

Lifetime-Oriented Optimal Relay Deployment for Three-tier Wireless Sensor Networks

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Abstract: In this paper we address the network deployment problem, in which we aim to maximize the lifetime of a sensor network with minimum total energy consumption by computing the optimal locations of relay nodes with energy consumption rate (ECR) constraint and their assignment relationship with sensor nodes. Firstly a mixed integer programming model with fewer variables is proposed to formulate the relay deployment problem under the constraints of network flows and ECR. Then a shortest path based heuristic algorithm is developed to give the suboptimal solution of the model by constructing an energy efficient three-tiered hierarchical structure consisting of many power-limited sensor nodes, a small set of relays, and multiple BSs. Finally the effectiveness and performance of the proposed strategies are illustrated through simulations. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor networks, Relay deployment, Energy efficiency, Heuristic algorithm, Three-tier structure.

1. Introduction

Wireless sensor networks (WSNs) have been used in a wide range of applications. In the network scenarios, Sensor nodes (SNs), such as sensors and transducers are deployed at strategic positions with fixed sensing and transmit energy, thus they can sustain a fixed length of lifetime. In addition to the deployment of SNs, one or multiple base stations (BSs) is necessary to collect data from the sensing field. However, due to geographic reasons, sometimes the BSs could only be established far away from the sensing field, resulting in very low data reception rate and high transmission energy consumption. To address this problem, a small number of Relay nodes (RNs), as energy-limited as SNs, can be placed between the sensing field and the

BS to forward data packets. Here we consider a large scale multi-hop relay routing from SNs to the BSs. Therefore, the SNs, RNs and BSs build up a three-tiered wireless network in such applications.

There is a renewed interest in research on relayed communication networks [1, 2]. In this paper, we consider three-tiered wireless networks [3, 4] that can be used for a wide range of applications, such as disaster area communications, environment information gathering, etc. Such realistic scenarios share similar characteristics: task-based SNs are distributed on the desired spots for sensing and sending local information; RNs, placed between SNs and the BSs, receive information packets from SNs and forward them to the BSs; the BSs, which is located distant away from the sensing field as in Fig. 1, collects all the data from RNs and processes

the information to make a decision. The RNs are battery powered, are temporally placed to enhance the network performance. As described in [5], the locations of SNs and the BSs are given at the first stage of network deployment. The data rates of SNs are also known, but may be different for different SN depending on the specific type of data sensed, which is reasonable since most of sensor networks gather data from SNs at a predefined period round by round. The total energy consumed by a RN per round of data collection is defined as energy consumption rate (ECR) of a RN [6, 7], which can be given a maximum threshold in case it will deplete energy too faster. If a RN k 's ECR is defines as C_k , its initial energy is defined as e_k , its lifetime $LT_k = e_k/C_k$. Therefore, it is important to consider ECR as a key constraint in the lifetime-oriented deployment.

Relay node deployment for WSNs has been studied in various contexts [8-10]. The problem of adding relays to improve the connectivity of multi-hop wireless networks was firstly addressed in [11]. A set of candidate points are given and the available relays must be deployed in a smaller set of these candidate points. The set of relay locations, are determined based on testing all the candidate points and choosing the combination, which results in higher connectivity measure. Obviously, this scheme is very complex as the network size increases and is an NP-hard problem. Later [12] further extended the problem by formulating it as a semi-definite programming (SDP) optimization problem. Secondly they proposed a routing algorithm, namely, Weighted Minimum Power Routing (WMPR) algorithm to increase the network lifetime by efficient utilization of the deployed relays. On the other hand, there are several works [13, 14] explicitly considering relay node placement to prolong network lifetime, e.g., [13] proposed two deployment strategies, namely, lifetime oriented deployment and hybrid deployment to overcome the BECR problems and [14] stresses on using energy provisioning and formulates the joint problem of energy provisioning and RNs deployment into a mixed-integer nonlinear programming problem (MINLP). Since an MINLP problem is NP-hard in general, a heuristic algorithm is proposed to address this problem.

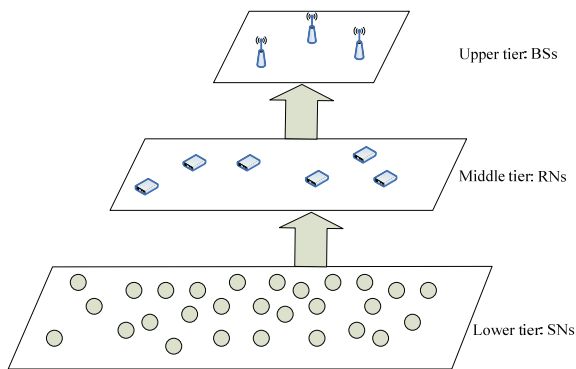


Fig. 1. A three-tiered wireless network.

As we know, most of researches have focused on the deployment problem for one or two tier sensor networks including multiple BSs except [16], which deploys sinks and relays to minimize the deployment cost of BSs and RNs and to guarantee that all sensor nodes in the network are double covered. But the lifetime of WSNs isn't considered in [16]. Furthermore, since relay nodes are responsible for data transmission between a lot of sensor nodes and multi BSs, it is obvious that the energy constraint of RNs has serious impact on the performance of large scale hierarchical sensor networks besides other constraint. Although some works have noticed the importance of relay and BSs energy constraint, to the best of our knowledge, this paper is the first to incorporate the ECR constraint and network traffic flow into deployment problem and gives an efficient solution.

The main contributions of this paper are as follows: first, we present a three-tiered wireless network architecture in which RNs are added to overcome the long distance communications between the SNs and the BSs layer and the RNs are energy constrained; secondly, a mixed linear programming model is defined and analyzed for relay node deployment and assignment; thirdly, an efficient yet practical solution is proposed using heuristic algorithms named by RDFMIP; finally, the simulation results are presented to demonstrate that the RDFMIP algorithm outperforms other relay placement schemes.

