The More Relay Nodes, The More Energy Efficient?

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***Abstract*—Existing work has been focused on minimizing the number of relay nodes to maintain the connectivity of a sensor network. However, we believe replacing batteries for nodes or redeploying the network is either labor-intensive or impossible, so it is more desirable to reduce energy consumption even if we need to use slightly more nodes. The question we are trying to answer is: is it possible to greatly reduce energy consumption by increasing the number of relay nodes? To properly answer this question, we first designed an algorithm that finds the most energy efficient relay nodes placement for a given number of relay nodes. By observing the energy saving with different numbers of available relay nodes, we found that slightly increasing the number of relay nodes can significantly reduce energy consumption. On the contrary, blindly adding relay nodes does not necessarily improve energy efficiency when the number of relay nodes exceeds a certain threshold.**

***Index Terms*—wireless sensor networks, relay node placement, network deployment, energy efficiency**

I. Introduction

This work is motivated by an important class of wireless sensor applications where the monitoring locations (i.e., sensor locations) are fixed and their placements are pre-determined according to domain knowledge, application requirements, and environment constraints. For instance, in subsurface contaminant monitoring, high resolution and expensive chemical or biological sensors are only deployed at pre-selected sites according to monitoring needs [1], often leading to a very sparse sensor network. This implies that these sensors may be placed far away from each other and the sink. Using high transmission power for each sensor node is not economical because sensor nodes are expensive and have short battery life. Comparing to sensor nodes, relay nodes are much less costly. Relay nodes are needed to forward readings from each individual sensor in multiple hops to the sink.

Existing work has focused on minimizing the number of relay nodes in homogeneous or heterogeneous sensor networks as detailed in Section V. While minimizing the number of relay nodes is desirable, it may not always provide the most energy efficient solution. Especially because replacing batteries or redeploying nodes can be impossible or labor intensive, so it is more desirable if energy consumed in data collection can be reduced greatly even with a slight increase of the number of relay nodes. To this end, we would like to study the tradeoff between relay nodes placement (i.e., the number of relay nodes and their locations) and energy efficiency in collecting data from a set of sensors deployed at pre-determined locations.

Our approach is to start with the minimal number of relay nodes using existing work, and then observe the impact of gradually increasing the number of relay nodes on total energy consumption in raw sensor data collection. By comparing the energy consumption and the number of relay nodes used, we can identify the most economical network deployment.

*This work is supported in part by NSF CSR grant CNS-0720875.

II. Problem Definition

We are given a set of N_s sensor nodes $\{s_i | i \in \{1, 2, \cdots, N_s\}\}$ and their locations $\{l_i = (x_i, y_i) | i \in \{1, 2, \cdots, N_s\}\}$, the location of the sink t: $l_t = (x_t, y_t)$. We assume that the transmission range of each node (either sensor or relay) is the same constant R. Each sensor transmits its sensed data through multi-hop routing to the sink t, and each relay node does not generate data itself. We are interested in applications that require raw sensor data instead of aggregated sensor data. The total energy cost of data gathering is $\sum_{i=1}^{N_s}(\lambda_i \times c_i + c_i^{'})$, where λ_i is the data generation rate of sensor node s_i, c_i is the per-bit transmission cost from sensor node s_i to the sink, and $c_i^{'}$ is the energy consumption of the node s_i switching from a power saving state (e.g., sleeping) to the transmission mode. Since each sensor node needs multiple hops either through other sensor nodes or relay nodes in order to get data to the sink, the total energy cost includes energy consumed by relay nodes. Our objective is to study the interplay between relay node placement (which determines the number and locations of relay nodes), transmission structure (which determines how sensor and relay nodes are connected), and energy consumption of data collection.

If we model the network as a graph with sensor nodes, relay nodes and the sink represented as vertices, then the links capture the transmission structure. For any two nodes u and v in the graph, there is an edge uv between them if and only if the Euclidean distance between u and v is no greater than the transmission range: $||u, v|| \leq R$.

III. Our Approaches

In order to find out the relationship between relay node placement and energy consumption of data collection from a given set of sensor nodes, we use the following steps to approach this problem.

