Mitigating Energy Holes Based on Transmission Range Adjustment in Wireless Sensor Networks

Chao Song [1+], Jiannong Cao[2], Ming Liu[1], Yuan Zheng[2], Haigang Gong[1], Guihai Chen[3]

[1]School of Computer Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

[2]Internet and Mobile Computing Laboratory, Department of Computing, Hong Kong Polytechnic University, Hong Kong, China

[3]State Key Laboratory for Novel Software Technology (Nanjing University), Nanjing 210093, China

+ Corresponding author: E-mail: scdennis@163.com

ABSTRACT

In a wireless sensor network (WSN), the energy hole problem is a key factor which affects the lifetime of the networks. In a WSN with circular multi-hop deployment (modeled as concentric coronas), sensors in one corona have the same transmission range termed as the transmission range of this corona, and different coronas have different transmission ranges, which compose a list termed as transmission range list. Based on our improved corona model with levels, we propose that a right transmission range of each corona is the decision factor for optimizing network lifetime after nodes deployment. We prove that searching optimal transmission range lists is a multi-objective optimization problem (MOP), which is NP hard. We propose a centralized algorithm and a distributed algorithm to build the transmission range list 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 indicate that the network lifetime under our solution approximates to that ensured by the optimal list. Compared with existing algorithms, our solution can make the network lifetime be extended more than two times longer.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols – *Routing protocols.*

General Terms

Algorithms, Performance, Theory

Keywords

WSNs; Energy Hole Problem; MOP; NP hard

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. 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 [6]. 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 ([1], [7], [9], and [12]), 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 the energy hole problem is corona model. In [1] the authors 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* [9][12], and involves partitioning the disk D of radius R into disjoint concentric sets termed *coronas*.

There are three approaches for improving the lifetime of sensor networks with the energy hole problem: i) Assistant approaches, such as deployment assistance, traffic compression and aggregation in [3]. ii) Node distribution strategies, Lian et al. in [7] propose a non-uniform sensor distribution strategy. The density of sensor increases when their distance to the sink decreases. iii) Adjustable transmission range, Jarry and Leone et al. [13] 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 transmission range of sensors into different levels. Nodes in the same corona have the same transmission range level termed as the transmission range of the corona, and different coronas have different transmission ranges, which compose a list termed as transmission range list. We conclude that the transmission ranges assignment of all coronas is the most effectively approach to prolong the network lifetime in uncertain node distribution. We propose two algorithms, which are CETT and DETL, for that assignment adapted in different strategies of node distribution.

Qshine08 July 28-31, 2008, Hong Kong, China

The remainder of the 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 the algorithm proposed in [1] and optimal solutions. Section 6 concludes this paper.

2. RELATED WORK

Li and Mohapatra [3] 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 expected 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, Yu and Sheu [8] propose an algorithm to resolve energy hole problem, which uses mobile sensors to heal energy holes. The cost of these assistant approaches is a lot.

Lian et al. [7] 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.

Wu and Chen [2] 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. But 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.

Olariu and Stojmenović [1] discuss the relationship between network lifetime and 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 out from corona C_i should forward data in corona C_i, and the transmission range in corona C_i is $(r_i\text{-}r_{i-1})$ (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 balancing the energy load among sensors in the network, Jarry and Leone et al. [13] 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 being 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 [11]; (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 [10]). In greedy forwarding, data packets are transmitted to a next-hop which is closest towards the destination; (6) 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.

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 [3], the energy consumption formulas that we use in the analysis and simulations throughout the rest of this paper are as follows:

$$E_{trans} = (\beta_1 + \beta_2 d^{\alpha})l$$

$$E_{rec} = \beta_3 l$$

Where E_{trans} denotes the energy consumption of transmitting and E_{rec} denotes the energy consumption of receiving, l(in bits/sec) is the data rate of each sensor node, and α is 2 or 4, the term d^{α} accounts for the path loss.