2. Problem Formulation

We define the deployment problem more precisely as follows: Given a complete graph $G=(N, A)$, where $N=\{1, \dots, n\}$ is the node set and $A=N \times N$ is the set of directed arcs. N consists of three subset N_s (SNs set), N_r (candidate relay location set) and N_b (BSs set). There is a network flow of f_{ij} associated with each pair of nodes $(i, j) \in A$. f_{ij} is the volume of the associated network flow which can be estimated and controlled initially. We do not assume that $f_{ij} = f_{ji}$ since the sensor reporting flow is not the same as the query flow. Also we give E_{ij} the transmission energy of sending one unit of data directly from i to j . E_{ij} is usually proportional to the distance between i and j and therefore generally can be represented as Euclidean distance multiplied by traffic according to the energy model in [16]. Each flow in multi-hop has three separate components: collection (sensor node-to-relay), transfer (inter-relay), and uplink (relay-to-BS). Each component has the respective per unit energy cost coefficient of $\delta_1, \delta_2, \delta_3$. Thus the cost per unit flow for gathering is $\delta_1 E_{ik}$, where i is a sensor node and k is a relay. Similarly inter-relay transfer has cost $\delta_2 E_{kl}$, where k, l are both relays and uplink has cost of $\delta_3 E_{lj}$ where l is a relay and j is a BS node. Usually, due to the inter-relay and relay-BS transfer

efficiencies, $\delta_2 < 1$ and $\delta_3 < 1$ is a transfer discount factor, while $\delta_1 = 1$.

This paper mainly studies the constrained relay deployment problem where the RNs can only be placed at a subset of candidate locations whose number is defined as P . Now we present the formulation of relay deployment (RDF) as below.

$$\min \sum_i \sum_j \sum_k \sum_m f_{ij} E_{ijkm} \varphi_{ijkm}, \quad (1)$$

Subject to:

$$\sum_k \sum_m \varphi_{ijkm} = 1 \quad \forall i \in N_s, \forall m, k \in N_r, \forall j \in N_b, \quad (2)$$

$$\sum_m \varphi_{ijkm} \leq X_k \quad \forall i \in N_s, \forall m, k \in N_r, \forall j \in N_b, \quad (3)$$

$$\sum_k \varphi_{ijkm} \leq X_m \quad \forall i \in N_s, \forall m, k \in N_r, \forall j \in N_b, \quad (4)$$

$$\sum_i \sum_j f_{ij} \sum_m E_{ijkm} \varphi_{ijkm} \leq C_k X_k \quad \forall k \in N_r, \quad (5)$$

$$X_k \in \{0,1\} \quad \forall k \in N, \quad (6)$$

where the variable φ_{ijkm} denotes the fraction of flow that transmits from node i to BS node j via relay located at k and m , N_s is the initial sensor node set and N_b is the BS set, both of them are subset of N . the variable X_k is defined by

$$X_k = \begin{cases} 1 & \text{if location } k \text{ is placed a relay} \\ 0 & \text{otherwise} \end{cases}, \quad (7)$$

The per unit transmission energy cost of φ_{ijkm} flow is defined by

$$E_{ijkm} = \delta_1 E_{ik} + \delta_2 E_{km} + \delta_3 E_{mj}, \quad (8)$$

where c_k is the energy consumption rate threshold (ECRT) of node k according to its battery level. By ECRT, we try to guarantee the lifetime of each relay. In the above formulation, Eq. (2) ensures that the total flow (f_{ij}) from i to j is transferred, while Eq. (3) and Eq. (4) guarantee that transfers only occur via relays. Eq. (5) ensures that the ECR constraint is being adhered to. With the deployment problem the relays are capacitated. Thus the model not only decides on the optimal location of the relays and the allocation of sensor nodes to relays.

The deployment problem can be furthermore formulated as a MILP (Mixed Integer Linear Programming) named by RDFMIP. The variables in our formulations are: p as the number of RNs to be placed as relays; f_k the flow from node i to relay k ;

f_{km} the flow from node i via relays k and m ; f_{mj} the flow from node i to BS j via relay m ;

$$\min \sum_i \left[\delta_1 \sum_k E_{ik} f_k^i + \delta_2 \sum_K \sum_M E_{km} f_{km}^i + \delta_3 \sum_m \sum_j E_{mj} f_{mj}^i \right], \quad (9)$$

Subject to:

$$\sum_k f_k^i = \sum_j f_{ij} \quad \forall i, \quad (10)$$

$$\sum_m f_{mj}^i = f_{ij} \quad \forall i, j, \quad (11)$$

$$\sum_m f_{km}^i + \sum_j f_{mj}^i - f_k^i = 0, \quad (12)$$

$$f_k^i \leq \sum_j f_{ij} X_k \quad \forall i, k, \quad (13)$$

$$\sum_i f_{mj}^i \leq \sum_i f_{ij} X_m \quad \forall m, j, \quad (14)$$

$$\sum_i E_{ik} f_{ik} \leq C_k X_k \quad \forall k, \quad (15)$$

$$\sum_k X_k = p_r, \quad (16)$$

$$f_{mj}^i, f_{km}^i, f_{ik} \geq 0, X_k \in \{0,1\} \quad \forall i, j, k, m, \quad (17)$$

Eq. (10) specifies the network traffic from i equals the traffic to BSs, Eq. (11) specifies the traffic from node i to BS j is transferred by relays. Eq. (12) represents the divergence equation of network flow from node i . Eq. (13) and Eq. (14) ensures no flow travels directly between SNs. Eq. (15) ensures that the energy constraints are being satisfied. Eq. (16) specifies the maximal number of relays could be placed, defined as p_r , this equation can be removed according to the need of real application.

