IMPACT OF TRANSMISSION POWER AND ROUTING ALGORITHMS IN DESIGNING ROBUST WIRELESS SENSOR NETWORKS

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ABSTRACT

In wireless sensor networks, accurate and complete sensor data is important to the analysis of a phenomenon. Therefore, designing a robust sensor network is of high importance. We first derive the relationships between transmission power, energy consumption and robustness of the network using analytical modeling. Then, we validate our model by using linear programming to find the optimal routing algorithm that will optimize the robustness of the sensor network. The optimal robust routing algorithm is then compared with other popular routing algorithms used in sensor networks and we find that the robustness achieved varies with different routing algorithms. This demonstrates the need for a cross-layer design approach when designing robust sensor networks.

In addition, we also prove that an energy-efficient routing algorithm that optimizes the lifetime of the sensor network does not optimize the robustness of the network. By using correlation analysis on the optimal routing algorithm, we design a robust geographic routing algorithm that only utilizes local neighborhood information to obtain nearly optimal robustness performance. Our algorithm also minimizes data losses in cases when sensor nodes fail.

I. INTRODUCTION

In wireless sensor networks, sensor data is sent from the place of event occurrence through intermediate sensor nodes to the sink. By increasing the transmission power of sensor nodes, less intermediate sensor nodes are needed to forward the data and therefore we expect the robustness of the network to increase. However, increasing the transmission power does not always lead to increased robustness as robustness also depends on the routing algorithm. We derive a relationship between the transmission power and the robustness of the network under optimal routing situations. Using optimization techniques, we find the routing algorithm that will optimize the robustness of the network and compare this optimal robust routing algorithm with other popular routing algorithms, namely, shortest path routing, greedy geographic routing and energy-efficient routing.

We find that these routing algorithms do not provide robustness close to the optimal routing algorithm in many cases and they use more energy per unit of robustness. Using correlation analysis on the optimal routing algorithm, we design a simple distributed routing protocol that only utilizes local neighborhood information that performs close to the optimal cases. Since only local neighborhood information is used, our protocol is scalable to large networks.

II. RELATED WORK

There are many energy-efficient routing algorithms proposed for sensor networks such as [1] and [2]. However, we will show that the optimal energy-efficient routing algorithm, which maximizes the lifetime of the network, is not optimally robust. In [3], a load balancing algorithm is used to distribute the load evenly among all the nodes, which is also our main objective. However, the algorithm requires global information and all nodes in the network need to periodically broadcast their existence to the base station. Another load balancing algorithm [4] aims to distribute energy usage evenly among all the nodes to extend the lifetime of the network but does not ensure that the sensor network is robust to node failures.

III. MODELING ROBUSTNESS IN WIRELESS SENSOR NETWORKS

Before we analyze the robustness of the sensor network, the parameters used in this paper are summarized in Table 1.

Table 1: Parameters Used In Modeling.

n	the number of sensor nodes in each row or column in the grid
l	length of the grid
V	set of vertices
E	set of edges
x	x-coordinate of a sensor location
y	y-coordinate of a sensor location
t	transmission range of each sensor
s	number of sensors within transmission range of the sink
c	maximum load transmitted by sensor nodes
p	maximum energy consumed by sensor nodes
k	path loss exponent
α	amount of data originating from each sensor node
β	optimal maximum load
λ	robustness performance metric
κ	energy consumed per unit of robustness
$f(u,v)$	total amount of data sent from u to v
$d(u,v)$	distance gained towards the sink when sending data from u to v
$w(u,v)$	transmission cost to send a unit of data from u to v

We consider a $n \times n$ grid topology of sensor nodes distributed in an area of $l \times l$ as shown in Fig. 1. The sensor network can be modeled using the representation of a graph $G=(V,E)$ where V is the set of vertices and E is the set of edges. The sink and all sensor nodes are in the set of vertices. The sensors are numbered from 1 to n^2-1 while the sink is numbered n^2. Each vertex is associated with a location information given by (x_i, y_i). For example, the first sensor's location is given by (x_1, y_1) and assigned the value of (1, 1). The sink's location is assigned the value of (n, n). Each sensor node has a maximum transmission range of t where t is a real number which lies between $\frac{l}{n}$ and $\sqrt{2}\left(\frac{n-1}{n}l\right)$. There is an edge ($u$, v) in E if the nodes are within transmission range of each other. Formally, this is stated as

$$\text{edge } (u,v) \in E \text{ iff } \sqrt{(x_u - x_v)^2 + (y_u - y_v)^2} \leq t$$