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, i.e. $\left\{\frac{1}{k}t_x, \frac{2}{k}t_x, \ldots, \frac{k}{k}t_x\right\}$, and sensors have k levels of transmission range to choose. The unit length of transmission range is denoted by d:

$$d = t_x / k \tag{1}$$

We partition the whole area with radius R into m adjacent concentric parts termed coronas (see Fig.1), which has discussed in [9][12]. The width of each corona is d, therefore,

$$m = R / d \tag{2}$$

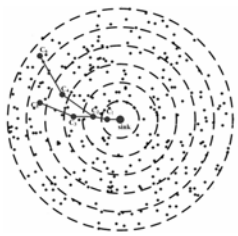


Figure 1. Concentric coronas

3.4 Problem Statement

Let x_i denote the transmission range of corona C_i, so vector $\vec{x} = [x_1, x_2, ..., x_m]^T$ denotes the transmission range list of all m coronas,

$$1 \le x_i \le k \ , \quad k = t_x / d \tag{3}$$

Let S_i denote the set of corona ID for the coronas which directly transmit data to C_i, therefore

$$S_i = \{ j \mid j - x_j = i, j = 1,2,\ldots,m \} \tag{4}$$

Let N_i denote the number of nodes in C_i. So we obtain the N_i vector function

$$\vec{N} = [N_1, N_2, ..., N_m]^T \tag{5}$$

According to the energy formulas in Section 3.2, the total energy consumption of transmitting data generated from C_i per unit time in C_i is:

$$E_{trans\ i}(\vec{x}) = N_i L[\beta_1 + \beta_2 (x_i d)^{\alpha}] \tag{6}$$

Each corona not only transmits data generated by itself but also forwards data generated by outer coronas. Let $N_{rec\ i}(\vec{x})$ 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,

$$N_{rec\ i}(\vec{x}) = \begin{cases} \sum_{j \in S_i} (N_j + N_{rec\ j}), & if\ S_i \ne \phi \\ 0, & if\ S_i = \phi \end{cases} \tag{7}$$

According to (4) and (7), we notice that each $N_{rec\ i}$ is determined by those x whose ID are bigger than i. Then we obtain the number of receiver nodes vector function of m coronas,

$$\vec{N}_{rec}(\vec{x}) = [N_{rec\ 1}(\vec{x}), N_{rec\ 2}(\vec{x}), ..., N_{rec\ m}(\vec{x})]^T \tag{8}$$

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 is:

$$E_{forward\ i}(\vec{x}) = N_{rec\ i}(\vec{x}) L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3] \tag{9}$$

Let $E_i(\vec{x})$ denote the total energy consumption per unit time in C_i, including the energy for transmitting data generated by itself and the energy for forwarding data from outer coronas. Therefore,

$$E_i(\vec{x}) = E_{trans\ i}(\vec{x}) + E_{forward\ i}(\vec{x}) \tag{10}$$

With the help of Eq. (6) and (9), we rewrite Eq. (10) as follows:

$$E_i(\vec{x}) = N_i L[\beta_1 + \beta_2 (x_i d)^{\alpha}] + N_{rec\ i}(\vec{x}) L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3] \tag{11}$$

Let $W_i(\vec{x})$ denote the *per node energy consuming rate* (*ECR*) [3] [1] in C_i. Therefore

$$W_i(\vec{x}) = \frac{E_i(\vec{x})}{N_i} \tag{12}$$

With the help of Eq. (11), we rewrite Eq. (12) as follows:

$$W_i(\vec{x}) = L[\beta_1 + \beta_2 (x_i d)^{\alpha}] + \frac{N_{rec\ i}(\vec{x})}{N_i} L[\beta_1 + \beta_2 (x_i d)^{\alpha} + \beta_3] \tag{13}$$

We obtain the ECR vector function of m coronas:

$$\vec{W}(\vec{x}) = [W_1(\vec{x}), W_2(\vec{x}), ..., W_m(\vec{x})]^T \tag{14}$$

Let $T_i(\vec{x})$ denote the lifetime of C_i. Therefore,

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

With the help of Eq. (11), we rewrite Eq. (15) as follows:

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

So we obtain the relation between *ECR* and lifetime of C_i.

$$T_i(\vec{x}) = \frac{\varepsilon}{W_i(\vec{x})} \tag{17}$$

We obtain the lifetime vector function of m coronas:

$$\vec{T}(\vec{x}) = [T_1(\vec{x}), T_2(\vec{x}), ..., T_m(\vec{x})]^T \tag{18}$$

