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Maximizing network lifetime based on transmission range adjustment in wireless sensor networks

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ABSTRACT

In a wireless sensor network (WSN), the unbalanced distribution of communication loads often causes the problem of energy hole, which means the energy of the nodes in the hole region will be exhausted sooner than the nodes in other regions. This is a key factor which affects the lifetime of the networks. In this paper we propose an improved corona model with levels for analyzing sensors with adjustable transmission ranges in a WSN with circular multi-hop deployment (modeled as concentric coronas). Based on the model we consider that the right transmission ranges of sensors in each corona is the decision factor for optimizing the network lifetime after nodes deployment. We prove that searching optimal transmission ranges of sensors among all coronas is a multi-objective optimization problem (MOP), which is NP hard. Therefore, we propose a centralized algorithm and a distributed algorithm for assigning the transmission ranges of sensors in each corona for different node distributions. The two algorithms can not only reduce the searching complexity but also obtain results approximated to the optimal solution. Furthermore, the simulation results of our solutions indicate that the network lifetime approximates to that ensured by the optimal under both uniform and non-uniform node distribution.

1. Introduction

Recent advances in wireless communications have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate in short distances. These tiny sensor nodes consist of sensing, data processing, and communicating components [1]. A sensor network is composed of a large number of sensor nodes that are densely deployed either inside the phenomenon or very close to it. Due to limited and non-rechargeable energy provision, the energy resource of sensor networks should be managed wisely to extend the lifetime of sensors. Although much attention has been paid to low-power hardware design and collaborative signal processing techniques, energy-efficient algorithms must be supplied at various networking layers [2].

Usually, a sensor network interfaces with the outside world via one or several sinks. The sensed data collected by the sensors is routed to the closest sink where it is further aggregated. Recently, it was noticed that the sensors closest to the sink tend to deplete their energy budget faster than other sensors [3–8], which is known as an energy hole around the sink. No more data can be delivered to the sink after energy hole appears. Consequently, a considerate amount of energy is wasted and the network lifetime ends prematurely.

The most widely used model for analyzing energy hole problem is corona model. Authors in [3] present the model of concentric coronas to analyze energy hole problem. They assume a sensor network endowed with one or more sinks, and assume that each sink is equipped with a steady energy supply and a powerful radio that can cover a disk of radius R centered at the sink. The sink organizes the sensors around it into dynamic infrastructure. This task is referred to as *training* [5,9], and involves partitioning the disk into disjoint concentric sets termed *coronas*.

There are three approaches for improving the lifetime of sensor networks with energy hole problem: (1) assistant approaches, such as deployment assistance, traffic compression and aggregation in [10]. (2) Node distribution strategies, Lian et al. [4] propose a non-uniform sensor distribution strategy. The density of sensors increases when their distance to the sink decreases. (3) Adjustable transmission range, Jarry et al. [11] propose a mixed routing algorithm which allows each sensor node to either send a message to one of its immediate neighbors, or to send it directly to the base station.

In this paper, we investigate an approach to maximize the network lifetime by using adjustable transmission range. Based on the corona model, we divide the maximal transmission range of

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sensors into several levels. Nodes in the same corona have the same transmission range level termed the transmission range of the corona, and different coronas have different transmission ranges, which compose a list termed transmission range list. We conclude that the transmission ranges assignment of all coronas is the most effectively approach to prolong the network lifetime after nodes deployment. We propose two algorithms, which are CETT and DETL, for that assignment adapted in different strategies of node distribution.

The remainder of this paper is organized as follows. Section 2 presents our literature review. Section 3 introduces the system model and the discussion of energy hole problem. Section 4 proposes the two algorithms which are CETT and DETL. Section 5 shows the effectiveness of CETT and DETL via simulation, and compares them with optimal solutions and existing algorithms. Section 6 concludes this paper.

2. Related work

Li and Mohapatra [10] investigate the problem of uneven energy consumption in a large class of many-to-one sensor networks. The authors describe the energy hole in a ring model (like corona model), and present the definitions of the per node traffic load and the per node energy consuming rate (*ECR*). Based on the observation that sensor nodes sitting around the sink need to relay more traffic compared to other nodes in outer sub-regions, their analysis verifies that nodes in inner rings suffer much faster energy consumption rates and thus have much shorter lifetime. The authors term this phenomenon of uneven energy consumption rates as the energy hole problem, which may result in serious consequences, e.g. early dysfunction of the entire network. The authors present some approaches to the energy hole problem, including deployment assistance, traffic compression and aggregation. Shiue et al. [12] propose an algorithm to resolve energy hole problem, which uses mobile sensors to heal energy holes. However, the cost of these assistant approaches is a lot.

Lian et al. [4] argue that in static situations, for large-scale networks, after the lifetime of the sensor network is over, there is still a great amount of energy left unused, which can be up to 90% of total initial energy. Thus, the static models with uniformly distributed homogenous sensors cannot effectively utilize their energy. The authors propose a non-uniform sensor distribution strategy. The density of sensor increases when their distance to the sink decreases. Their simulation results show that for networks with high density, the non-uniform sensor distribution strategy can increase the total data capacity by an order of magnitude.

Olariu and Stojmenović [3] discuss the relationship between the network lifetime and the width of each corona in concentric corona model. The authors prove that in order to minimize the total amount of energy spent on routing along a path originating from a sensor in a corona and ending at the sink, all the coronas must have the same width. However, the authors assume that all nodes in corona C_i should forward data in corona C_{i-1}, and the transmission range in corona C_i is $(r_i - r_{i-1})$ (here C_i is the sub-area delimited by the circles of radii r_{i-1} and r_i). If each corona has different width and different transmission range, we think, this assumption may lead to the waste of energy for transmission. For example, as shown in Fig. 1, the width of corona C_i is larger than that of corona C_{i-1} and all nodes in C_i have the same transmission range of $(r_i - r_{i-1})$ that is larger than the width of corona C_{i-1}. Divide the corona C_i into two sub-coronas, namely s_1 and s_2 (see in Fig. 1). The width of sub-corona s_1 is equal to that of corona C_{i-1}, so nodes in s_1 will transmit data to C_{i-1}. The nodes in sub-corona s_2 which are close to corona C_{i-1} with transmission range larger than the width of corona C_{i-1} may transmit data across corona C_{i-1} to