Note that this formulation has substantially fewer variables than a formulation of RDF. RDF shows usage of $O(n^4)$ variables, whilst RDFMIP uses $O(n^3)$ variables. Thus we hope to solve much larger problems with our formulation.

3. Algorithm Description

Here we develop a heuristic algorithm to solve RDFMIP. This is motivated by the knowledge that, if there is no energy constraint on the relays, the shortest path algorithm can provide a good basis for

relay deployment problems (see [12, 17]). Given a set of relays without energy constraint, the shortest path algorithm such as Floyd will optimally place relays to sensor networks. However, since we have relay constraints for the RDFMIP, we can develop a heuristic method for relay selection, the shortest path procedure and a rerouting procedure for flow that violates energy constraints. We set off with an initial placement of relays. To this, we apply the shortest path algorithm. If the energy and flow constraints are satisfied at any stage, we have a feasible solution for the RDFMIP and we record its value. If not, we reroute excess flow using a heuristic procedure.

Since the above approach is biased by our initial placement of RNs, we attempt a greedy swap procedure to investigate if other potential locations (in the neighborhood of the placed RN set) yield better solutions. We repeat this process until some termination criteria are satisfied. Furthermore, it is possible to use an exact multicommodity flow approach to perform the allocation of candidate locations to the placed RNs in an efficient manner. However, since this is a computationally expensive procedure, we only apply it to the fixed number of best RN solutions (defined as l in our algorithm) found during the heuristic approach.

We start by creating an ordered list L , which is a permutation of all the candidate locations. We refer to the locations in L as candidate RN. Initially the candidates are ranked in descending order of $ECRT_k$ for each location $k \in N_r$. We refer to the k^{th} element of L as $L(k)$ for each $k \in N_r$. Define $S(L, s) = \{L(i) : i \leq s\}$ where $s \in N_r$. Initially the first s locations are taken as trial locations. Trial locations are locations that are chosen to place RNs in a given iteration of the heuristic. Suppose that at some iteration of the heuristic $L = \{\dots\}$ and $s=3$, then $S(L, s) = \{1, 2, 3\}$, i.e. 1, 2 and 3 are the trial locations. We also define $v(S)$ to be the objective value calculated by the heuristic (this might not necessarily be the true objective value) corresponding to $S = S(L, s)$.

The algorithm below gives a description of the heuristic. The number of candidate locations for relay placement is denoted as p . Since the number p is very large, we keep track of the l best solutions found by the algorithm ($l=6$ in our simulation), denoted as $\{S_k^*\}_l$ where $S_k^* = (L_k^*, s_k)$, L_k^* is the list corresponding to the k^{th} best solution and s_k is the number of relay locations in the set. The main loop performs a descent in which relay locations are swapped one at a time. In each iteration v^* is the best solution found so far. The final two procedures of the heuristic perform a search in the vicinity of the l best solutions and evaluate the exact objective value for the l best sets of locations found.

```

Main RDFMIP
begin
  initialize  $L$  to be RNs in descending order of  $ECRT_k$ 
   $L_o = L$ 
  for ( $i=0$  to  $l-1$ ) do

```

```

     $z^* = \infty$ 
    if ( $i=l-1$ )
       $L = L_o$ 
    for ( $g=1$  to  $p$ ) do //swap every node with the  $g^{\text{th}}$ 
    relay
       $\{S_k^*\}_l, L, v^* = \text{Evaluation}(g, l)$ 
      repeat //add a relay until no improvements
         $v = v^*$ 
         $p = p+1$ 
         $\{S_k^*\}_l, L, v^* = \text{Evaluation}(g, l)$ 
      while ( $v < v^*$ )
        if ( $i=0$ ) then
           $L = L_o$ 
           $L = \text{swap}(0)$ 
           $\{S_k^*\}_l = \text{Minim}()$ 
           $\text{Multicommodity}(\{S_k^*\}_l)$ 
        end

```

The following paragraphs describe the procedures that are referred to above.

3.1. Evaluation of Relays Selection

This function takes locations in $S(L, s)$, uses them as trial locations and evaluates the location selection using a heuristic. Every other location is then swapped with the trial location $L(g)$ and the resulting selection of locations is evaluated using the same heuristic. The relay location receiving the flow from i to j is stored in r_{ij} . The shortest path distance from i to j is given by d_{ij} . All flow is initially routed along the shortest paths irrespective of relay constraints. The flows are then adjusted by rerouting some of the flow away from RNs exceeding their energy constraint, to obtain a feasible solution. It is important to note that we always ensure that there are no duplicate solutions in the set of l best solutions. This is important for the effectiveness of The *Minim* and the *Multicommodity* procedure.

```

 $\{S_k^*\}_l, L, v^* = \text{Evaluation}(g, l)$ 
begin
  repeat  $p+1-l$  times
     $d, s = \text{CreateStruct}(p, L)$ 
     $v = \sum_i \sum_j d_{ij}^t f_{ij}$ 
    if (a relay has exceeded it's ECRT
    constraint) then
       $v = \text{Rerouting}(l, L, r, d)$ 
      if ( $v^* > v$ ) then  $v^* = v$ 
      if ( $v < v(S_k^*)_l$ ) then update  $\{S_k^*\}_l$ 
       $L = \text{Swap } g, l+1$ 
       $L = \text{SwapSeq } l$ 
    return

```

3.2. Construction of Three-tier Network Structure

Given a set of nodes, this procedure creates a network with three layers: sensor nodes in the bottom

layer, relay nodes in the centre layer and BS nodes in the top layer. The arc costs in this network are given by the collection (layer 1 to layer 2), transfer (layer 2 to layer 2) and uplink (layer 2 to layer 3) costs. It then uses the Floyd Shortest Path algorithm to assign nodes to RNs irrespective of constraints. r_{ij} represents the successor of node i , that is the RN which transfers the traffic from i to j . The shortest distances from i to j are returned in d_{ij} . Also note that this algorithm has complexity $O(pn^2)$, where p is the number of trial RNs.