Data is sent from a sensor node through intermediate sensor nodes to the sink if the sink is not within direct transmission range of the sensor. We let $f(u,v)$ be the total amount of data transmitted from sensor node u to sensor node v. These data includes data from other sensor nodes and data originating from the node itself. We let G be a weighted graph with a weight function w. The weight $w(u,v)$ of the edge $(u,v) \in E$ is the cost of transmission from node u to node v. The transmission cost is dependant on the distance between the nodes as well as the propagation model used. In general, $w(u,v) \propto d^k$ where d is the distance between 2 nodes and k is the path loss exponent. The value of k depends on the propagation environment and ranges from 1.6 to 6 [5]. Fig. 1 illustrates a sample network topology of 16 nodes.

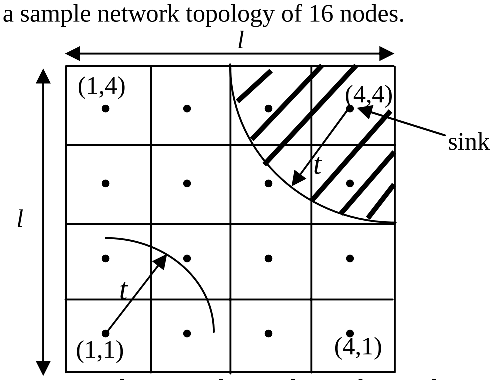

Figure 1: Sample Network Topology of 16 nodes

A. Optimal Robust Routing Algorithm

Sensor networks may be deployed in harsh environments where sensor nodes may fail easily or be subjected to attacks such as jamming or physical damage. We define robustness as gradual performance degradation of the network when one or more sensor nodes fail or malfunction. When this happens, the sensor nodes will not be able to receive or forward data from other sensor nodes, resulting in data loss. Therefore, the optimal robust routing algorithm minimizes the load that each sensor node forwards towards the sink. It distributes the load among all its possible forwarding neighbors such that the maximum load being transmitted by any sensor node is minimized. This ensures that minimal sensor data is lost when any node fails to forward sensor data and the performance of the network would degrade gracefully when nodes begin to fail. To compare the optimal robustness algorithm with other routing algorithms, we define a performance metric, λ, to measure robustness. It is the value of $1/\beta$ where β is the maximum load transmitted by any sensor node. For high robustness, it is necessary for β to be low so that the loss or malfunction of any sensor node would not have a high impact on the total amount of sensor information received by the sink.

B. Impact of Transmission Power on Robustness

Once the sink is disconnected from the network, the sensor network fails as no information can reach the user from the sensors. Therefore, we are interested in the number of sensors that are connected to the sink. The density of the sensor network is given by

$$\rho = \frac{\text{Number of sensors}}{\text{Area}} = \frac{n^2}{l^2}$$

We need to calculate the shaded area as shown in Fig. 1. This area is given by $A = \frac{\pi}{4}\left(t + \sqrt{\frac{l^2}{2n^2}}\right)^2$. For $t \leq \frac{n-1}{n}l$, the number of sensors within the transmission range of the sink is

$$s \approx \rho A - 1 = \frac{\pi\left(t + \sqrt{\frac{l^2}{2n^2}}\right)^2 n^2}{4l^2} - 1$$

This means that, for a fixed grid topology, for $t \leq \frac{n-1}{n}l$, s is approximately directly proportional to t^2. If each sensor has α units of data to send, the total amount of data received by the sink is $(n^2 - 1)\alpha$. Therefore, the optimal maximum load, β, being forwarded by a sensor within the transmission range of the sink is $(n^2 - 1)\alpha / s$. This results in $\beta \propto 1/t^2$ and $\lambda \propto t^2$. This implies that, if we increase the transmission power linearly, there is a quadratic increase in robustness. For a 6×6 grid topology, Fig. 2 illustrates numerical values of β as the transmission range increases for the optimal robust routing protocol.