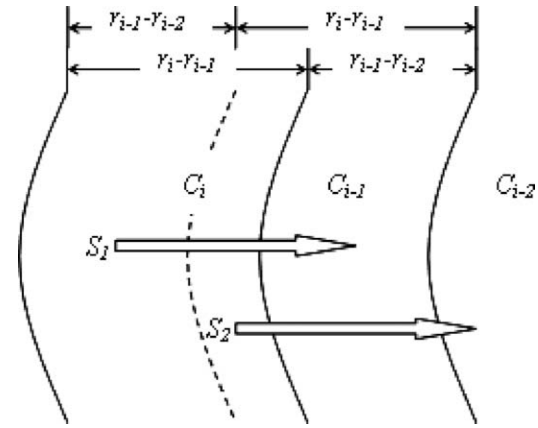


Fig. 1. The problem of wasting energy for transmission between coronas with different widths.

corona C_{i-2} that is closer to the sink node. Because of the authors' assumption that the data transmitted from all nodes in corona C_i should be forwarded for the next hop in corona C_{i-1} rather than corona C_{i-2}, these nodes in s_2 with transmission range $(r_i - r_{i-1})$ which can transmit data to C_{i-2} but should transmit to C_{i-1}, will waste energy for transmission.

Wu et al. [13] propose a non-uniform node distribution strategy to achieve the sub-balanced energy depletion. The authors state that if the number of nodes in coronas increases from corona C_{R-1} to corona C_1 in geometric progression with common ratio $q > 1$, and there are $N_{R-1}/(q-1)$ nodes in corona C_R, then the network can achieve sub-balanced energy depletion. Here, N_i denotes the number of nodes in corona C_i. However, the node distribution strategy can hardly work in the real world, because in most cases the node distribution is random, and hence an uncontrollable node density in local area.

For balancing the energy load among sensors in the network, Jarry et al. [11] propose a mixed routing algorithm which allows each sensor node to either send a message to one of its immediate neighbors, or to send it directly to the base station, and the decision is based on a potential function depending on its remaining energy. However, when the network area radius is bigger than the sensor's maximal transmission range, the proposed algorithm can not be applicable.

3. System model and problem statement

In this section, the system model used in this paper will be introduced first, followed by the analysis of energy hole problem based on our proposed improved corona model.

3.1. Network model

We assume our sensor network model as follows: (1) once deployed, the sensors must work unattended, and all sensor nodes are static. Each sensor has a non-renewable energy budget, and the initial energy of each sensor is $\varepsilon > 0$; (2) each sensor has a maximum transmission range, denoted by t_x, and assumed to be much smaller than R (the furthest possible distance from a sensor to its closest sink); (3) sensors are required to send their sensed data constantly at a certain rate. For sake of simplicity, we assume that each sensor node generates and sends l bits of data per unit time; (4) we assume there is a perfect MAC layer in the network, i.e. transmission scheduling is so perfect that there is no collision and retransmission. Initially the network is well connected. The issue that what node density can ensure network connectivity is investigated in [14]; (5) based on greedy forwarding approach sensor nodes transmit data packets to the sink. Quite a few of such techniques have been proposed (for example, see [15]). In greedy forwarding, data packets are transmitted to a next hop which is closest towards the destination.

Definition (*Network lifetime*). Li and Mohapatra [10] present the definition of system lifetime, which is the time till a proportion of nodes die. A corona of sensor nodes in the network is said to be dead when it is unable to forward any data or send its own data. So the network lifetime in this paper is defined as the duration from the very beginning of the network until the first corona of sensor nodes die.

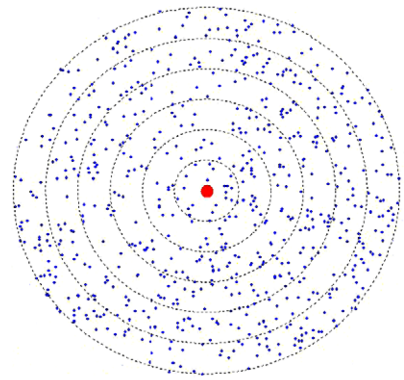


Fig. 3. Concentric coronas.

3.2. Energy model

A typical sensor node comprises three basic units: sensing unit, processing unit, and transceivers. Our energy model only involves the power for receiving and transmitting data without considering the energy consumed for sensing and processing data, which depends on the computation hardware architecture and the computation complexity. According to [10], the energy consumption formulas that we use in the analysis and simulations throughout the rest of this paper are as Eq. (1) and Eq. (2).

Here E_{trans} denotes the energy consumption of transmitting and E_{rec} denotes the energy consumption of receiving, L is the data rate of each sensor node, and α is 2 or 4, the term d^{α} accounts for the path loss. According to [10], some typical values for the above parameters in current sensor technologies are as follows:

$$\beta_1 = 45 \times 10^{-9}\ \text{J/bit},$$
$$\beta_2 = 10 \times 10^{-12}\ \text{J/bit/m}^2\ (\text{when } \alpha = 2,$$
$$\text{or, } \beta_2 = 0.001 \times 10^{-12}\ \text{J/bit/m}^4\ (\text{when } \alpha = 4),$$
$$\beta_3 = 135 \times 10^{-9}\ \text{J/bit}.$$

3.3. Corona model for adjustable transmission range

In order to save energy, sensors can adjust their transmission ranges. For simplicity, we divide t_x into k levels, and sensors have k levels of transmission range to choose (see Fig. 2). The unit length of transmission range is denoted by d in Eq. (3).

We partition the whole area with radius R into m adjacent concentric parts termed coronas (see Fig. 3), which has discussed in [5,9]. The width of each corona is d, therefore it satisfies Eq. (4).

We assume that all nodes in the same corona have the same transmission range termed the transmission range of this corona. So when the transmission range of a corona is i, the length of the range satisfies Eq. (5).