3.3. Reroute of Network Flow

Rerouting is performed by removing RNs from the network that have reached their ECRT constraint and rerouting the excess flow via RNs that have not yet reached their constraint. We use H to denote the set of RNs that have not yet reached their ECRT constraint. The excess flow is rerouted via the cheapest alternative in H (Note that it is possible for this alternative path to include two new relay locations that was not used before). However this procedure does not guarantee optimality, since the flow to be rerouted is chosen arbitrarily. Optimal solutions could be obtained by solving a linear program which is too computationally expensive to perform for each iteration of the heuristic. Note however that we do solve the flow problem exactly for the l best sets. It should also be noted that if the energy consumption rate of the RN placed in the location exceeds its constraint then it is never selected as a potential location since such a location is unlikely to be in the optimal solution. We use μ_k to denote the energy consumption for collecting data flow by RN located at location k .

```

v=Rerouting(l, L, r, d)
begin
 $\mu_k = \sum_i \sum_{j:r_{ij}=k} d_{ik}^2 f_{ij}$ 
 $H = \{k : \mu_k < C_k\}$ 
while ( $\exists k$  s.t.  $\mu_k > C_k$ ) do
  for  $(i, j) \in N \times N$ 
    if ( $\mu_{r_{ij}} > C_{r_{ij}}$ ) then
       $k = \text{argmin}_{t \in H} (c_{it} + d_{ij})$ 
 $\phi = \min\{\mu_{r_{ij}} - C_{r_{ij}}, C_k - \mu_k\}$ 
       $v = v + \phi$ 
       $\mu_{r_{ij}} = \mu_{r_{ij}} - \phi$ 
       $\mu_k = \mu_k + \phi$ 
      if ( $\mu_k \geq C_k$ ) then  $H = H - \{k\}$ 
return

```

3.4. Procedure of Swap

This process simply *swap* the node $L(i)$ with node $L(j)$. So if $L=\{1, 2, 3, 4, 5, 6, 7, 8\}$ after one

application of *Swap*(1,5) we would now have $L=\{5, 2, 3, 4, 1, 6, 7, 8\}$.

3.5. Procedure of SwapSeq

```

A SwapSeq is the following sequence of Swaps:
 $L = \text{SwapSeq } l$ 
begin
  for  $(k=1 \text{ to } p-l-1)$  do
     $L = \text{Swap } (l+k, l+k+1)$ 
return;

```

3.6. Procedure of Minim

The *minim* finds l local minima by using a descent procedure starting from the l best solutions. The final solutions returned by the procedure are minimal with respect to the neighborhood operation of swapping any selected RN location with any non-RN location. For solution S_l^* we accept any improvement, while for other solutions $S_2^*, \dots, S_l^*$ we use a steepest descent method. Note that the algorithm never searches the same neighborhood twice as $\{S_k^*\}_l$ are always different and because our implementation includes a check to skip any of these if they were already searched in a previous iteration of the repeat loop.

```

 $\{S_k^*\}_l = \text{Minim}()$ 
begin
  repeat
     $M = l$ 
    for  $(j=1 \text{ to } M)$  do
       $L_j = L_j^*$ 
      For  $(l=L_j-1 \text{ to } l_j^*+1)$  do
        if  $(j=1)$  then  $L=L_j$ 
        for  $(g=l \text{ to } 1)$  do
          if  $(j>1)$  then  $L=L_j$ 
           $\{S_k^*\}_l, L, v = \text{Evaluation}(g, l)$ 
      Until no improvement in  $\{S_k^*\}_l$ 
  return

```

3.7. Procedure of Multicommodity

This procedure takes the l best solutions found and solves the Linear Programming formulation given by RDFMIP with the S_k accordingly for each solution. That is we solve the LP for each of the l solutions using the relay locations that were found for each corresponding solution. The linear programs can be solved by CPLEX.

4. Experiment

The simulations were performed in NS-2 and the radio model used by our simulations can be seen in [18], in which the energy consumption of unit data

transmission of between a distance of d meters is given by

$$E_t = E_{elec} + E_{amp}d^4,$$

where E_{elec} and E_{amp} are the energy consumed by the electronic components of the sensor and the amplifier circuit, respectively. Meanwhile, the receiving energy consumption is given by

$$E_r = E_{elec}$$

In the simulations, E_{elec} and E_{amp} were configured as 60 nJ/bit and 12 pJ/bit/m², respectively. In addition, the total energy bound of each sensor and relay was configured as 30 J and 280 J, respectively. The bandwidth of wireless channel was specified as 1 Mbps, and the length of reporting packet was configured to be 512 bit. The data reporting rates of SNs are generated according to uniform distribution in [1,3] packets per simulation step. The transmission and sensing radius of relay nodes and sensor nodes were specified as 20 m, and the energy consumed in performing each sensing action was specified as 5×10^{-3} J. The sensors were deployed according to Gaussian distribution in a square field measuring 6000 $\times$ 6000m and only die due to energy completion. We pick five of them as BSs by using k-means clustering algorithm [19]. Each sensor sends data to its physically closest BS. The candidate locations for relay placement are divided into various numbers of grids ranging from 500 to 1500. Each relay allocates a certain fraction of their energy capacity as ECR threshold for relaying traffic. This ECR threshold is the same for all relays in our simulation. We call this parameter C_q .