1) Find out the minimum number of relay nodes needed to maintain network connectivity. This has been modeled as Steiner Minimum Tree with Minimum number of Steiner Points and bounded edge length (SMT-MSP) [2]. Various approximation algorithms have been developed to address this NP-hard problem. We will use the Minimum Spanning Tree Heuristic [2] referred as "SMT" later in the paper. We denote the number of relay nodes needed for SMT as N_{SMT}. Figure 1 shows an example of the data transmission structure generated by SMT where there are 10 sensor nodes.

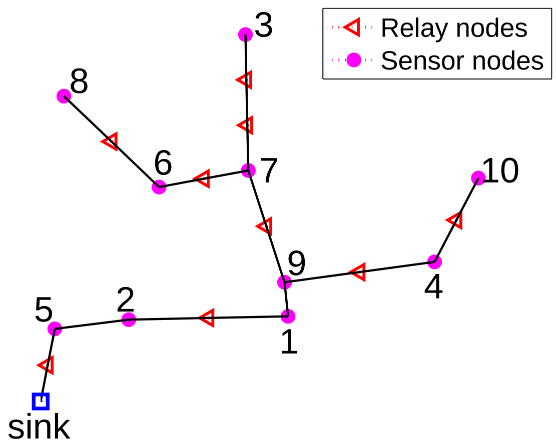


Fig. 1. SMT requires 9 relay nodes.

2) Find out the most energy efficient transmission structure, assuming that the number of relay nodes is infinite (i.e., we can use as many relay nodes as necessary). With constant transmission range of each node, the energy consumed by transmitting a packet from a sensor node to the sink is proportional to the number of hops from the node to the sink and the packet size. Therefore, to minimize energy consumption, we should minimize the number of hops from the node to the sink, and the relay nodes should be placed on the straight line between each sensor node and the sink. In other words, a star topology is the most energy efficient structure. We will refer to this as "STAR" later in the paper. We denote the number of relay nodes needed for this structure as N_{STAR}. Figure 2 illustrate an example of this structure with 10 sensor nodes with pre-specified locations.
3) Find out the most energy efficient relay node placement and transmission structure when $n_{SMT} < N_r < n_{STAR}$, where N_r is the number of relay nodes. This is an NP-hard problem as proven in our previous work [3]. We designed an algorithm that uses iterative improvement processes based on Steiner Minimum Tree. We will refer to our algorithm as "SMT-II".
4) By comparing the energy consumption and the number of relay nodes used, insights will be gained that will help the network deployment process.

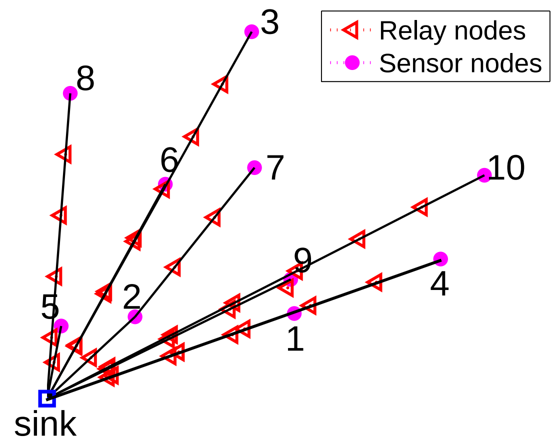
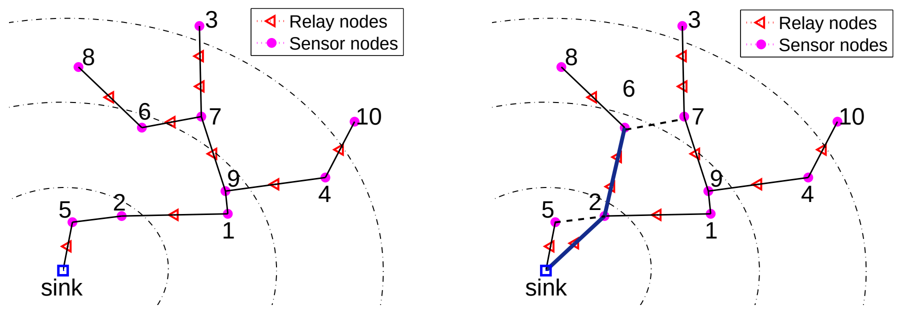


