - \{u\}$;
  return $\mathcal{C}(s)$;

With the above definitions in hand, the whole CAA is shown in Algorithm 2. At the beginning of each step, for each sensor in S, a cluster centered at this sensor will be found according to Algorithm 1. Then, in order to save the deployed relays, the cluster with the smallest compactness (i.e., sensors in this cluster are closer to each other than those in other clusters) is selected, where the compactness $\mathcal{W}(\mathcal{C}(s))$ whose mathematical expression is given by

$$\mathcal{W}(\mathcal{C}(s)) = \frac{\sum\limits_{u,v \in \mathcal{C}(s), u \neq v} \angle uKv}{|\mathcal{C}(s)|}, \tag{2}$$

is defined as the weight of a cluster $\mathcal{C}(s)$. At the end of this step, we employ a traditional two-tiered RNP algorithm-F2tRNP in [8] whose time complexity and approximation ratio are O(n^5) and 7, respectively, to build the paths between the sink and the sensors in this selected cluster.

Algorithm 2: The Cluster-based Approximation Algorithm (CAA).

Input: A sensor set $S = \{s_1, s_2, ..., s_n\}$ and the sink K.
Output: A relay set $R = \{r_1, r_2, ..., r_m\}$.
begin
1 $\forall s \in S$, $F_r(s) = F_c(s)$;
while $S \neq \varnothing$ **do**
2 $\forall s \in S$, find $\mathcal{C}(s)$ and calculate $\mathcal{W}(\mathcal{C}(s))$, and then sort the clusters in an ascending order according to their weights;
3 $\mathcal{C}(u)$ = the least weighted cluster $\mathcal{C}(s)$ among all the clusters;
4 $\bar{R}$ = the relays deployed by the algorithm in [8] to build the paths between the sink and the sensors in $\mathcal{C}(u)$;
5 $R = R \bigcup \bar{R}$;
6 $\forall s \in \mathcal{C}(u)$, $F_r(s) = F_r(s) - \mathcal{F}_{\mathcal{C}(u)}(s)$;
7 $\forall s \in \mathcal{C}(u)$, if $F_r(s) = 0$, then $S = S - \{s\}$;
return R;

B. Analysis of Algorithm

1) Time Complexity: First of all, the time complexity of Algorithm 1 is analyzed. The steps 1-3 of Algorithm 1 take an time complexity O(n^2) mainly due to the sorting procedure. Obviously, the body of the main loop has a linear time complexity, and the loop will last for at most n iterations. Therefore, the time complexity of the main loop is O(n). As a result, Algorithm 1 has a time complexity of O(n^2).

Next, the time complexity of the CAA is shown. As detailed in Algorithm 2, step 2 and step 4 mainly contribute to the time complexity of the CAA. At step 2 of the CAA, Algorithm 1 is applied to find the clusters, which takes a running time O(n^3) since the time complexity of Algorithm 1 is O(n^2). Then, the time complexity of F2tRNP is O(n^5), which indicates that the time complexity of step 4 is O(n^5). As the main loop will execute up to n iterations, the time complexity of the CAA is O(n^6).

2) Approximation Ratio: Let APT and OPT be the set of relays deployed by the CAA and an optimal solution to the LCRNP problem, respectively. When the CAA builds paths for a cluster, the lifetime constraint is ignored, which means that as the LCRNP problem is solved within a cluster, the LCRNP problem is reduced to the RNP problem. Let APT_i and OPT_i denote the set of relays deployed by the F2tRNP and an optimal solution to the RNP problem for the cluster i, respectively. Then, the approximation ratio is calculated as

$$\frac{|APT|}{|OPT|} = \frac{\sum\limits_{i=1}^{l} |APT_i|}{|OPT|} = \sum_{i=1}^{l} \frac{|APT_i|}{|OPT_i|} \frac{|OPT_i|}{|OPT|}, \tag{3}$$

where l denotes the total number of clusters.