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

From above formulas, we can see there are three factors affecting $\vec{W}(\vec{x})$ or $\vec{T}(\vec{x})$, namely, $\vec{N}$, $\vec{N}_{rec}(\vec{x})$, and $\vec{x}$. $\vec{N}$ is determined by the node distribution, and as discussed above $\vec{N}_{rec}(\vec{x})$ is affected by $\vec{x}$. So after all nodes have been deployed, there is only one factor contributing to the network lifetime, which is transmission range list $\vec{x}$. In order to maximize lifetime and mitigate energy hole problem, we need to search an optimal transmission range list $\vec{x}$.

Theorem 1 To search optimal transmission range list $\vec{x}$ is NP hard.

Proof: In order to proving theorem 1, we give a definition as follows:

Definition *General Multi-objective Optimization Problem (MOP)* [4]:

Search the vector $\vec{x} = [x_1, x_2, ..., x_m]^T$ which will satisfy the m inequality constraints:

$$g_i(\vec{x}) \le 0 \quad i = 1,2,...,m$$

The p equality constraints

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

And will optimize the vector function

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

where $\vec{x} = [x_1, x_2,..., x_n]^T$ is the vector of decision variables.

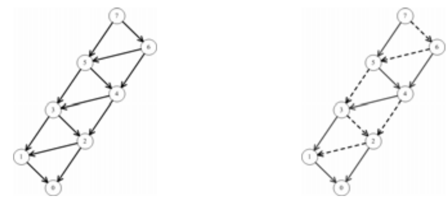
In this section, we can see the problem of maximizing lifetime and mitigating energy hole involves how to maximize $\vec{T}(\vec{x})$ or to minimize $\vec{W}(\vec{x})$, and by Eq.(13)&(16) each $W_i(\vec{x})$ and $T_i(\vec{x})$ is determined by N_i, $N_{rec\ i}(\vec{x})$, and x_i. According to Eq.(7), we notice that each $N_{rec\ i}$ is determined by those x with ID bigger than i. Vector $\vec{x}$ satisfies inequality(4), and according to Eq.(4)(7)(8)(13)(14)(16)(18), we conclude that vector $\vec{x}$ determines not only the vector $\vec{N}_{rec}$ but also $\vec{T}$ and $\vec{W}$. So $\vec{x}$ is the vector of decision variables for optimizing $\vec{T}(\vec{x})$ and $\vec{W}(\vec{x})$, and the optimizing problem is a multi-objective optimization problem. According to [5], MOP is NP hard. Therefore, the problem of searching optimal transmission range list for mitigating energy hole problem is NP hard. ■

4. ALGORITHM FOR ENERGY-EFFICIENT TRANSMISSION RANGE LIST

In this section, the spanning transmission tree will be introduced first, then we will propose two algorithms for generating transmission range list for different node distributions.

4.1 Optimal Spanning Transmission Tree

Each sensor has k transmission range levels to be chosen, which are $1d, 2d, \cdots, kd$, so sensors in one corona have k coronas to be the next hop corona. So we can obtain a directed graph in Fig.2(a), where vertex denotes each corona. And if corona C_i can transmit data to corona C_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 itself. In Section 3.4 we have discussed that in order to maximize 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.2(b)). We call the tree *optimal spanning transmission tree*.



(a) (b)

Figure 2. Spanning transmission tree

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

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.

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, $V = \{C_0, C_1, \dots, C_m\}$.

CETT keeps two sets:

S_i: set of trees with i vertexes whose network lifetime approximate to the optimal trees with i vertexes. $S_i = \{T_0, T_1, T_2 \dots\}$, for each tree, $T_j = (V_j', E_j')$. Obviously, $V_j' \subseteq V$, and $E_j' \subseteq E$. Parameter *MAXCOUNT* denotes the upper limited number of trees in S.

R_i: set of edges which start from vertex C_i. Obviously, the number of edges in R_i is not more than k.

The pseudo-code of CETT is presented is Fig.3. The algorithm is operated as follows:

(1) Set each S_i ($1 \le i \le m$) to empty. Add a tree $T_o(V_0', E_0')$ 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*, and there is the correspondence between one edge and one tree in S_{i-1}. If there are q edges in R_i and p trees in S_{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.