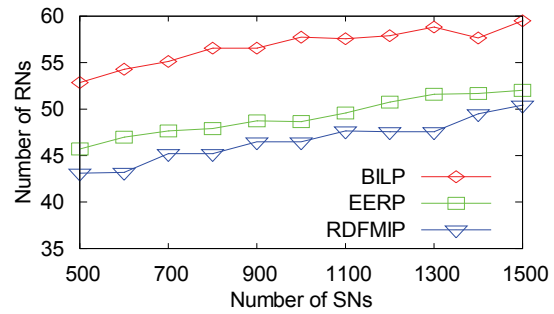
4.1. Impact of RNs Number

In the first simulation, we remove the constraint of equation (16) to compute the minimal number of RNs needed to minimize energy consumption of networks, which is important to decide the relay deployment cost of different algorithms.

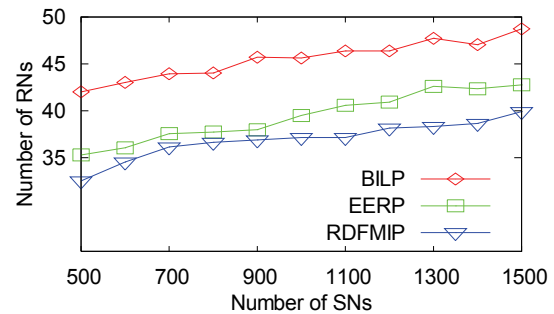
The performance of RDFMIP is compared to the following two methods; the first algorithm adopted a Binary Integer Linear Programming (BILP) model to optimally locate sufficient RNs to achieve minimum energy consumption in WSNs, which is similar as [20] but removing signal to noise ratio constraint. This algorithm aims to determine optimal locations to install RNs in the target sensing field and determine optimal route to forward sensing data packet from SNs directly to SNs or indirectly via RNs without considering the network flow and ECR constraints. The second algorithm formulates the relay deployment problem as a nonlinear programming problem and then propose an approximation algorithm to compute the optimal positions of RNs with the optimal energy allocated to them such that lifetime of sensor network can be maintained by

minimum energy [21] named by EERP algorithm. Both of the methods do not consider the optimization for multiple BSs.

Fig. 2 shows that the number of RNs increases as the number of SNs number when $C_q = 0.02\%$ and $C_q = 0.05\%$. In the BILP algorithm, in order to install RNs, the sufficient number and the suitable locations are selected based on the distribution of SNs in the sensing field. In some area where SNs are out of transmission range from other nodes, RNs is needed to receive and forward the packet to BS. Thus, the BILP algorithm needs a larger number of relay nodes than either the other two algorithms. In the EERP algorithm, the number of relay nodes increases proportional to that of SNs since the positions of the relays are determined regularly. The number of relays deployed in the RDFMIP algorithm is slightly less than that in the EERP algorithm since the grid points at which RNs are selected to cover the maximum number of sensor nodes and optimized for multiple BSs.



(a) $C_q = 0.02\%$



(b) $C_q = 0.05\%$

Fig. 2. Variation of RNs number with SNs changes.

Fig. 3 shows how the number of RNs in the middle tier network changes with different candidate relay locations. We see that the quality of the solution improves with the initial number of candidate locations that are considered. At first there is a significant improvement, as the number of candidate locations is increased (e.g. from 500 to 1000 to 2000). However, as the number of candidate locations increases beyond a certain value, it does not yield any significant improvements in the solution. This can be

shown in Fig. 3, where the curves smooth after the initial steep decrease in the number of nodes required for the transfer. For a given number of possible initial locations, the number of RNs required to transfer the data of SNs increases with the number of SNs.

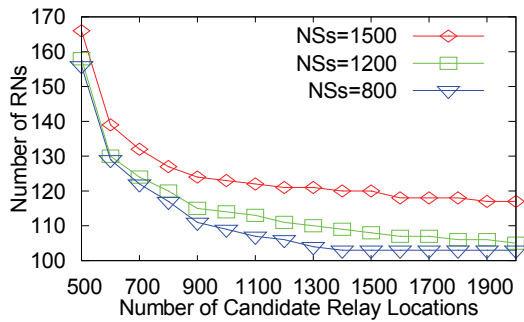


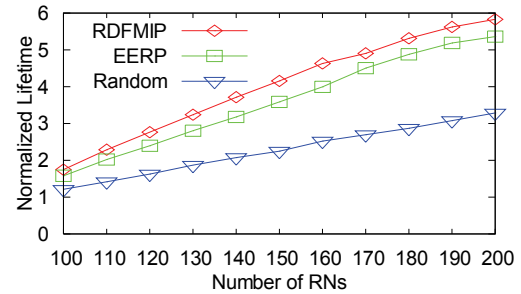
Fig. 3. Variation of the number of RNs with the number of candidate locations.

From the results we can see that different number of RNs has some impacts on the performance comparison, there exists a minimum number of RNs to guarantee the sensor networks working well. The required minimum number of RNs varies with the given number of SNs, their candidate locations and data rates, and the used deployment strategy. During our simulation analysis, we find that the RDFMIP algorithm always needs a lower minimum number of RNs than the other two schemes. We thus computer an upper bound on the minimum number of RNs required by RDFMIP algorithm for a given SNs number and their locations. We compute this bound for each simulation case and use the results as the default number of RNs in the remaining of this section.

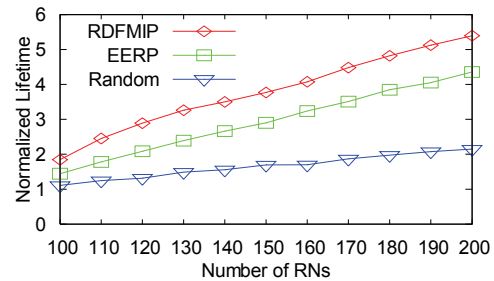
To investigate how these three algorithms perform in the case of the number of RNs is comparable to the number of SNs, we temporarily extend the communication range constraint of RNs ranged from 20 m to 50 m. The results are shown in Fig. 4. It illustrates the simulation results for different network size with different number of extra RNs. Specifically, X-axis represents the number of RNs that should be placed in the network, and Y-axis denotes the normalized network lifetime (normalized by the results of no relay deployment). The two curves show the achieved network lifetime by applying the three different relay deployment schemes.