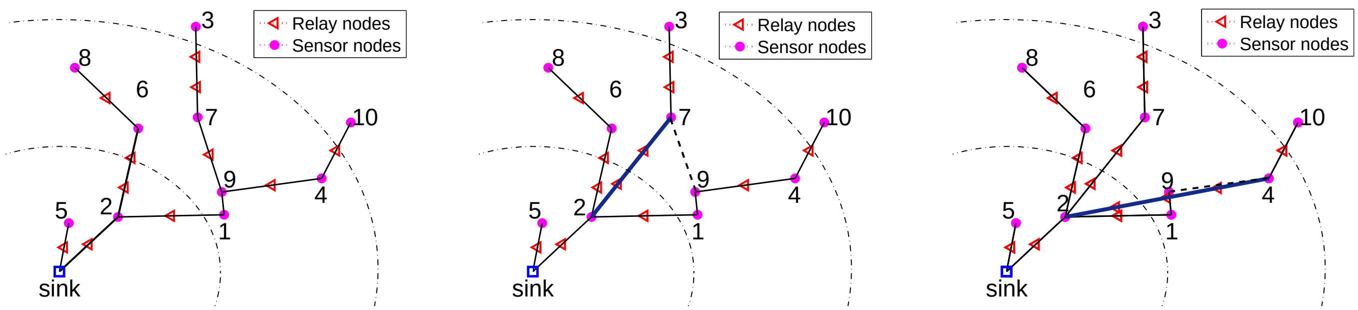
Fig. 2. STAR requires 35 relay nodes.

The SMT-II Heuristic: Our objective is to find the most energy efficient relay node placement and transmission structure with a given number of relay nodes. The general idea is to start with an initial structure generated from SMT and then gradually add the remaining relay nodes if energy cost can be reduced. The details are as follows. After getting an approximate Steiner-tree, we use $d = \alpha R (\alpha > 1)$ as the search radius to divide the sensor and relay nodes into different distance levels depending on their distance from the sink. Nodes at a lower level are closer to the sink. For each sensor node s_i, we calculate the potential energy savings if we create a straight line path from s_i to its nearest lower-level sensor node s_u. We then sort sensor nodes in the descending order of energy savings; implement the path changes (i.e., replace the original path between s_i and s_u with a straight line interspersed with additional relay nodes) starting from the one with the biggest energy savings until all the remaining relay nodes are deployed. If we implemented all the changes and we still have remaining relay nodes, then we increment the search radius by βR, divide the nodes into new distance levels and repeat the procedure above. We will stop until all the relay nodes are placed or all the sensor nodes have the same distance levels.

Figure 3 uses an example to illustrate the SMT-II algorithm. We assume there are 14 relay nodes available. We use $2R$ as the initial search radius and R as the step length of search radius increment. After we generate an approximate Stein-tree using 9 relay nodes, we first use $2R$ to divide the sensor nodes into four distance levels (Figure 3 (a) left). Two nodes (node 2 and node 6) have the potential to reduce energy consumption. Since we still have five remaining relay nodes, we implement path changes for these two nodes (Figure 3 (a) right) that use three out of the five remaining nodes. No other changes are applicable using this search radius, we hence increase the search radius to $3R$, the nodes are divided into three distance levels (Figure 3 (b) left). Three nodes (nodes 7, 4, and 8) have the potential to reduce energy consumption. However, we only have two remaining relay nodes, so we select the two



(a)



(b)

Fig. 3. An example for SMT-II: The locations of the sink and 10 sensor nodes are pre-determined by the application. There are 14 relay nodes available to be placed. (a) the process and results of using search radius $2R$; (b) the process and results of using search radius $3R$. Note that links deleted are shown in dashed lines and links newly added are shown in solid thick lines.