There are two patterns of transmission ranges among all coronas: (1) $k = 1$, each node in corona C_i serves as the next hop relay for the nodes in corona C_{i+1}, here, C_i denotes the ith corona that is composed of nodes whose distances to the sink are between $(i) - 1)$ and i unit length. Fig. 4(a) illustrates a possible path which is routed from a subset of sensors in the outermost corona to the sink, and each hop involves sensors from adjacent coronas. Ref. [13] is based on this pattern; (2) $k > 1$, nodes in each corona may not be the next hop relay for the nodes in its adjacent outer corona, and a data packet may traverse more than one corona using only one hop transmission. A possible path of data forwarding is shown in Fig. 4(b). This paper focuses on searching right transmission range lists to prolong the network lifetime based on the second pattern.

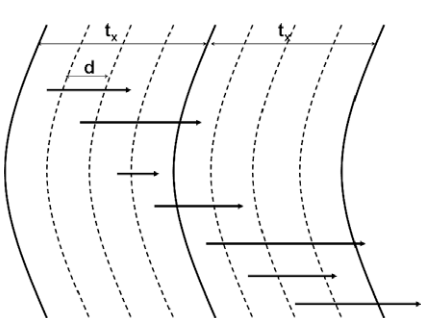


Fig. 2. Adjustable transmission ranges.

3.4. Problem statement

Let x_i denote the transmission range level of corona C_i, so vector of x denotes the transmission range list of all m coronas and satisfies Eq. (6).

Let S_i denote the set of corona ID for the coronas which directly transmit data to C_i, therefore it satisfies Eq. (7),

Let N_i denote the number of nodes in C_i. So we obtain the N_i vector function in Eq. (8).

According to Eq. (1) and Eq. (2), the total energy consumption of transmitting data generated from C_i per unit time in C_i is Eq. (9).

Each corona not only transmits data generated by itself but also forwards data generated by outer coronas. Let $N_{rec\,i}$ denote the number of nodes in outer coronas whose generated data need to forward in C_i, namely the *received nodes* in C_i. Therefore, it satisfies Eq. (10).

According to Eq. (7) and Eq. (10), we notice that each $N_{rec\,i}$ is determined by those x with ID bigger than i. Then we obtain the number of received nodes vector function of m coronas in Eq. (11).

The energy consumption of forwarding data from outer coronas in corona C_i includes energy consumption for receiving and transmitting data. According to the energy formulas in Section 3.2, the total energy consumption of forwarding data generated from other coronas per unit time in C_i satisfies Eq. (12).

Let E_i denote the total energy consumption per unit time in C_i, including the energy for transmitting data generated by itself and that for forwarding data from outer coronas. Therefore, it satisfies Eq. (13).

With the help of Eq. (9) and Eq. (12), we rewrite Eq. (13) as Eq. (14).

Let W_i denote the *per node energy consuming rate* (*ECR*) [3,10] in C_i. Therefore it satisfies Eq. (15).

With the help of Eq. (14), we rewrite Eq. (15) as Eq. (16).

We obtain the *ECR* vector function of m coronas in Eq. (17).

Let T_i denote the lifetime of corona C_i. Therefore, it satisfies Eq. (18).

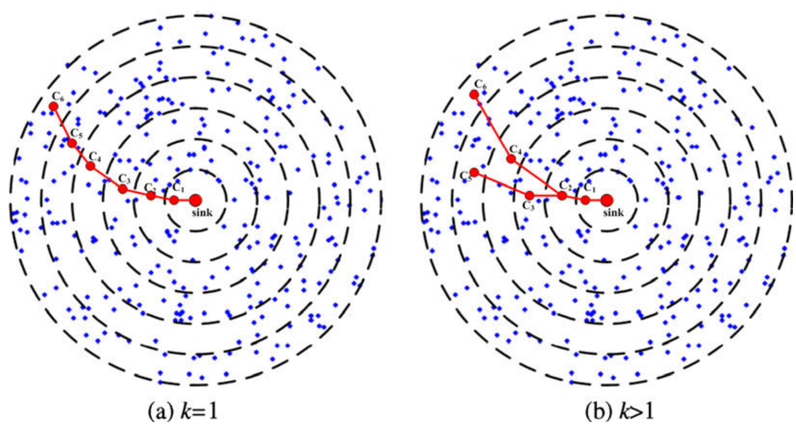


Fig. 4. Two patterns of transmission ranges among all coronas.

With the help of Eq. (14), we rewrite Eq. (18) as Eq. (19).

So we obtain the relation between *ECR* and lifetime of C_i in Eq. (20).

We obtain the lifetime vector function of m coronas in Eq. (21).

According the definition of the network lifetime, we notice that the network lifetime is the minimal in $\{T_1, T_2, \ldots, T_m\}$.

From above formulas, we can see there are three factors affecting the network lifetime, which are the number of nodes, received nodes and transmission range of each corona. The number of nodes in each corona is determined by the node distribution, and as discussed above the received nodes of each corona is affected by the transmission range list. So after all nodes have been deployed, there is only one factor contributing to the network lifetime, which is the transmission range list (see in Fig. 5). In order to maximize the network lifetime, we need to search an optimal transmission range list.

Theorem 1. *To search optimal transmission range list is NP hard.*

Proof. In order to proving Theorem 1, we need prove the problem is Multi-objective optimization problem (MOP) which is NP hard. We give the definition of MOP as follows:

Definition. General multi-objective optimization problem (MOP). [16]

Search the vector of x which will satisfy the m inequality constraints in Eq. (22).

The p equality constraints are in Eq. (23).

And will optimize the vector function in Eq. (24).

The vector of x is the vector of decision variables.