As the approximation ratio of the F2tRNP is 7, we have an upper bound for equation (3)

$$\frac{|APT|}{|OPT|} \leq 7 \sum_{i=1}^{l} \frac{|OPT_i|}{|OPT|}. \tag{4}$$

As the optimal solution for the sensors in a cluster should be no more than the optimal solution for all the sensors, the inequality $\frac{|OPT_i|}{|OPT|} \leq 1$ ($i = 1, 2, ..., l$) holds, which results in that

$$\frac{|APT|}{|OPT|} \leq 7l. \tag{5}$$

Due to the fact that $l \leq n$, the approximation ratio of the CAA is O(n).

IV. Augmented CAA

A. Description of ACAA

As the execution of the CAA, the multi-hop routes for the deployed WSNs are gradually determined. If all the packets are transmitted according to the routes arranged by the CAA, no relays will die early. However, when another routing algorithm is adopted after the deployment, the packets may be transmitted via the paths built for the sensors in other clusters, which may severely reduce the network lifetime. For the cases in which other route algorithms are adopted, the ACAA is proposed to ensure that the deployed networks have an improved lifetime even the routes cannot be determined based on the CAA.

The major reason leading the early death of relays is described in Fig. 3, where sensors and relays in the same color are the sensors in the same cluster and the relays deployed for this cluster, and the paths built by the CAA are represented by the solid arrows. In Fig. 3, r_3 (which is deployed by the CAA to build paths for s_3 and s_4) has a 1-hop neighbor s_2, which is a sensor in another cluster. As one of other routing algorithms is applied, a new path which is denoted by the dashed arrow may be built between s_2 and r_3. Then, s_2 transmits its packets to r_3, which will drain the energy of r_3 fast. As a result, the paths between s_3, s_4 and the sink are broken down, which announces the early death of this network. Thus, the relays having 1-hop neighbors in other clusters may suffer more traffic loads. In the following paper, we call such relays as Traffic-Prone-Relays (TPRs).

Therefore, the ACAA tries to mitigate the traffic load of the TPRs by deploying additional relays. In the first step, a set of relays are deployed by the CAA. Then, the ACAA starts a step of iterative search. In each iteration, the nodes on a path built in the last step are sequentially examined, and the examination

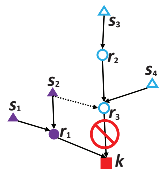


Fig. 3. The main reason leading the early death of relays.

starts from the sensor to the node adjacent to the sink. Each iteration terminates until a node u whose parent[1] is a TPR is encountered or all the nodes (except the sink) on this path are examined, and the ACAA stores u. As this search step is applied to all the paths, a set U of nodes whose parents are TPRs are found. Finally, another path is built between each node in U and the sink by the F2tRNP. The ACAA is detailed in Algorithm 3.

Algorithm 3: Augmented CAA (ACAA).

Input: A sensor set $S = \{s_1, s_2, ..., s_n\}$ and the sink K.
Output: A relay set $R = \{r_1, r_2, ..., r_m\}$.
begin
1 R =the relays deployed by the CAA to build the paths between the sensors and the sink;
2 P =the set of paths built by the CAA between the sensors and the sink;
forall the $p \in P$ **do**
3 u =the first node whose parent is a TPR in p, and the search procedure starts from the sensor to the sink;
4 $U = U \bigcup \{u\}$;
5 $\bar{R}$ =the additional relays deployed by the F2tRNP to build the paths between the nodes in U and the sink;
6 $R = R \bigcup \bar{R}$;
return R;

B. Analysis of Algorithm

As shown in Algorithm 3, the CAA and the F2tRNP are respectively employed in step 1 and step 5, and the time complexity of step 3 is O(n^2). Therefore, the time complexity of the ACAA is also O(n^6).

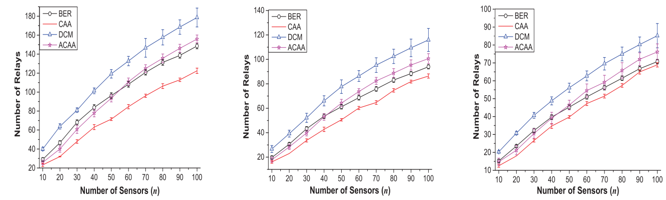
Let APT_{ACAA} and OPA be the set of relays deployed by the ACAA and an optimal solution to the LCRNP problem, respectively. Let APT_{CAA} and APT_{F2tRNP} be the set of relays deployed by the CAA at step 1 and the set of relays deployed by the F2tRNP at step 5, respectively. Next, the approximation ratio is given by

$$\frac{|APT_{ACAA}|}{|OPT|} = \frac{|APT_{CAA}|}{|OPT|} + \frac{|APT_{F2tRNP}|}{|OPT|}. \quad (6)$$