Symbol	Meaning
N_s	total number of sensor nodes
N_r	total number of relay nodes
R	transmission range of a node
$maxd$	maximum distance between sink and sensor nodes
s_i	sensor node i, $i \in \{1, 2, \cdots, N_s\}$
r_i	relay node i, $i \in \{1, 2, \cdots, N_r\}$
l_i	location of sensor/relay node i
t	server or sink
l_t	location of the server
λ_i	data rate of sensor node s_i
c_i	cost of sending data from s_i to the server t
$c_i^{'}$	energy cost due to s_i's transition of power saving states
d	search radius
k_{s_i}	distance level of sensor node s_i
$\|s_i, s_j\|$	the Euclidean distance from s_i to s_j
T	collection tree T
n_e	total number of extra relay nodes
$n_r(T)$	number of relay nodes used in the collection tree T
m_{s_i}	number of extra relay nodes used for optimizing s_i's path
$\omega(T)$	cost needed if collection tree T is used
$\delta(s_i)$	cost decrease after changing node s_i's path to the server
$\Delta(T, T')$	cost decrease after replacing collection tree T by T'

TABLE I
NOTATIONS USED IN THE PAPER

nodes that will yield the most energy savings to implement path changes, which are node 7 (Figure 3 (b) middle) and node 4 (Figure 3 (b) right).

Table I lists all the symbols used in the paper and the pseudo code of the algorithm is shown in Algorithm 1.

Complexity Analysis of SMT-II: As shown in Table I, we assume the total number of sensor nodes is N_s, the total number of relay nodes is N_r, and the total number of extra relay nodes is n_e. In line 1, we use an SMT heuristic that takes $N_s \log N_s$ time. Lines 7 to 42 is a while loop, we assume this loop will repeat N_l times. In the while loop (lines 7 to 42), (1) From lines 8 to 12, the time complexity is N_s. (2) From lines 13 to 21, the for loop will repeat N_s times. In line 14, to find S_{v_i} we should compare the distance from S_i to all the sensor nodes and check their distance levels, the complexity of line 14 is $N_s \log N_s$. Therefore, the time complexity for lines 13 to 21 is $N_s^2 \log N_s$. (3) From lines 23 to 25, we will implement $T'(s_i)$ for all S_i, so the time complexity is N_s. Thus the time complexity from lines 23 to 30 is N_s. In line 33, the complexity is $N_s \log N_s$, so the time complexity from lines 32 to 40 is $N_s \log N_s$. Therefore, the time complexity from lines 22 to 41 is $N_s \log N_s$. To combine all the above, the time complexity for SMT-II is : $N_s \log N_s + N_l * (N_s + N_s^2 \log N_s + N_s \log N_s) = N_l * O(N_s^2 \log N_s)$. The worst case for N_l is that in each iteration, only one relay node is used, then the while loop will repeat n_e times. However, this will only occur when $z > n_e$ in line 22 in the first iteration. In this case, $n_e < N_s$. Therefore, so the time complexity for SMT-II is $O(N_s^3 \log N_s)$. Note that the scenario we are considering is sparse networks where sensor nodes are expensive and only deployed in locations of interest, so N_s is a relatively a small number.

IV. Performance Evaluation

To find out the relationship between the number of available relay nodes and total energy consumption in collecting data

Algorithm 1 The SMT-II Heuristic

Input: a set of N_s sensor nodes $\{s_i | i \in \{1, 2, \cdots, N_s\}\}$ and their locations; location of sink t; number of relay nodes N_r; transmission range R; data rate of node i λ_i.