In this section, we can see the problem of maximizing the network lifetime involves how to maximize the lifetime of all coronas, and by Eq. (19) the lifetime of each corona is determined by N_i, $N_{rec\,i}$, and x_i. According to Eq. (10), we notice that each $N_{rec\,i}$ is determined by those x with ID bigger than i. Each x_i satisfies Eq. (6), and according to Eq. (10) and Eq. (19), we conclude that the transmission range list determines not only the received nodes of each corona but also the lifetime of each corona. So the transmission range list is the vector of decision variables for optimizing the lifetime of each corona, and the optimizing problem is a multi-objective optimization problem (MOP). According to [17], MOP is NP hard. Therefore, the problem of searching optimal transmission range list for maximizing the network lifetime is NP hard. □

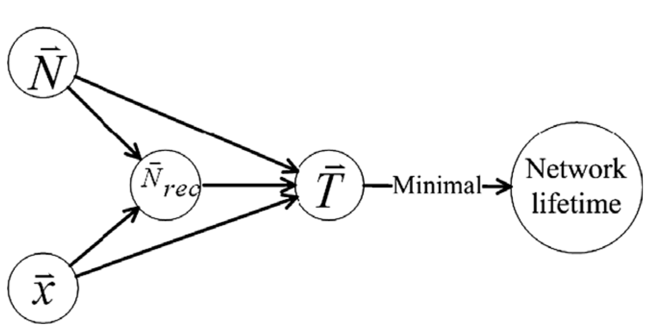


Fig. 5. The relationship of factors affecting the network lifetime.

4. Algorithms for energy-efficient transmission range list

In this section, we introduce the spanning transmission tree. Then we will propose two algorithms for generating transmission range list for different node distributions.

4.1. Spanning transmission tree

Each sensor has k transmission range levels to choose, which are $1d,\ 2d, \ldots,\ kd$, so sensors in one corona have k coronas to be the next hop corona. So we can obtain a directed graph in Fig. 6, where vertex denotes each corona. And if corona C_i can transmit data to coronaC_j, there will be a directed edge $(C_i,\ C_j)$ from C_i to C_j. We term this graph as *available transmission graph*. For convenience of notation we write C_0 as the sink node. The characters of the available transmission graph are as follows:

(1) Out-degree: vertexes with ID bigger than k have k out-degrees. The out-degree of each vertex whose ID is not bigger than k is equal to its corona ID.

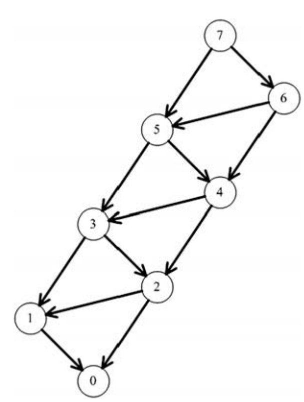


Fig. 6. Available transmission graph ($k = 2$).

(2) In-degree: the vertexes of outmost k coronas have $(m-i)$ in-degrees (where m is the number of coronas, and i is the corona ID), and each of other vertexes has k in-degrees, including the sink node.
(3) The directed edge $(C_i,\ C_j)$ $(1 \leqslant i, j \leqslant m)$ should be with condition $i > j$.

In Section 3.4 we have discussed that in order to maximize the network lifetime, we need to search an optimal transmission range list. According to the list we can obtain a spanning tree with sink as its root from the available transmission graph (see Fig. 7). We call the tree *spanning transmission tree*. The following are the characters of the spanning transmission tree:

(1) Out-degree: each vertex has only one out-degree.
(2) In-degree: each vertex has not more than k in-degrees.
(3) The directed edge $(C_i,\ C_j)$ $(1 \leqslant i, j \leqslant m)$ should be with condition $i > j$.

Since searching optimal transmission range lists is NP hard, we propose two algorithms, which are CETT (Centralized Algorithm for Energy-efficient Transmission Trees) and DETL (Distributed Algorithm for Energy-efficient Transmission Range List), to obtain approximate optimal transmission range lists for different node distributions.

4.2. Centralized Algorithm for Energy-efficient Transmission Trees (CETT)

Because the sensor nodes sitting around the sink need to relay more traffic compared to those nodes in outer sub-regions, that is mean the energy consumption of the coronas near to sink is the decision factor for the network lifetime, especially in uniform node distribution. CETT is an algorithm of searching approximate optimal spanning transmission trees with maximal network lifetime from inner corona to outmost step by step. In uniform node distribution or non-uniform deterministic node distribution introduced in [13], before nodes deployment we can obtain the transmission range list by CETT based on the information about deployment, such as radius of the whole area, density and so on. After deployment nodes in each corona transmit data according to the transmission range list.

For an available transmission graph,
$G = (V, E)$ where V is a set of vertexes and
E is a set of edges
If there are m coronas, $V = \{C_0,\ C_1, \ldots,\ C_m\}$.
CETT keeps two sets:

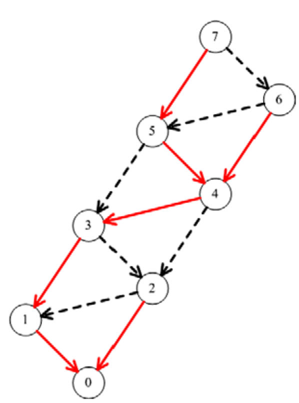


Fig. 7. Spanning transmission tree $(k = 2)$.

S_i: set of trees with i vertexes whose network lifetime approximates to the optimal trees with i vertexes. $S_i = \{tree_0,\ tree_1,\ tree_2 \ldots\}$, for each tree, $tree_j = (V'_j, E'_j)$. Obviously, they are satisfies Eq. (25). Parameter *MAXCOUNT* denotes the upper limited number of trees in S.
R_i: set of edges which start from vertex C_i such as (C_i, C_{i+1}) and (C_i, C_{i+2}). Obviously, the number of edges in R_i is not more than k.

The pseudo-code of CETT is presented in Fig. 8. The algorithm is operated as follows:

(1) Set each S_i $(1 \leqslant i \leqslant m)$ to empty. Add a tree $tree_o(V'_0,\ E'_0)$ to S_i, which $V'_0 = \{C_0\}$ and E'_0 is empty. Set i=0.
(2) $i = i$+1. Try to add each edge in R_i to each tree in S_{i-1} as a *temporary tree*. If there are q edges in R_i and p trees inS_{i-1}, obviously, there will be $q \times p$ temporary trees. Compute the network lifetime of all the temporary trees.
(3) Set T_{max} as the maximal network lifetime among all these temporary trees in this loop. Add the temporary trees whose network lifetime are between T_{max} and $T_{max}\times(1 - TIMERANGE)$ to S_i. Here, parameter *TIMERANGE* denotes the percentage of T_{max} which is used to determine the range of temporary trees added to S_i. If the number of selected temporary trees is more than *MAXCOUNT*, then just add *MAXCOUNT* temporary trees whose network lifetime is longer than others to S_i.
(4) If i is equals to the number of coronas m, then select the trees with the maximal network lifetime in S_m as the finial results; if not, go to step (2) for the next loop.