Fig. 4(a) shows the results of the network lifetime with different number of RNs when 2000 SNs are deployed. From these results we can see that if we can place RNs in an energy-efficient way, significant gain can be achieved even when only a small number of RNs are deployed. For example, when only 10 % of relay nodes are deployed, the network lifetime can be further extended more than 70 % by applying the RDFMIP heuristic deployment method. We can also see that if we deploy nodes randomly, the gain is very

minor. For example, the network lifetime increased only 50 % if we deploy them randomly even 1000 RNs are deployed. On the other hand, the network lifetime can be 3 times if the 1000 relays are deployed in an efficient way, as demonstrated by the figure.



(a) SNs=2000



(b) SNs=1000

Fig. 4. Normalized network lifetime with different number of RNs.

Fig. 4(b) shows the results for a smaller network size with SNs number is 1000. From these results we can see that significant network lifetime improvement still can be achieved by relay deployment. For example, when only 10 % of additional relays are placed, the network lifetime can be improved by more than 40 %. If we compare the results in Fig. 4(a) and Fig. 4(b), we can see that more network lifetime improvement can be achieved in a larger network, where 10 % additional relays can bring 70 % lifetime improvement. This is because in larger network, the energy hole around the BS is more significant. This also suggests that the proposed algorithm can effectively alleviate the energy whole problem.

It can be seen that there are some small fluctuations in the Fig. 4. This is because as the number of RNs increases, the marginal effects of the network topology vary and that only a small number of RNs can be used to improve the network performance significantly. However, the curve trends of RDFMIP and EERP are still relatively stable with the performance improvement only slightly decreased. Also, in Figs. 4 and 5, while RDFMIP performs roughly up to 5 times of without relay, EERP raises

the gain up to 3 times. This demonstrates the importance of considering the traffic patterns during node deployment stages. Furthermore, the performance of RDFMIP is higher than EERP since the ECR constraint can guarantee RDFMIP tries to find the more eligible locations for relay deployment.

Fig. 5 shows the results of the normalized remaining energy (normalized by the results of RDFMIP deployment) with different number of RNs. We can see that the RDFMIP and EERP solution have much less total remaining energy than BILP, since the energy consumption of the former two algorithms is more balanced by assigning more RNs to the SNs with higher traffic flows. This also explains that the remaining energy of BILP increases much faster than the other two solutions. It is because BILP deploy RNs without considering the impact of network flow.

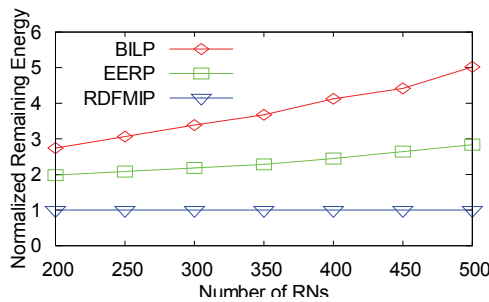


Fig. 5. Normalized remaining energy with different number of RNs.

In Fig. 6, the energy consumption by RNs in three algorithms is compared with simulation steps. The energy cost spent by relay nodes per step in RDFMIP is much lower than that in BILP, and is about the same as that in EERP. Because in BILP algorithm relay nodes send their data to the BS via 1-hop or 2-hop communication, the energy cost is much higher. In OERD and EERP, relay nodes are permitted to send their data to the BS via multi-hop relay communication. By this way a large number of energy consumption is decreased in relay nodes. In EERP and RDFMIP, the amount of energy consumption spent by relay nodes in RDFMIP is slighter smaller than that of EERP in each step due to its optimization of three-tier network.

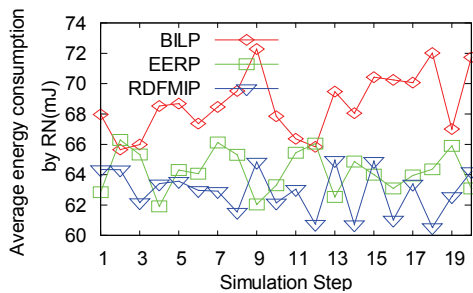


Fig. 6. Average energy consumption by RNs with simulation step.

4.2. Scalability with Number of SNs

We next investigate how our solution performs with different number of SNs. Fig. 7 shows the results of the network lifetime with different number of SNs. It is clear to see that our RDFMIP scheme performs much better than the other solutions. As the number of SNs increases, the lifetime of both EERP and RDFMIP increase faster and is much higher than that of BILP. From the results we can see that the lifetime of BILP first increases and then decreases slightly. We analyses that the reason may be that the energy whole phenomenon [22] becomes more serious when the number of SNs increases. The energy whole problem can result in a case that the RNs close to the BS are depleted while most of other RNs still have most of the energy. As the number of SNs increases, more traffic will accumulate close to the BS. This reduces the lifetime seriously if the deployment is not aware of the traffic accumulations such as the BILP scheme. On the other hand, EERP and our solution successfully solve this problem by using algorithms deploying more RNs close to the BS. In addition, RDFMIP algorithm performs better than EERP since it assigns the RNs to SNs according to the network flow and its energy consumption rate.