Output: location of relay nodes $\{r_i = (x_i, y_i) | i \in \{1, 2, \cdots, N_r\}\}$; collection tree T.

identify l_{r_i}, T and $n_r(T)$ from an SMT heuristic;
$d = \alpha R$;
radiusIncreased = TRUE;
$n_e = N_r - n_r(T)$;
$k_t = 0$; $z = 0$;
$maxd = \max\{d(t, s_i) | i = \{2, 3, \ldots, (N_s + 1)\}\}$;
while ($n_e > 0$ and $(d - R) > maxd$) **do**
  if (radiusIncreased==TRUE) **then**
    for all s_i **do**
      $k_{s_i} = \lceil \frac{\|t, s_i\|}{d}) \rceil$
    end for
  end if
  for all s_i **do**
    find the node s_{v_i} in lower level of s_i that has the shortest Euclidean distance from s_i;
    construct a potential collection tree $T'(s_i)$ by the following:
    (a) add a link between s_{v_i} and s_i; (b) add necessary relay nodes on the added link to ensure communication; (c) remove the path between s_i and its closest upstream node s_{u_i} in T;
    $\delta(s_i) = \Delta(T, T'(s_i))$; // calculate the potential cost reduced
    $m_{s_i} = n_r(T'(s_i)) - n_r(T)$; //calculate the number of extra relay nodes used
    if ($m_{s_i} > 0$ and $k_{s_{v_i}} \leq k_{s_{u_i}}$ and $\delta(s_i) > 0$) **then**
      $z = z + m_{s_i}$;
    end if
  end for
  if $(z \leq n_e)$ **then**
    for all s_i **do**
      implement $T'(s_i)$;
    end for
    $n_e - = z$;
    if ($n_e > 0$) **then**
      $d = d + \beta R$;
      radiusIncreased=TRUE;
    end if
  else
    radiusIncreased=FALSE;
    sort $\delta(s_i)$ in descending order;
    find the node s_j with the largest $\delta(s_j)$;
    if ($m_{s_j} > 0$ and $k_{s_{v_j}} \leq k_{s_{u_j}}$ and $\delta(s_j) > 0$) **then**
      $n_e = n_e - m_{s_j}$;
      if ($n_e > 0$) **then**
        $T = T'(s_j)$;
      end if
    end if
  end if
end while

from all sensor nodes, we implemented all three algorithms (SMT, STAR, and SMT-II) in MATLAB. We used the parameters from MICAz data specification for all sensor and relay nodes in the evaluation, so the transmit range of each node is 100 meters, the RF power is 0dBm and the data transmission rate is 250kbps. The metric used was energy per second consumed by transmitting data generated from all sensor nodes to the base station.

We assume a 2D terrain of 1000 meters by 1000 meters. We use $2R$ as the initial search radius and R as step length of search radius increment. To demonstrate that our algorithm works for a variety of scenarios, we tested the algorithms for the following cases: grid or random sensor node deployment, uniform or non-uniform data generation rate, and varying node densities.

Figures 4 to 5 demonstrate the impact of the number of available relay nodes on data collection energy consumption when sensor nodes are deployed in a grid fashion. Figure 4 is for the case when all sensor nodes have the same data generation rate of 50 kbps, and Figure 5 is for the case when each sensor node has a data generation rate randomly chosen from 50 kbps, 100 kbps, 150 kbps, or 200 kbps. We observe that in all cases, the most energy consuming structure is SMT, and the most energy efficient structure is STAR. As the number of available relay nodes increases from N_{SMT}, less energy is consumed using SMT-II until it converges to the lower bound provided by STAR. We also observe that the energy consumption curve flattens out gradually as the number of relay nodes increases. This implies that by adding a few extra relay nodes to N_{SMT}, energy consumption can be reduced greatly. However, the benefit becomes less obvious when we further add more relay nodes. Therefore, blindingly increasing the number of relay nodes may not always lead to significant energy saving. This trend is especially true for higher node density (i.e., more sensor nodes in the area of the same size), if we compare the energy consumption with 49 sensor nodes with the case of 25 or 36 sensor nodes.

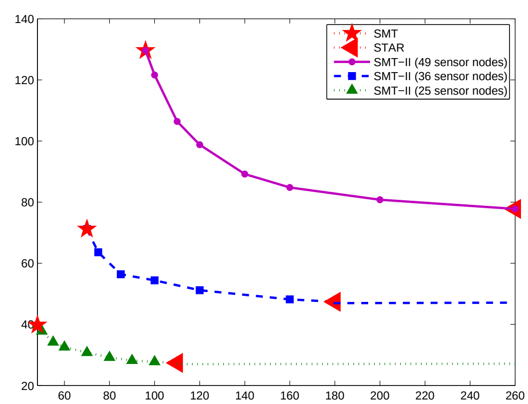


Fig. 4. Sensor nodes with uniform data generation rate of 50 kbps are deployed in a grid fashion.