C. Relationship between Energy Consumption and Robustness

We let the energy required to transmit 1 unit of sensor data over 1 unit distance be E_m and the distance from the data source to the sink be h units. Therefore, the total energy required to send 1 unit of sensor data to the sink is hE_m when t is 1 unit distance. By increasing the transmission range, higher energy is required. When t>1, the energy required per hop is $t^k E_m$. However, the number of hops required to reach the sink is reduced to $\lceil h/t \rceil$. If h/t is integer, the total energy required is $ht^{k-1}E_m$. Since $\lambda \propto t^2$, the energy required per unit of robustness, κ, is proportional to $ht^{k-1}E_m / t^2$. Assuming that every sensor node attempts to forward its data to its furthest neighbor, $\kappa \propto t^{k-3}$. For the free space propagation model where k is 2, this means that the benefit of increase in robustness outweighs the increase in total energy needed for transmission.

D. Impact of Routing Algorithms on Robustness

If the optimal robust routing algorithm is used, increasing the transmission range would result in quadratic increase in robustness. Another common routing algorithm that is used is the shortest path routing algorithm. We distribute the load evenly among all the possible shortest paths and determine the maximum load transmitted by the sensor nodes. We compare the two algorithms using a 6×6 grid topology with each sensor node having 1 unit of data to send to the sink. The value of *l* is 6 units. Fig. 2 shows that using the shortest path routing algorithm does not always result in increased robustness when transmission range increases. Furthermore, its robustness performance at transmission ranges smaller than *l* is clearly not close to optimal robustness performance.

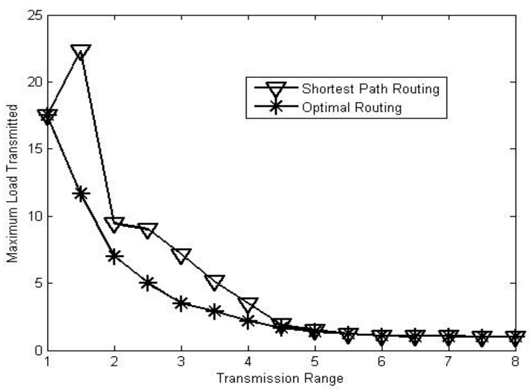

Figure 2: Shortest path routing versus optimal robust routing

There is a sharp decrease in robustness when we increase the transmission range from 1 unit to 1.5 units. We investigate this abnormality using a small grid of 3×3 nodes. When the transmission range is 1 unit distance, each sensor node can only transmit to another node horizontally or vertically. The nodes which transmitted the largest amount of load are shown in Fig. 3. If we increase the transmission range to 1.5 units as shown in Fig. 4, the maximum load transmitted may increase instead as the node indicated is on the path of many shortest paths from the sensor nodes to the sink.

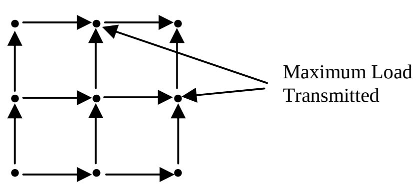

Figure 3: Illustration of shortest path routing when *t*=1 unit

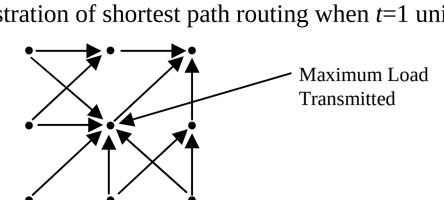

Figure 4: Illustration of shortest path routing when *t*=1.5 units

IV. Designing A Distributed Robust Routing Algorithm

A cross-layer design approach is required for designing robust sensor networks. The routing algorithm at the network layer needs to be designed in conjunction with the transmission power at physical layer to achieve optimal robustness performance. In this section, we will use linear programming to find the optimal routing protocol to validate our model. We consider a grid of 6×6 grid of sensor nodes each with 1 unit of data ($\alpha = 1$) to be sent to the sink. Each sensor node is 1 unit distance away from other sensor nodes in the x and y axes. E_m is 1 unit of energy. Free-space propagation model, where *k* is 2, is used to calculate the energy required for longer transmission range.