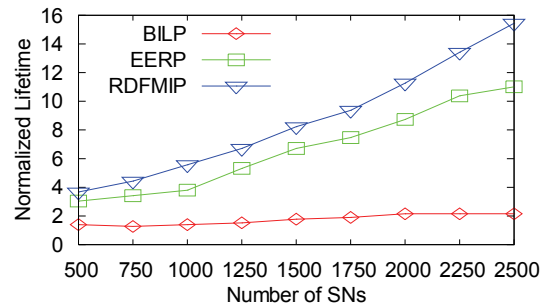


Fig. 7. Normalized network lifetime with different number of SNs

Fig. 8 shows the results of the total remaining energy with different number of SNs. As the number of SNs increases, all the three schemes show a similar trend and are not very sensitive to the number of SNs. As we expected, the RDFMIP solution has the lowest remaining energy, which is followed by EERP solution. BILP performs worse due to without considering the impact of network flow in its relay deployment model.

Fig. 9 compares the average transmission energy of RDFMIP scheme to that of the other two schemes. As the number of SNs increases, the average transmission energy decreases. Compared to the other schemes, the additional transmission energy required in our scheme decreases significantly as the number of SNs increases (see the lower plot in Fig. 9 which shows the difference in average transmission energy).

Fig. 10 plots the variance of the remaining energy of the sensors after the lifetime expires. The variance

of the remaining energy in RDFMIP scheme is much smaller than the other two schemes, which indicates that the remaining energy of RDFMIP scheme reaches almost uniform distribution. This result satisfies the requirement of sensor networks since we balance the network flow among the RNs by rerouting method. On the other hand, higher variance of the other two deployment schemes indicates that the remaining energy of the sensors fluctuate seriously, which results in low energy efficiency.

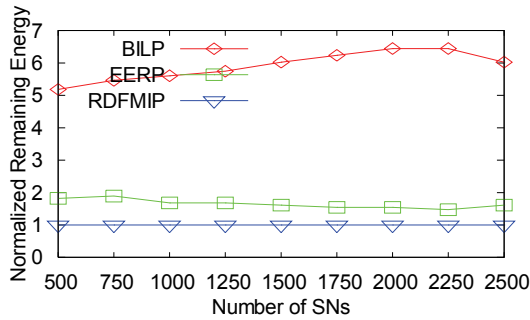


Fig. 8. Normalized remaining energy with different number of SNs.

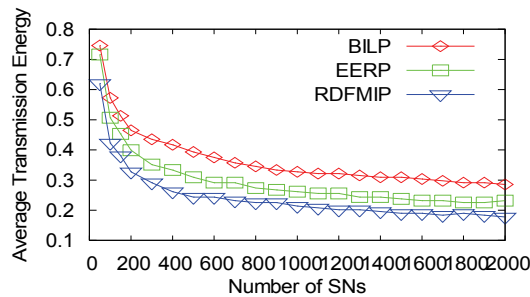


Fig. 9. Comparison of the average transmission energy with different number of SNs.

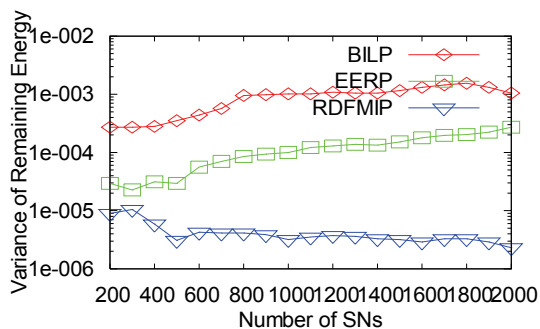


Fig. 10. The variance of the remaining energy.

We also vary the number of candidate relay locations in the networks to show whether it has an impact on the computation complexity of RDFMIP. As depicted in Fig. 11 for the 3000-SNs networks,

the run time increases significantly when the number of candidate relays increases.

Fig. 12 shows the normalized lifetime in the network with different number of BSs (normalized by lifetime of the network deployed by BILP with one BS). Results are averaged over 50 simulation runs. Simulation results depict that the lifetime increases almost linearly as the number of BSs increase. Comparing the results when the number of BS is 7, we can see that our proposed RDFMIP algorithm can increase the lifetime by 100 % and 35 % compared to algorithms BILP and EERP, respectively.

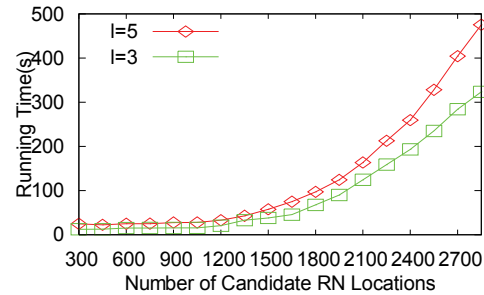


Fig. 11. Running time of RDFMIP with different l .

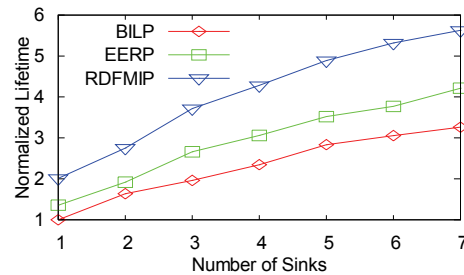


Fig. 12. Lifetime with different number of BSs.

5. Conclusions

This paper proposes a novel relay nodes deployment algorithm under the constraints of network flow and energy level for three tier wireless sensor network. We assume that the positions of SNs can be predetermined by the sensor placement algorithm of the application and the data reporting traffic patterns can be estimated too. The problem is then to select the optimal locations of RNs together with the optimal assignment of sensor-relay so that the energy consumption of the network can be minimized under the energy constraint of relays. In our heuristic algorithm that was used, the maximum sensor assigned to the minimum number of relays performs better in term of the energy consumption with respect to network size. The computation complexity of RDFMIP is analyzed mathematically and the performance is validated through simulation. The simulation results have showed its performance

advantage compared with traditional algorithms. RDFMIP algorithm not only minimizes the energy consumption of sensor networks, but also save the number of RNs.