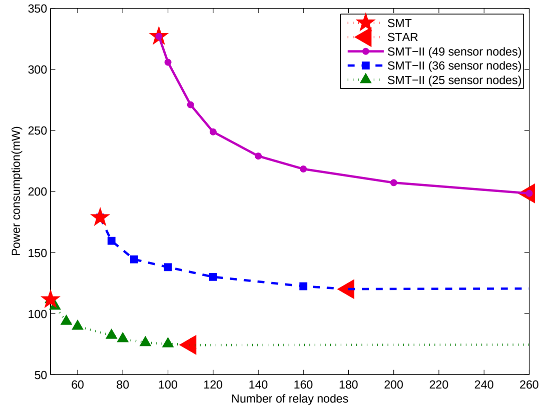


Fig. 5. Sensor nodes with different data generation rates are distributed in a grid fashion.

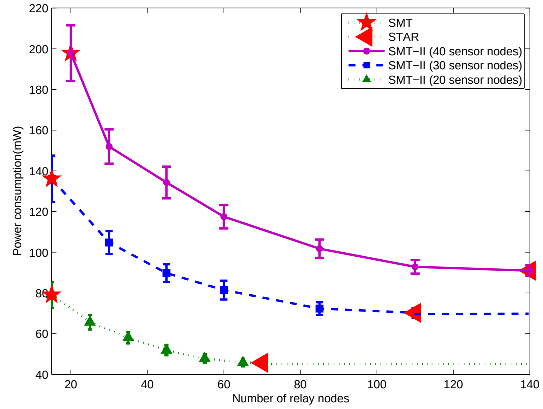


Fig. 7. Sensor nodes with different data generation rates are randomly and uniformly distributed.

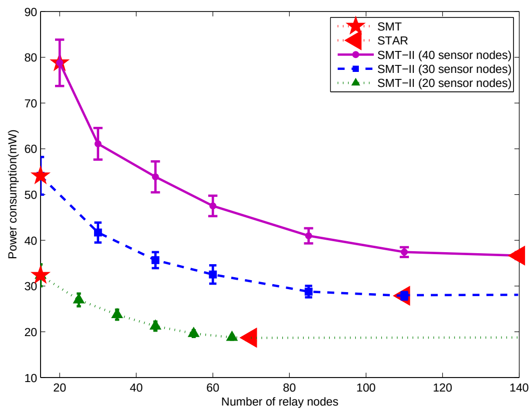


Fig. 6. Sensor nodes with uniform data generation rate of 50 kbps are randomly and uniformly distributed

Figures 6 to 7 demonstrate the impact of the number of available relay nodes on data collection energy consumption when sensor nodes are uniformly and randomly deployed. All results are generated after 30 simulation runs and shown with 95% confidence intervals. The performance trends are similar to the case when sensor nodes are deployed in a grid fashion.

In summary, we can see that in all the cases above, the most energy consuming structure is Steiner Minimum Tree with the smallest number of relay nodes (N_{SMT}), and the most energy efficient structure is the star structure with the largest number of relay nodes (N_{STAR}). Our algorithm (SMT-II) is able to find energy efficient relay node placement with a given number of relay nodes that fall between N_{SMT} and N_{STAR}. This is very useful in real network deployment.

V. Related Work

Several variants of relay node placement in wireless sensor networks have been studied in the literature that consider different network models: single-tiered networks; two-tiered networks; and heterogeneous networks.