As the lifetime constraint is not considered at step 5, the RNP problem can be easily solved. Let OPT_{RNP} be an optimal solution to the RNP problem at step 5. We have $|OPT| \geq |OPT_{RNP}|$ since in the worst case the input of step 5 is the sensor set, i.e., $U = S$, which leads to

$$\frac{|APT_{ACAA}|}{|OPT|} \leq \frac{|APT_{CAA}|}{|OPT|} + \frac{|APT_{F2tRNP}|}{|OPT_{F2tRNP}|} \leq 7l + 7. \quad (7)$$

[1] A parent of node u on path p denotes a node (on p) next to u and with less hop count to the sink.



(a) $(\mathcal{R}_s, \mathcal{R}_r) = (10, 10)$. (b) $(\mathcal{R}_s, \mathcal{R}_r) = (10, 15)$. (c) $(\mathcal{R}_s, \mathcal{R}_r) = (10, 20)$.

Fig. 4. The comparison of deployment cost between different algorithms.

Due to the fact that $l \leq n$, the approximation ratio of the ACAA is also O(n).

V. Performance Evaluation

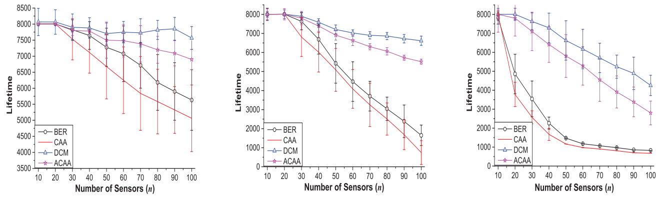
In the simulations, all the sensor are with the same energy model, i.e., $\forall s \in S$, $E(s) = e_s$, $\mathcal{R}(s) = \mathcal{R}_s$ and $I_{tx}(s) = i^s_{tx}$. At the same time, all the deployed relays also share a common energy model, i.e., $\forall r \in R$, $E(r) = e_r$, $\mathcal{R}(r) = \mathcal{R}_r$, $I_{tx}(r) = i^r_{tx}$ and $I_{rx}(r) = i^r_{rx}$, where e_s, $\mathcal{R}_s$, i^s_{tx}, e_r, $\mathcal{R}_r$, i^r_{tx} and i^r_{rx} are predetermined constants. Besides, sensors are randomly placed on a square field with the side length of 200 meters. To demonstrate the efficiency of this work, the algorithms proposed in this paper are compared with the Best Effort Relaying (BER) algorithm [7] and the Density Control Method (DCM) [4] under different amount of sensors (the number of sensors varies from 10 to 100). The simulations are implemented under both the homogeneous scenario, i.e., $\mathcal{R}_s = \mathcal{R}_r = 10$, and the heterogeneous scenario, i.e., $\mathcal{R}_s = 10$ and $\mathcal{R}_r = 15$ or 20. Each data on the figures is generated based on the method of batch means with 50 simulation runs for the confidence level of 95%. In the simulations, we assume that the TI CC2530 transceiver is employed, and the parameters for the energy model are set as Table I. Finally, the simulation platform is developed by the MATLAB R2008b, and simulations are executed on a 3.40-GHz Windows Work Station with 16 GB memory.

TABLE I
Parameter setting for the energy model.

e_s	150 mAH
e_r	3200 mAH
i^s_{tx}	1.86×10^{-2} mAH
i^r_{tx} $(\mathcal{R}_r = 10)$	1.86×10^{-2} mAH
i^r_{rx} $(\mathcal{R}_r = 10)$	3.24×10^{-2} mAH
i^r_{tx} $(\mathcal{R}_r = 15)$	2.79×10^{-2} mAH
i^r_{rx} $(\mathcal{R}_r = 15)$	4.86×10^{-2} mAH
i^r_{tx} $(\mathcal{R}_r = 20)$	3.72×10^{-2} mAH
i^r_{rx} $(\mathcal{R}_r = 20)$	6.48×10^{-2} mAH

A. Deployment cost

The deployment cost is measured in terms of the number of deployed relays. The comparison results between different algorithms on the deployment cost are shown in Fig. 4. Obviously, the CAA significantly outperforms other algorithms in Fig. 4. The maximal number of relays



(a) $(\mathcal{R}_s, \mathcal{R}_r) = (10, 10)$.
(b) $(\mathcal{R}_s, \mathcal{R}_r) = (10, 15)$.
(c) $(\mathcal{R}_s, \mathcal{R}_r) = (10, 20)$.