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

Figure 3. Pseudo-code of CETT

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

CETT is a centralized algorithm and is used in uniform node distribution. Before nodes deployment we can obtain the transmission range list of coronas 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.

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. But in non-uniform node distribution, the condition of nodes distribution 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 DETL (Distributed Algorithm for Energy-efficient Transmission Range List).

The algorithm DETL is based on the factors which affect lifetime of each corona. From Eq.(16), we notice that after nodes deployment, the transmission range and received nodes of each corona are the two factors which affect the network lifetime. If a corona has locally maximal ECR value, i.e. it will have locally minimal lifetime, it need adjust its transmission range or received nodes in order to prolong its lifetime.

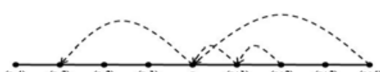


Figure 4. Adjacent coronas

Definition *Adjacent Coronas*: Take corona C_a as an example (see Fig.4), 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.4 as an example, the number of transmission range levels 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 is Fig.5. 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 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;

(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 ends; if not, the transmission range list of the network has been updated, then go to step (2) for the next optimizing loop.

```
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);
```

Figure 5. Pseudo-code of DETL

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

Proof: In DETL, each loop has three steps: i) 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)*; ii) shorten transmission range of corona C_a and select the *group* with minimal *ECR*. The maximal number of transmission range levels is *k*, so the upper limit for computational complexity of this step is *O(k)*. iii) 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 $O(k^2)$. 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

We use a custom simulator in our simulations. For ease of reading we have listed all the parameters in Table 1.

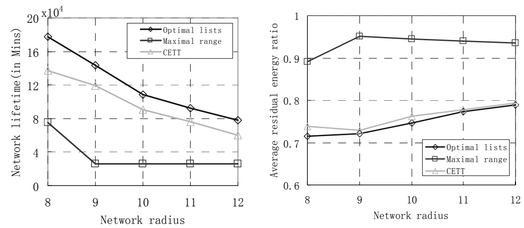
Table 1. Simulation Parameters

Parameter		Value
Initial energy of each node (ε)		50 J
Maximum transmission range (t_x)		20m
Number of transmission range levels (*k*)		4
Length of unit data (*L*)		4×10^2 bits
Unit time		60 seconds
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

5.2 Comparison with Other Algorithms

We compare the proposed algorithms with two other algorithms: (i) *Optimal lists*: the transmission range lists are obtained by enumerating all available lists and selecting the lists with maximal lifetime; (ii) *Maximal range*: the algorithm is presented by [1], 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. In particular, parameters related to CETT are as follows: *MAXCOUNT* = 200, *TIMERANGE* = 0.5.

Fig.6(a) shows the network lifetime with the three algorithms in uniform node distribution. We can see that the network lifetime with the three algorithms decreases with the growth of network radius. Note that the algorithm of CETT performs better than that of *Maximal range*, and is appropriated to the *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.6(b). We observe that the residual energy ratio of the network with CETT is approached to 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.



(a) (b)

Figure 6. Average network lifetime and residual energy ratios of different algorithms

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. After deployment, nodes in each corona adjust their transmission range by DETL. Fig.7 shows the average network lifetime ratio of the lifetime obtained by CETT to that obtained by *optimal lists*, and the ratio of DETL to *optimal lists* in non-uniform node distribution, where the number of nodes in each corona is random, but nodes in each corona are deployed uniformly. 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. The list got by CETT is based on the assumption of uniform node distribution, so in non-uniform node distribution we need DETL to optimize list for adapting actual node deployment.

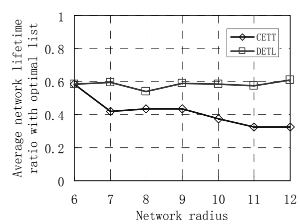
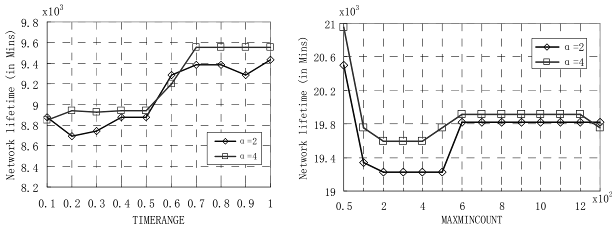


Figure 7. Average network lifetime ratios with optimal list in non-uniform node distribution

5.3 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* in algorithm CETT in Fig.8 (a), 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 more trees for the next searching step. We don't think that locally optimal sub-trees must be the part of whole optimal trees, so in the searching process we need to store more sub-trees.