Theorem 2. *The calculation complexity of CETT is* $O(m \times k \times MAXCOUNT)$.

Proof. Let us investigate the complexity of CETT for the worst case. Each R_i at most has k elements, and each S_i at most has *MAXCOUNT* trees, so in each searching loop the number of generated temporary trees is at most $MAXCOUNT \times k$. There are m coronas, i.e. there will be m loops, so the upper limit for computational complexity of CETT is $O(m \times k \times MAXCOUNT)$. □

4.3. Distributed Algorithm for Energy-efficient Transmission Range List (DETL)

By CETT, we can obtain a transmission range list based on uniform node distribution or non-uniform deterministic node distribution. But in non-uniform random node distribution presented in [13], the condition of nodes distribution such as density and number of nodes in each corona is unknown until the deployment is finished, and we need another distributed algorithm to optimize the lists derived from CETT after nodes deployment. We propose the algorithm of DETL (Distributed Algorithm for Energy-efficient Transmission Range List).

```
Algorithm: CETT
1.  for i=1 to Number of coronas
2.      CreateTempTrees(R, S, i);
3.      SelectMaxTemptreesToS(S);
4.  endfor;
5.  GetMaxTimeFromS(S);
```

Fig. 8. The pseudo-code of the algorithm CETT.

The algorithm DETL is based on the factors which affect lifetime of each corona. From Eq. (19), we notice that after nodes deployment, the transmission range and received nodes of each corona are the two factors affecting the network lifetime. If a corona has locally maximal per node energy consuming rate (*ECR*), i.e. it will have locally minimal lifetime, it need adjust its transmission range or received nodes in order to prolong its lifetime.

Definition (*Adjacent coronas*). Take corona C_a as an example (see Fig. 9), the adjacent coronas of C_a are the coronas which are adjacent to C_a in available transmission graph, i.e. the coronas which C_a can transmit data to and the coronas which can transmit data to C_a. Take Fig. 9 as an example, the number of transmission range levels (k) is 4, so the adjacent coronas of C_a are $C_{a-1},\ C_{a-2},\ C_{a-3},\ C_{a-4}$, and $C_{a+1},\ C_{a+2},\ C_{a+3},\ C_{a+4}$.

In DETL, in order to balance the *ECR* of all coronas, each corona independently adjusts its strategy of sending and receiving data according to the *ECR* of its adjacent coronas. The pseudo-code of DETL is presented in Fig. 10. Steps are as follows:

(1) Before nodes deployment we suppose the nodes distribution is uniform, and obtain transmission range lists by CETT. Select one of the lists obtained by CETT as the initial list for the network.
(2) After nodes deployment, according to the current transmission range list, nodes in each corona compute their *ECR*.
(3) Each corona compares its *ECR* with that of its adjacent coronas. Take corona C_a in Fig. 9 as an example, if *ECR* of C_a is the maximal value among its adjacent coronas, then go to step (4); if not, there will be no adjustment for C_a and go to step (7).
(4) Inner coronas: shorten transmission range of corona C_a. Form a *group* that comprises a sender corona C_a and a new receiver corona, such as $(C_a,\ C_{a-2}),\ (C_a,\ C_{a-1})$. Then let the maximal *ECR* value of coronas in each group be the group's *ECR* value, and compute *ECR* of coronas in each group with different transmission ranges of C_a. So there will be not more than $(k-1)$ groups for inner coronas.
(5) Outer coronas: if an outer adjacent corona C_b has transmitted data to C_a, change transmission range of C_b, and then compose the sender coronas $C_b,\ C_a$ and the new receiver corona as a *group*, such as $(C_{a+1},\ C_a,\ C_{a-2}),\ (C_{a+2},\ C_a,\ C_{a-1}),\ (C_{a+4},\ C_a,\ C_{a+3})$. Then let the maximal value of coronas in each group be the group's *ECR* value, and compute *ECR* of each group with different transmission ranges of C_b.
(6) Compare *ECR* value of each group, and select the minimal value. If the minimal *ECR* value is less than the current value of corona C_a, then adopt the new transmission range assignment in the group with the minimal *ECR* value; if not, there will be no adjustment for C_a.
(7) If all coronas have no adjustment, then the algorithm is finished; if not, the transmission range list of the network will be updated, then go to step (2) for the next optimizing loop.

Theorem 3. *The upper limit for calculation complexity for each loop in DETL is* $O(k^2) + 2O(k)$.

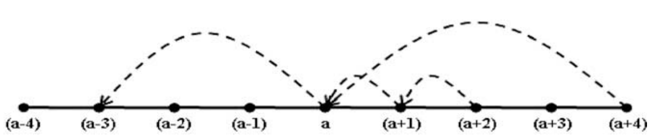


Fig. 9. Adjacent coronas ($k = 4$).

```
Algorithm: DETL
do
    IsAdjusted = FALSE;
    for each node in corona i
        if IsMaxECR(i)=TRUE then
            SelectMinECRGroupFromInner(i);
            SelectMinECRGroupFromOuter(i);
            if MinECR(i) < OriginalECR(i) then
                AssignRange(MinECRGroup, i);
                IsAdjusted = TRUE;
            endif;
        endif;
    endfor;
while(IsAdjusted);
```

Fig. 10. The pseudo-code of the algorithm DETL.