In the *single-tiered network model*, the problem is to deploy a minimum number of relay nodes in a WSN so that between every pair of sensor nodes, there is a connecting path consisting of relay and sensor nodes and such that each hop of the path is no longer than the common range of the sensor nodes and the relay nodes. Lin et. al formulated the problem as the Steiner Minimum Tree with minimum number of Steiner points and bounded edge length problem (SMT-MSP), proved the NP-hardness of the problem, and proposed a 5-approximation algorithm [2]. Chen et. al then presented a 3-approximation algorithm for this problem [4]. Cheng et. al presented a faster 3-approximation algorithm, and a randomized algorithm with an approximation ratio of 2.5 [5]. In [6], Bredin et al. extended the relay node placement problem to the case of k-connectivity, instead of 1-connectivity, and presented polynomial time O(1)-approximation algorithms for any fixed k. In [7], Kashyap et al. presented a 10-approximation algorithm ensuring 2-connectivity. All of the above assume that the transmission range of the relay nodes is the same as that of sensor nodes. In [8], Lloyd and Xue generalized to the case where relay nodes have transmission range greater than the transmission range of sensor nodes and presented a 7-approximation algorithm.

In the *two-tiered network model*, sensor nodes are grouped into clusters each covered by an application node. Motivated by the works [9] and [10], Hao et al. in [11] formulated two-tiered relay node placement problems under the assumption that the sensor nodes have a communication range $r > 0$ and the relay nodes have a communication range $R \geq 4r$. They studied two problems. One is for the connected relay node single cover problem, they aimed to deploy a minimum number of relay nodes so that (1) every sensor node is within distance r of a relay node and that (2) between every pair of relay nodes, there is a connecting path consisting of relay nodes such that each hop of path is not longer than R. The other is for the 2-connected relay node double cover problem, they aimed to place a minimum number of relay nodes in the playing field of a sensor network such that (1) each sensor node can communicate with at least two relay nodes and (2) the relay node network is 2-connected. In [12], Tang et al. presented 4:5-approximation algorithms under the assumption that $R \geq 4r$ and that the sensor nodes are uniformly distributed. In [13], under the assumption that $R = r$, but no restriction on the distribution of the sensor nodes, Liu et al. presented a $(6+\epsilon)$-approximation algorithm for connected relay node single cover problem and a $(24+\epsilon)$-approximation algorithm for the 2-connected relay node double cover problem, where $\epsilon > 0$ is any given constant. In [8], Lloyd and Xue studied the problem for connected relay node single cover problem with the condition $R = r$ relaxed to $R \geq r$, and presented a $(5+\epsilon)$-approximation algorithm. Srinivas et al. [14] presented better approximation algorithms under the assumption $R \geq 2r$.

In *heterogeneous wireless sensor networks*, sensor nodes possess different transmission ranges. Wang et. al. in [15] studied the problem for connected relay node single cover problem in heterogeneous wireless sensor networks. In [16], Han et. al. studied two problems: (1) full fault-tolerant relay node placement, which aims to deploy a minimum number of relay nodes to establish $k(k \geq 1)$ vertex-disjoint paths between every pair of sensor and/or relay nodes; (2) partial fault-tolerant relay node placement, which aims to deploy a minimum number of relay nodes to establish $k(k \geq 1)$ vertex-disjoint paths only between every pair of sensor nodes.

Our work differs from existing work described above in that we consider the interplay between relay node placement and data transmission structure, and the impact of the interplay on energy efficiency in sensor data collection. Ganesan et. al. considered a similar problem where data correlation is exploited to guide the placement of relay nodes [17]. In contrast, we are more interested in applications such as groundwater monitoring where network is sparse and data correlation is rather weak.

VI. Conclusion

This paper studies the tradeoff between relay nodes placement and energy efficiency in collecting data from a set of sensors deployed at predetermined locations. We have observed that SMT will provide a transmission structure that requires the minimum number of relay nodes at the price of very high energy consumption. We designed the SMT-II algorithm that will provide an energy efficient relay node placement and transmission structure with limited number of available relay nodes. We observe that energy consumption can be significantly reduced by slightly increasing the number of relay nodes over the minimum number necessary to maintain connectivity. We also observe that further increasing the number of relay nodes will not make much improvement in energy efficiency.