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References

- [1]. S. Lee and M. Younis, Optimized Relay Placement to Federate Segments in Wireless Sensor Networks, *IEEE Journal on Selected area in Communication*, Vol. 28, Issue 5, 2010, pp. 742-752.
- [2]. A. Bhattacharya, A. Kumar, Delay constrained optimal relay placement for planned wireless sensor networks, in *Proceeding of the 18th International Workshop on Quality of Service (IWQoS)*, 9-11 October, 2010, pp. 622-632.
- [3]. M. Soltan, M. Maleki, and M. Pedram, Lifetime-Aware Hierarchical Wireless Sensor Network Architecture with Mobile Overlays, in *Proceedings of the IEEE Radio and Wireless Symposium*, 25-28 February 2007, pp. 325-328.
- [4]. C. Rahul Shah, R. Sumit, J. Sushant, B. Waylon, Data MULEs: modeling and analysis of a three-tier architecture for sparse sensor networks, *Ad Hoc Networks*, Vol. 1, Issue 2, 2003, pp. 215-233.
- [5]. W. Feng, W. Dan and L. Jiangchuan, Traffic-Aware Relay Node Deployment: Maximizing Lifetime for Data Collection Wireless Sensor Networks, *IEEE Transactions on Parallel and Distributed Systems*, Vol. 22, Issue 8, 2011, pp. 1415-1423.
- [6]. C. Subramanian, G. Lapilli, F. Kreit, J. P. Pinelli, I. Kostanic, Experimental and Computational Performance Analysis of a Multi-Sensor Wireless Network System for Hurricane Monitoring, *Sensors & Transducers*, Vol. 10, Special Issue, 2011, pp. 206-244.
- [7]. U. Datta, P. K. Sahu, Sumit Kundu, Outage and Energy Performance of Layered CDMA Wireless Sensor Network with Space Diversity, *Sensors & Transducers*, Vol. 130, Issue 7, 2011, pp. 23-37.
- [8]. X. F. Han, X. Cao, E. L. Lloyd, Fault-Tolerant Relay Node Placement in Heterogeneous Wireless Sensor Networks, *IEEE Transactions on Mobile Computing*, Vol. 9, Issue 5, 2010, pp. 643-656.
- [9]. S. Misra, S. D. Hong, G. Xue, and J. Tang, Constrained Relay Node Placement in Wireless Sensor Networks to Meet Connectivity and Survivability Requirements, in *Proceeding of the IEEE INFOCOM*, April 15-17, 2008, pp. 281-285.
- [10]. E. Zhi Ang, T. Hwee-Pink Tan, K. G. Winston, Routing and Relay Node Placement in Wireless Sensor Networks Powered by Ambient Energy Harvesting, in *Proceeding of the Wireless Communications and Networking Conference*, April 5-8, 2009, pp. 1-6.
- [11]. S. Maruyama, K. Nakano, K. Meguro, M. Sengoku, and S. Shinoda, On location of relay facilities to improve connectivity of multi-hop wireless networks, in *Proceeding of the 10th Asia-Pacific Conf. Commun. and 5th International Symposium on Multi-Dimensional Mobile Commun.*, 5-7 February 2004, pp. 749-753.
- [12]. A. S. Ibrahim, K. G. Seddik, Connectivity-aware network maintenance and repair via relays deployment, *IEEE Transactions on Wireless Communications*, Vol. 8, Issue 1, 2009, pp. 356 – 366.
- [13]. X. Kenan, H. Hossam, T. Glen, W. Quanhong, Relay Node Deployment Strategies in Heterogeneous Wireless Sensor Networks, *IEEE Transactions on Mobile Computing*, Vol. 9, Issue 2, 2010, pp. 145-159.
- [14]. Y. T. Hou, S. Yi, H. D. Sherali, S. F. Midkiff, On energy provisioning and relay node placement for wireless sensor networks, *IEEE Transactions on Wireless Communications*, Vol. 4, Issue 5, 2005, pp. 2579 - 2590.
- [15]. L. Sitanayah, K. N. Brown, and C. J. Sreenan, Multiple Sink and Relay Placement in Wireless Sensor Networks, in *Proceedings of the Workshop on AI in Telecommunications and Sensor Networks (WAITS 2012)*, Montpellier, France, August 2012, pp. 132-143.
- [16]. E. L. Lloyd and G. Xue, Relay Node Placement in Wireless Sensor Networks, *IEEE Transaction on Computers*, 1, Vol. 56, Issue1, 2007, pp. 134 - 138.
- [17]. L. Sitanayah, K. N. Brown, C. J. Sreenan, Fault-tolerant relay deployment for k node-disjoint paths in wireless sensor networks, in *Proceedings of the Wireless Days (WD)*, 2011, pp. 21-26.
- [18]. W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, An application Specific Protocol Architecture for Wireless Microsensor Networks, *IEEE Transactions on Wireless Communications*, Vol. 4, Issue1, 2002, pp. 660 – 670.
- [19]. J. Flathagen, P. E. Engelstad, Constrained-based Multiple Sink Placement for Wireless Sensor Networks, in *Proceeding of the IEEE 8th International Conference on Mobile Adhoc and Sensor Systems (MASS)*, 2011, pp. 783 – 788.
- [20]. C. Prommak and S. Modhirun, Optimal Network Design for Efficient Energy Utilization in Wireless Sensor Networks, *Journal of Computer Science*, Vol. 8, Issue 1, 2012, pp. 149-158.
- [21]. S. C. Ergen, P. Varaiya, Optimal Placement of Relay Nodes for Energy Efficiency in Sensor Networks, in *Proceeding of the IEEE International Conference on Communications*, Istanbul, Turkey, 11-14 December 2006, pp. 3473-3479.
- [22]. J. Li, P. Mohapatra, Analytical modeling and mitigation techniques for the energy hole problem in sensor networks, *Journal of Pervasive and Mobile Computing*, Vol. 3, Issue3, 2007, pp. 233-254.