Proof. In DETL, each loop has three steps: (1) each corona compares its *ECR* with *ECR* values of its adjacent coronas. Each corona has $2k$ adjacent coronas, so the computational complexity of this step is $O(k)$; (2) shorten transmission range of corona C_a and select the *group* with minimal *ECR* value. The maximal number of transmission range levels is k, so the upper limit for computational complexity of this step is $O(k)$; (3) change transmission range of each outer adjacent corona of C_a which has transmitted data to C_a and select the *group* with minimal *ECR*. There are k outer adjacent coronas for each corona and each adjacent corona has at most k transmission range levels, so the upper limit for computational complexity of this step is $O(k^2)$. Therefore, in DETL the upper limit for computational complexity of each loop is $O(k^2) + 2O(k)$. □

5. Simulation results

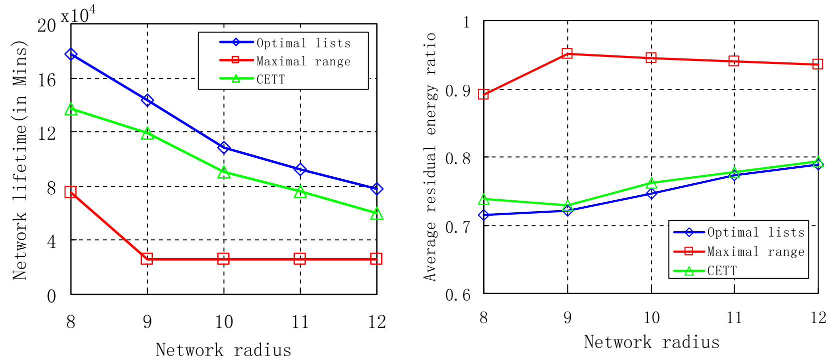
In this Section, we evaluate the performance of the proposed algorithms CETT and DET.

5.1. Simulation environment

The initial energy of each sensor (ε) is 50 J. The maximal transmission range of sensors is 20 m. The number of transmission range levels is 4. The data generating rate of each sensor is 4×10^2 bits/min. The density of node distribution is 5/m^2. The parameter α in the energy formulas is 4, and others have presented

Table 1
Simulation parameters.

Parameter	Value
Initial energy of each node (ε)	50 J
Maximal transmission range (t_x)	20 m
Number of transmission range levels (k)	4
Length of unit data (L)	4×10^2 bits
Unit time	60 s
Density (ρ)	5/m^2
Energy model	
α	4
β_1	45×10^{-9} J/bit
β_2	10^{-15} J/bit/m^4
β_3	135×10^{-9} J/bit



(a) Network lifetime (b) Residual energy ratio

Fig. 11. Algorithms in uniform node distribution.

in Section 3.2. For ease of reading we have listed all the parameters in Table 1.

5.2. Comparison with other algorithms

We compare the proposed algorithms with three other algorithms: (1) *Optimal lists:* the transmission range lists are obtained by enumerating all available lists and selecting the lists with maximal lifetime; (2) *Maximal range:* the algorithm is presented in [3], in which all nodes in each corona have the same transmission range of the maximal transmission radius and all sensors whose distance to the sink is less than the maximal transmission radius should transmit data directly to the sink; (3) *q-Switch:* authors in [13] propose a non-uniform node distribution strategy to achieve nearly balanced energy depletion in the network, i.e. the number of nodes in coronas increases from corona C_{R-1} to corona C_1 in geometric progression with common ratio $q > 1$, and there are $N_{R-1}/(q-1)$ nodes in corona C_R. In their *q-Switch* routing protocol each sensor use the same maximum transmission range, and the network lifetime can be the maximal by using the protocol in their proposed non-uniform deterministic node distribution.

Fig. 11(a) shows the network lifetime with the three algorithms in uniform node distribution. In particular, parameters related to CETT are as follows: $MAXCOUNT = 200$, $TIMERANGE = 0.5$. We can see that the network lifetime with the three algorithms decreases with the growth of network radius. This is because the data traffic is increasing while the radius is increasing, especially for the inner coronas. Note that the algorithm of CETT performs better than that of *Maximal range*, and approximates to *Optimal lists*. Average residual energy ratios, which is the ratio of energy remained when the network lifetime ends to the sum of initial energy of all the nodes, with the three algorithms in uniform node distribution are shown in Fig. 11(b). We note that while the network radius is increasing the lifetime of network is decreasing, but the total initial energy is increasing, so the residual energy ratio is slowly increasing. We observe that the residual energy ratio of the network with CETT approximates that with *Optimal lists*, and is better than that of the network with *Maximal range* which is about 0.9. This also implies the effectiveness of our algorithm.

Before node deployment, we suppose the node distribution is uniform and obtain a transmission range list by CETT as the initial list for nodes after deployment in non-uniform random node distribution. After deployment, nodes in each corona adjust their transmission range by DETL. Fig. 12 shows the average network lifetime ratio of the lifetime obtained by CETT to that obtained

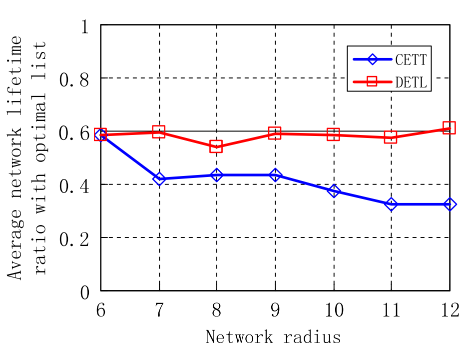
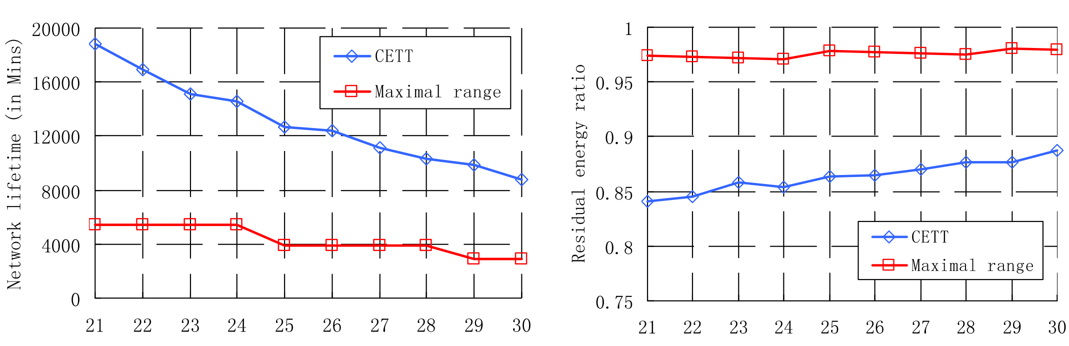


Fig. 12. Average network lifetime ratios with optimal list in non-uniform node distribution.