Fig. 5. The comparison of lifetime between different algorithms.

saved by the CAA comparing with the DCM under different communication radii are 31.7803 ($31.7803/63.8093 \approx 49.81\%$), 16.2532 ($16.2532/39.2532 \approx 41.41\%$) and 12.7665 ($12.7665/30.7665 \approx 41.49\%$), respectively. In comparison to the BER, the maximal saving of relays by the CAA are 14.5989 ($14.5989/46.6279 \approx 31.31\%$), 7.6667 ($7.6667/30.6667 \approx 25.00\%$) and 5.5476 ($5.5476/23.5476 \approx 23.56\%$), respectively.

Hence, the CAA is the best choice when the routes can be determined by the CAA. On the other hand, although the deployment cost of the ACAA is much larger than the CAA, it still outperforms the DCM and deploys fewer relays than the BER when the amount of sensors is relatively small.

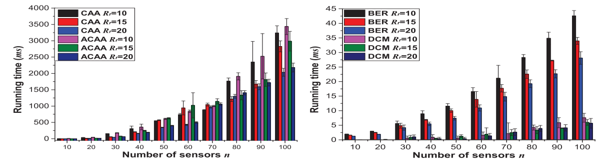
B. Lifetime

When the network routes are determined by the CAA, the networks built by the CAA can keep alive until all the packets generated by sensors are sent to the sink. Therefore, it is meaningless to measure the network lifetime under the condition that the routes are determined by the CAA. To evaluate the lifetimes of the WSNs built by the CAA and the ACAA under much harsher conditions, the geographic routing algorithm [9] that is widely used in WSNs is employed to test the network lifetime. In this paper, the network lifetime is defined as the maximal number of rounds during which the packet of each sensor can be sent to the sink via a path consisting of alive relays.

Fig. 5 shows the lifetime of networks built by different algorithms. Unfortunately, the lifetime of networks built by the CAA decreases remarkably as the increment of the amount of sensors. This implies that when the routes cannot be determined by the the CAA, the CAA is not a rational choice. In contrast, the DCM guarantees a long lifetime due to its high deployment cost, which indicates that this method is best when only the lifetime is considered. As shown in Fig. 4 and Fig. 5, the ACAA can significantly prolong the lifetime with the additionally deployed relays, which are fewer than those deployed by the DCM. This indicates that when both lifetime and deployment cost are considered and the routes cannot be determined by the CAA, the ACAA is an appropriate choice.

C. Running time

The comparison of the running time in terms of millisecond between different algorithms is shown in Fig. 6. Although the running time of the CAA and ACAA is much longer than



(a) CAA and ACAA.
(b) BER and DCM.

Fig. 6. The comparison of running time between different algorithms.

that of the other two algorithms, considering the extremely low deployment cost, we believe that the extra running time is worthwhile.

VI. Conclusion

This paper has investigated the LCRNP problem in WSNs. Due to its NP-hard nature, a cluster-based approximation algorithm-CAA has been proposed to approximately solve the LCRNP problem. Besides, an another algorithm-ACAA has been proposed to improve the network lifetime when the routes cannot be determined by the CAA. Through rigorous analysis, the CAA and the ACAA have been shown with the same time complexity $O(n^6)$ and the same approximation ratio $O(n)$. Finally, extensive simulations have been conducted to verify the efficiency of the proposed algorithms.

Acknowledgment

This work was supported by the Natural Science Foundation of China under grant 61673371 and 71661147005, Youth Innovation Promotion Association, CAS (2015157) and the Program project of Beijing Municipal Education Commission (KM 201511417008), open project of Beijing Key Laboratory of Information Service Engineering (Zk20201402).

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