Further development of our research includes extending our algorithm to consider different network models such as two-tiered network model, heterogeneous wireless sensor networks, and two-tiered heterogeneous wireless sensor networks. It is also interesting to extend our work to the case of k-connectivity and improve our solution to achieve higher approximation and lower time complexity.

References

[1] Q. Han, A. P. Jayasumana, T. Illangasekare, and T. Sakaki, "A wireless sensor network based closed-loop system for subsurface contaminant monitoring," in *Proceedings of the NSF Workshop on Next Generation Software (NSFNGS)*, 2008.

[2] G.-H. Lin and G. Xue, "Steiner tree problem with minimum number of steiner points and bounded edge-length," *Inf. Process. Lett.*, vol. 69, no. 2, pp. 53–57, 1999.

[3] J. Augustine, Q. Han, P. Loden, S. Lodha, and S. Roy, "Energy-efcient shortest path algorithms for convergecast in sensor networks," in *submitted for publication*, 2009.

[4] D. Chen, D.-Z. Du, X.-D. Hu, G.-H. Lin, L. Wang, and G. Xue, "Approximations for Steiner trees with minimum number of Steiner points." *J. Glob. Optim.*, vol. 18, no. 1, pp. 17–33, 2000.

[5] X. Cheng, D.-Z. Du, L. Wang, and B. Xu, "Relay sensor placement in wireless sensor networks," *Wirel. Netw.*, vol. 14, no. 3, pp. 347–355, 2008.

[6] J. L. Bredin, E. D. Demaine, M. Hajiaghayi, and D. Rus, "Deploying sensor networks with guaranteed capacity and fault tolerance," *MobiHoc '05: Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, pp. 309–319, 2005.

[7] A. Kashyap, S. Khuller, and M. Shayman, "Relay placement for higher order connectivity in wireless sensor networks," in *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, April 2006, pp. 1–12.

[8] E. L. Lloyd and G. Xue, "Relay node placement in wireless sensor networks," *IEEE Trans. Comput.*, vol. 56, no. 1, pp. 134–138, 2007.

[9] G. Gupta and M. Younis, "Fault-tolerant clustering of wireless sensor networks," in *Wireless Communications and Networking, WCNC , IEEE*, vol. 3, March 2003, pp. 1579–1584 vol.3.

[10] J. Pan, Y. T. Hou, L. Cai, Y. Shi, and S. X. Shen, "Topology control for wireless sensor networks," in *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM, 2003, pp. 286–299.

[11] B. Hao, H. Tang, and G. Xue, "Fault-tolerant relay node placement in wireless sensor networks: formulation and approximation," in *High Performance Switching and Routing, 2004. HPSR. 2004 Workshop on*, 2004, pp. 246–250.

[12] B. H. J. Tang and A. Sen, "Relay node placement in large scale wireless sensor networks," in *Computer communications*, vol. 29. Elsevier Science, Amsterdam, PAYS-BAS (1978) (Revue), 2006, pp. 490–501.

[13] P.-J. W. Hai Liu and X. Jia, *Fault-Tolerant Relay Node Placement in Wireless Sensor Networks*. Springer Berlin / Heidelberg, 2005, vol. 3595.

[14] A. Srinivas, G. Zussman, and E. Modiano, "Mobile backbone networks –: construction and maintenance," in *MobiHoc '06: Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing*. New York, NY, USA: ACM, 2006, pp. 166–177.

[15] Q. Wang, K. Xu, G. Takahara, and H. Hassanein, "Transactions papers - device placement for heterogeneous wireless sensor networks: Minimum cost with lifetime constraints," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 7, pp. 2444–2453, July 2007.

[16] X. Han, X. Cao, E. Lloyd, and C.-C. Shen, "Fault-tolerant relay node placement in heterogeneous wireless sensor networks," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, May 2007, pp. 1667–1675.

[17] D. Ganesan, R. Cristescu, and B. Beferull-Lozano, "Power-efficient sensor placement and transmission structure for data gathering under distortion constraints," *ACM Transactions on Sensor Networks (TOSN)*, vol. 2, no. 2, pp. 155–181, May 2006.