(a) Network lifetime (b) Residual energy ratio

Fig. 13. Algorithms with more than 20 coronas.

by *Optimal lists*, and the ratio of DETL to *Optimal lists* in a circular sensor network with random node distribution. All the simulation results with different network radiuses are averaged over 100 independent runs. We notice that the ratio obtained by CETT is below 0.6 and is decreasing while network radius is increasing. The ratio obtained by DETL is about 0.6, and the optimizing effect shows more clearly while network radius is increasing. In non-uniform node distribution the list got by CETT is based on the assumption of uniform node distribution, so we need DETL to optimize list for adapting actual node deployment.

The number of coronas for the simulations in Figs. 11 and 12 is less than 12, but in large-scale network it is hard for enumerating all available transmission range lists. So we compare CETT with existing algorithms. In uniform node distribution, we compare CETT with *Maximal range*, and Fig. 13 shows the network lifetime and residual energy ratio of networks with the two algorithms. The parameters related to CETT are as follows: *MAXCOUNT* = 1000, *TIMERANGE* = 0.5. Like the simulation results in Fig. 11, while the network radius is increasing the network lifetime is decreasing and the residual energy ratio is slowly increasing. We notice that CETT performs much better than *Maximal range* in large-scale network. Compared with *Maximal range*, CETT makes the network lifetime be extended more than two times longer. The residual energy ratios of different network radius in *Maximal range* are more than 0.95, and those in CETT are all below 0.9.

We have performed simulations to compare CETT and *q-Switch* in large-scale network with non-uniform deterministic node distribution proposed in [13]. The corona width in [13] is equal to the maximal transmission range, but CETT is based on our proposed corona model with levels. To have a fair comparison, we transform the corona model used in [13] to the corona model with levels. Therefore, we divide the corona whose width is t_x into k sub-coronas. Let each k adjacent sub-coronas from the outer coronas to the inner ones be a group. The number of nodes in each group increases in geometric progression from the outer groups to the inner ones according to the non-uniform node distribution strategy in [13]. Sub-coronas in the same group have the same number of nodes. The parameters related to [13] are as follows: $q = 2$, the number of nodes in each corona in the outmost group is 20. Take the network with 12 coronas as an example, the number of nodes in each corona from C_{12} to C_5 is 20, and the number of nodes in each corona from C_4 to C_1 is 40. The simulation results are shown in Fig. 14. We can see that both the network lifetime and residual energy ratio in CETT approximate to the optimal ones in *q-Switch*. In the other word, the results shows that the performance of the transmission range lists obtain by CETT approximates to the optimal lists in the non-uniform deterministic node distribution, and this can implies the effectiveness of CETT in non-uniform node distribution.

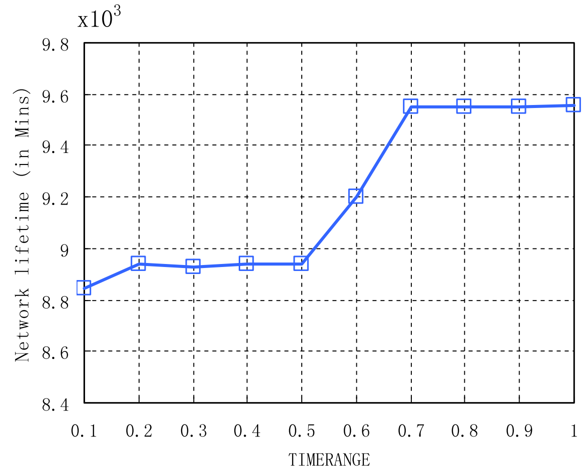


Fig. 15. Network lifetime with different values of *TIMERANGE*.

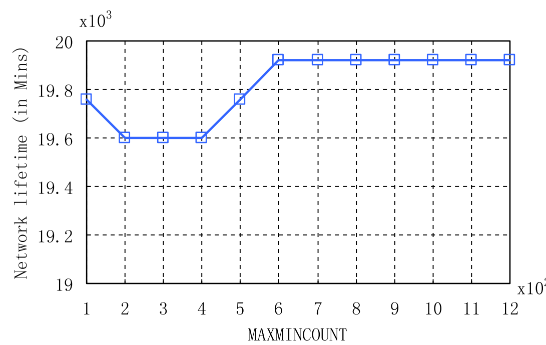
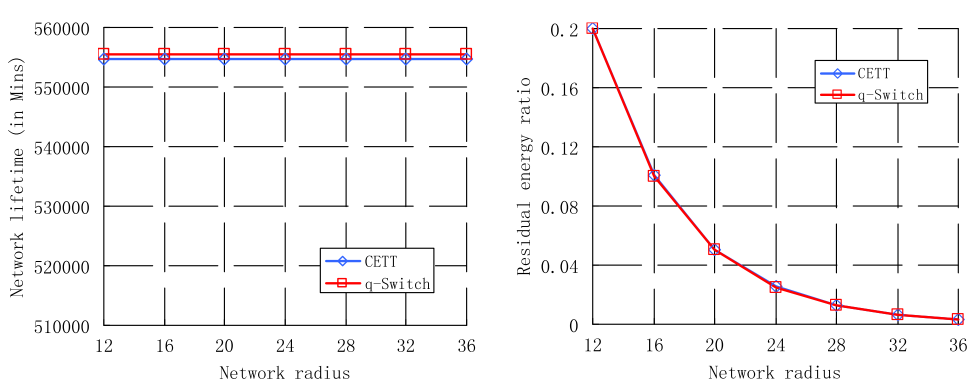


Fig. 16. Network lifetime as a function of *MAXCOUNT*.

5.3. Network lifetime with different parameter values

We illustrate the simulation results of the network lifetime of 30 coronas in uniform node distribution with different values of parameter *TIMERANGE* for algorithm CETT in Fig. 15, while the parameter *MAXCOUNT* is 200. We notice that the network lifetime increases while *TIMERANGE* is increasing. The reason is while *TIMERANGE* is increasing, the algorithm CETT in each loop can store



(a) Network lifetime (b) residual energy ratio

Fig. 14. Algorithms in non-uniform deterministic node distribution.