A. Optimization of Robustness Using Linear Programming

To find out how the optimal routing algorithm distributes the load among all its neighbors, we use optimization techniques using linear programming in 3 steps. In step 1, we minimize the maximum load transmitted by any sensor node by expressing the problem as a linear program:

minimize *c* subject to the following constraints:

$$f(u,v) = 0 \text{ for each } (u,v) \notin E \quad (1)$$

$$f(u,v) \geq 0 \text{ for each } (u,v) \in E \quad (2)$$

$$\sum_{v \in V} f(u,v) \leq c \text{ for each } u \in V \text{ - \{sink\}} \quad (3)$$

$$\sum_{v \in V} f(u,v) - \sum_{v \in V} f(v,u) = \alpha \text{ for each } u \in V \text{ - \{sink\}} \quad (4)$$

$$\sum_{v \in V} f(u,v) = 0 \text{ for } u \in \{\text{sink}\} \quad (5)$$

$$\sum_{v \in V} f(v,u) = (n^2 - 1)\alpha \text{ for } u \in \{\text{sink}\} \quad (6)$$

The variable *c* is the maximum amount of data transmitted by any sensor node among all the sensor nodes in the network. Constraint (1) means that if two sensor nodes are not within the transmission range, the flow between each other is 0. If two sensor nodes are within transmission range, the flow between each other must be non negative as stated in constraint (2). Constraint (3) states that the total amount of transmission data by any sensor node cannot exceed *c*. Constraint (4) states that all received data are to be forwarded and every sensor node has α units of data to be sent to the sink. Constraints (5) and (6) states that the sink is not sending any data and should receive all the data from the sensor nodes. The result obtained is c_m.

If there is only 1 unique solution, we can end here. If there are many solutions in step 1, we continue with step 2 by minimizing the maximum energy used by any sensor nodes by solving the following linear program:

minimize *p* subject to the following constraints:

Constraints (1), (2), (4), (5) and (6)

$$\sum_{v \in V} f(u,v) \leq c_m \text{ for each } u \in V \text{ - \{sink\}} \quad (7)$$

$$\sum_{v \in V} f(u,v) w(u,v) \leq p \text{ for each } u \in V \text{ - \{sink\}} \quad (8)$$

The variable p is the maximum amount of energy consumed by sensor nodes. Constraint (7) states that the total transmission for any sensor node cannot exceed c_m. Constraint (8) states that the energy consumed by any sensor node cannot exceed p. The result obtained is p_m.

If there is only one unique solution, we can stop here. Otherwise, in step 3, we minimize the total energy consumed by all the sensor nodes by solving the following linear program:

minimize $\sum_{u \in V} \sum_{v \in V} f(u,v) w(u,v)$ subject to the following constraints:

Constraints (1), (2), (4), (5), (6) and (7)

$$\sum_{v \in V} f(u,v) w(u,v) \leq p_m \text{ for each } u \in V \text{ - \{sink\}} \quad (9)$$

Constraint (9) states that the total energy consumed by any sensor node cannot exceed p_m.

B. Correlation Analysis

After obtaining the optimal routing algorithm, we find that $f(u,v)>0$ only if node v is nearer to the sink than node u is. Therefore, the neighbors that will forward the data from node u will be the neighbors that are nearer to the sink than node u is. A correlation test is used to determine whether there is any linear relationship between the amount of load to forward to a particular neighbor among all the possible neighbors and the actual distance gained towards the sink. This distance, $d(u,v)$, is defined as

$$\sqrt{(x_u - x_{n^2})^2 + (y_u - y_{n^2})^2} - \sqrt{(x_v - x_{n^2})^2 + (y_v - y_{n^2})^2}$$

where u is the node in consideration and v is any neighbor of that node. Fig. 5 shows that there is little or no correlation between the forward distance and the amount of data to forward to that neighbor. This means that greedy geographic routing, in which a node forwards its data to the neighbor which has the largest distance gained towards the sink, is not optimal.