Fig.8 (b) 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 this may include some sub-trees which are locally optimal but not be a part of whole optimal tree, and these sub-trees can affect the searching results.



(a) (b)

Figure 8. Network lifetimes with different values of TIMERANGE and MAXCOUNT

Fig.9 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 1.5625m. The maximal transmission range of each sensor node is 5m. 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. Because while *k* is bigger, each node can have more levels of transmission range to choose, and the strategy for transmission range can be more flexible, i.e. each corona can adjust its transmission range according to its condition.

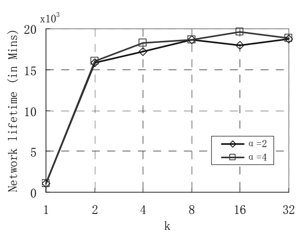


Figure 9. Network lifetime with different *k*

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 network lifetime after nodes deployment. Then we prove the problem of searching an optimal transmission range list 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.

7. ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China under Grants No.60703114, 60573131, 60673154; Hong Kong RGC under CERG grant PolyU 5102/07E, Hong Kong Polytechnic Univ. under ICRG grant G-YF61; the National Grand Fundamental Research 973 Program of China under Grant No.2006CB303000.

8. REFERENCES

[1] S. Olariu and I. Stojmenovic. Design guidelines for maximizing lifetime and avoiding energy holes in sensor networks with uniform distribution and uniform reporting. In Proc. of IEEE INFOCOM, Apr. 2006.

[2] Xiaobing Wu, Guihai Chen, , Sajal K. Das. Avoiding energy holes in wireless sensor networks with nonuniform node distribution. Accepted by IEEE Transactions on Parallel and Distributed System, 2007.

[3] J. Li and P. Mohapatra. Analytical modeling and mitigation techniques for the energy hole problems in sensor networks. Pervasive and Mobile Computing, vol. 3, no. 8, pp. 233-254, 2007.

[4] Carlos A. Coello Coello. Evolutionary multi-objective optimization and its use in finance. In Jean-Philippe Rennard (editor), Handbook of Research on Nature Inspired Computing for Economy and Management, Idea Group Publishing, Hershey, UK, 2006 (accepted).

[5] Gilles Mouzon, Mehmet B. Yildirim. Genetic algorithm to solve a multi-objective scheduling problem. In Proc. the 3rd Aannual GRASP Symposium, Wichita State University, 2007.

[6] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. A survey on sensor networks. IEEE Communications Magazine, vol. 40, no. 8, pp. 102-114, 2002.

[7] J. Lian, K. Naik, and G. Agnew. Data capacity improvement of wireless sensor networks using non-uniform sensor distribution. In International Journal of Distributed Sensor Networks, vol. 2, no. 2, pp. 121 – 145, April-June 2006.

[8] H. Y. Shiue, G. J. Yu, and J. P. Sheu. Energy hole healing protocol for surveillance sensor networks. In Workshop on WASN 2005, Taoyuan, Taiwan.

[9] A. Wadaa, S. Olariu, L. Wilson, K. Jones, and M. Eltoweissy. Training a sensor networks. In MONET, January 2005.

[10] B. Karp and H. T. Kung. GPSR: greedy perimeter stateless routing for wireless networks. In Proc. of MOBICOM, 2000.

[11] C. Bettstetter. On the minimum node degree and connectivity of a wireless multihop network. In Proc. of ACM MobiHoc 2002.

[12] S. Olariu, A. Wadaa, L. Wilson, and M. Eltoweissy. Wireless sensor networks: leveraging the virtual infrastructure. In IEEE Network, 18(4), (2004), 51-56.

[13] A. Jarry, P. Leone, O. Powell, J. Rolim. An optimal data propagation algorithm for maximizing the lifespan of sensor networks. In Proc. of DCOSS, 2006.