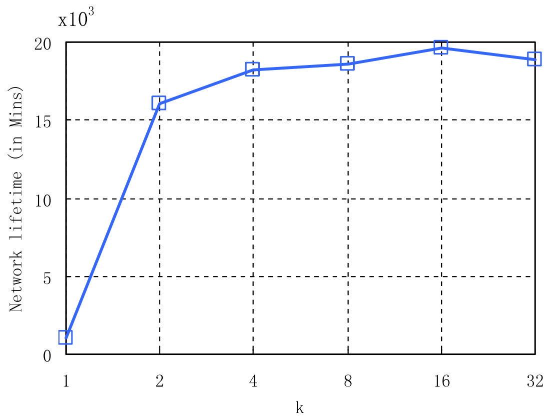


Fig. 17. Network lifetime with different number of transmission range levels.

more trees for the next searching step. But in the searching process of CETT the optimal *temporary tree* may not be the part of final optimal trees, so we notice that the network lifetime is slowly increasing while the value of *TIMERANGE* is from 0.2 to 0.5 and from 0.7 to 1.

Fig. 16 shows the network lifetime of 20 coronas with different values of parameter *MAXCOUNT* in algorithm CETT, while parameter *TIMERANGE* is 0.5. We notice that the network lifetime does not increase while *MAXCOUNT* is increasing. Increasing *MAXCOUNT* can enlarge the range of searching trees, but like parameter *TIMERANGE* this may include some optimal *temporary tree* in the searching process of CETT which may not be a part of whole optimal tree. In Theorem 2 we can see that increasing the parameter *MAXCOUNT* will increase the complexity of CETT, so a right value of *MAXCOUNT* can affect the performance of CETT.

Fig. 17 shows the simulation results with different number of transmission range levels (k), and parameters related to CETT are as follows: $MAXCOUNT = 100$, $TIMERANGE = 0.5$. We simulate 160 coronas, and the width of each corona is 0.15625 m. The maximal transmission range of each sensor node is 5 m. The sensors whose distance to the sink is less than their transmission range should transmit directly to the sink. We notice that the network lifetime is increasing while k is increasing. That is because while k is bigger, each node can have more levels of transmission range to choose. Therefore, the strategy for transmission range assignment can be more flexible, and each corona can adjust its transmission range according to its condition.

6. Conclusions

In this paper, we propose an improved corona model with levels in order to investigate the transmission range assignment strategy used to maximize the lifetime of wireless sensor networks. We conclude that an energy-efficient transmission range of each corona is the decision factor for optimizing the network lifetime after nodes deployment. Then we prove the problem of searching optimal transmission range lists is a multi-objective optimization problem, and that is also NP hard. To address the problem, we propose two algorithms, CETT and DETL in both uniform and non-uniform node distribution. In all simulations, we can see the network lifetime is significantly extended when the two algorithms proposed in this paper are adopted.

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Appendix A

$$E_{trans} = (\beta_1 + \beta_2 d^{\alpha})L \tag{1}$$

$$E_{rec} = \beta_3 L \tag{2}$$

$$d = t_x/k \tag{3}$$

$$m = R/d \tag{4}$$

$$i \times d = i \times (t_x/k) \tag{5}$$

$$1 \leqslant x_i \leqslant k, \quad k = t_x/d, \quad \vec{x} = [x_1, x_2, \ldots, x_m]^T \tag{6}$$

$$S_i = \{j | j - x_j = i, \ j = 1, 2, \ldots, m\} \tag{7}$$

$$\vec{N} = [N_1, N_2, \ldots, N_m]^T \tag{8}$$

$$E_{trans\,i}(\vec{x}) = N_i L[\beta_1 + \beta_2 (x_i d)^{\alpha}] \tag{9}$$

$$N_{rec\,i}(\vec{x}) = \begin{cases} \sum_{j \in S_i} (N_j + N_{rec\,j}), & \text{if } S_i \neq \phi \\ 0, & \text{if } S_i = \phi \end{cases} \tag{10}$$

$$\vec{N}_{rec}(\vec{x}) = [N_{rec\,1}(\vec{x}), N_{rec\,2}(\vec{x}), \ldots, N_{rec\,m}(\vec{x})]^T \tag{11}$$

$$E_{forward\,i}(\vec{x}) = N_{rec\,i}(\vec{x}) L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3] \tag{12}$$

$$E_i(\vec{x}) = E_{trans\,i}(\vec{x}) + E_{forward\,i}(\vec{x}) \tag{13}$$

$$E_i(\vec{x}) = N_i L[\beta_1 + \beta_2 (x_i d)^{\alpha}] + N_{rec\,i}(\vec{x}) L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3] \tag{14}$$

$$W_i(\vec{x}) = \frac{E_i(\vec{x})}{N_i} \tag{15}$$

$$W_i(\vec{x}) = L[\beta_1 + \beta_2 (x_i d)^{\alpha}] + \frac{N_{rec\,i}(\vec{x})}{N_i} L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3] \tag{16}$$

$$\vec{W}(\vec{x}) = [W_1(\vec{x}), W_2(\vec{x}), \ldots, W_m(\vec{x})]^T \tag{17}$$

$$T_i(\vec{x}) = \frac{\varepsilon N_i}{E_i(\vec{x})} \tag{18}$$

$$T_i(\vec{x}) = \frac{\varepsilon N_i}{N_i L[\beta_1 + \beta_2 (x_i d)^{\alpha}] + N_{rec\,i}(\vec{x}) L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3]} \tag{19}$$

$$T_i(\vec{x}) = \frac{\varepsilon}{W_i(\vec{x})} \tag{20}$$

$$\vec{T}(\vec{x}) = [T_1(\vec{x}), T_2(\vec{x}), \ldots, T_m(\vec{x})]^T \tag{21}$$

$$g_i(\vec{x}) \leqslant 0, \quad \vec{x} = [x_1, x_2, \ldots, x_m]^T, \quad i = 1, 2, \ldots, m \tag{22}$$

$$h_i(\vec{x}) = 0, \quad i = 1, 2, \ldots, p \tag{23}$$

$$\vec{f}(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \ldots, f_k(\vec{x})]^T \tag{24}$$

$$V'_j \subseteq V, \quad E'_j \subseteq E \tag{25}$$

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