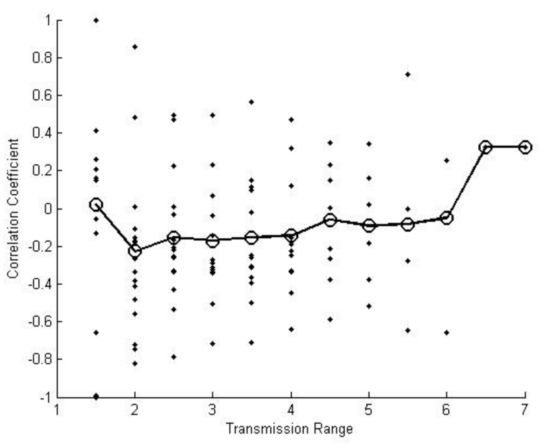

Figure 5: Correlation coefficients for each individual sensor node range from -1 to 1. The average correlation coefficients for different transmission ranges are connected using a line.

C. Distributed Robust Geographic Routing Algorithm for Wireless Sensor Networks

Since there is little or no correlation between the amount of load to forward and the distance of u's neighbors from the sink, our proposed robust geographic routing algorithm distributes the total amount of data to transmit among all u's neighbors that are nearer the sink than u is. The algorithm is as follows for any sensor node u:

i. Calculate $d(u,v)$ if $(u,v) \in E$.
ii. For every edge $(u,v) \in E$ with $d(u,v) > 0$, insert v in the set F.
iii. For every node $w \in F$, assign $f(u,w) = \dfrac{\sum_{v \in V} f(v,u) + \alpha}{m}$ where m is the number of nodes in the set F.

V. Results and Discussion

In this numerical analysis, the robust geographic routing algorithm is compared to four other different routing algorithms which are the shortest path routing algorithm, the greedy geographic routing algorithm, the energy-efficient routing algorithm and the optimal robust routing algorithm.

For the shortest path routing algorithm, all possible paths from the source to the sink are constructed and the load is distributed equally among all the possible paths.

For the greedy geographic routing algorithm, the load is sent directly to the sink if the sink is within transmission distance of the node. Otherwise, the load is sent to another sensor which is nearest to the sink. If there is more than one node which satisfies this property, the load is equally distributed between the nodes.

For the energy-efficient routing algorithm, linear programming is used to find the routing algorithm which maximizes the lifetime of the network. We define the lifetime of the network as the time when the first sensor node exhausts its energy. Therefore, we will minimize the energy consumed by any sensor node among all the sensor nodes. The methodology used is similar to that presented in section IV.A, except that step 2 is performed before step 1.

A. Maximum Load

Fig. 6 shows that our robust geographic routing algorithm performs close to the optimal robust routing algorithm and outperforms other routing algorithms in almost all cases. At higher transmission ranges, the energy-efficient routing algorithm shows no significant increase in robustness because the lifetime of the network is of higher importance than robustness. This shows that increasing the transmission range has minimal impact on robustness for the energy-efficient routing algorithm.

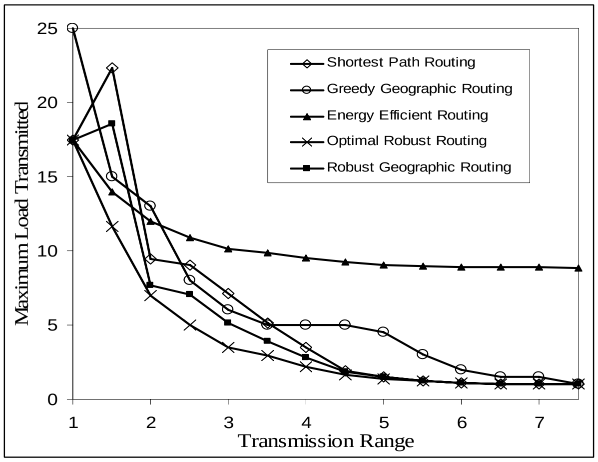

Figure 6: Maximum load transmitted using different routing algorithms

B. *Total Energy Usage*

Fig. 7 illustrates the total amount of energy consumed by all the sensor nodes. Although our robust geographic routing algorithm performs the worst in most cases, the difference is not very significant. This is because our robust geographic routing algorithm distributes energy more evenly across the entire network, therefore there is an increase in total energy consumption.

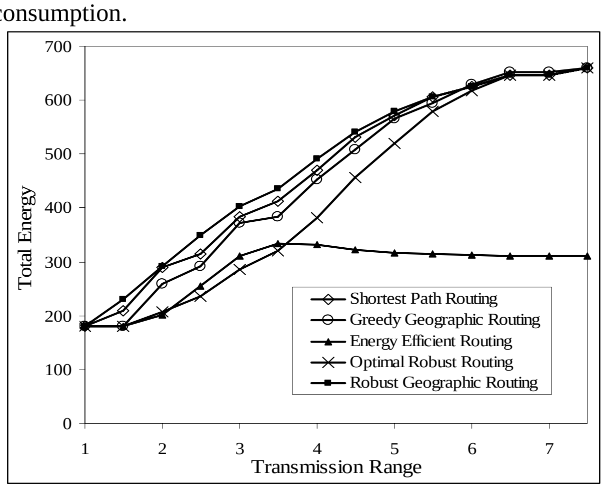

Figure 7: Total energy consumed by all the sensor nodes using different routing algorithms

C. *Energy Consumption and Robustness*

We determine the energy utilized to achieve one unit of robustness, κ. Fig. 8 illustrates the results obtained for different routing algorithms. When considering the cost, our robust geographic routing algorithm performs close to the optimal robust routing algorithm in most cases. The energy-efficient routing algorithm performs the worst in most cases. Although total energy usage is minimized, the cost of providing robustness is high as compared to other routing algorithms presented.

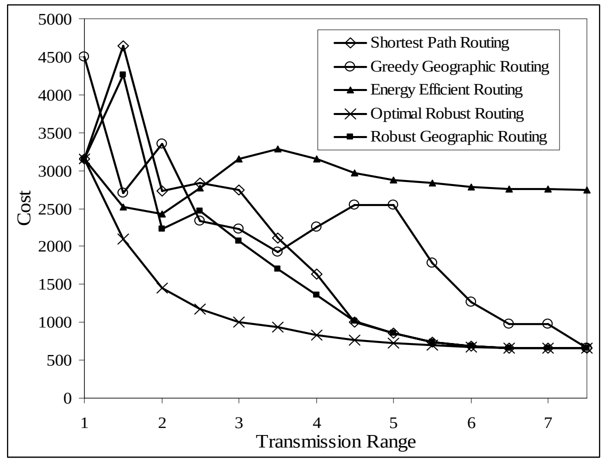

Figure 8: Energy utilized per unit of robustness using different routing algorithms

VI. CONCLUSION

In wireless sensor networks, accurate and complete sensor network data is crucial to understand and analyze a phenomenon. We have proven by analytical modeling that there exists a quadratic relationship between transmission power and the robustness of the network. We have also derived a relationship between the total energy consumption and the robustness of the network. We have shown that the robustness of the network also depends on the routing algorithm used, therefore a cross-layer design approach is needed to design robust sensor networks. By using optimization techniques to validate our model, we find the optimal routing algorithm that will optimize the robustness of the network. Then, using correlation analysis, we find that by simply distributing equally the load among the forwarding sensor nodes in geographic routing will provide a result close to the optimal case. We find that this simple routing algorithm outperforms the shortest path routing algorithm, the greedy geographic routing algorithm and the optimal energy-efficient routing algorithm based on robustness requirements. The advantage of this routing algorithm is that it only requires local neighborhood information which allows it to scale to very large sensor networks.

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