Effect of Overhearing Transmissions on Energy Efficiency in Dense Sensor Networks

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ABSTRACT

Energy efficiency is an important design criteria for the development of sensor networking protocols involving data dissemination and gathering. In-network processing of sensor data, aggregation, transmission power control in radios, and periodic cycling of node wake-up schedules are some techniques that have been proposed in the sensor networking literature for achieving energy efficiency. Owing to the broadcast nature of the wireless channel many nodes in the vicinity of a sender node may *overhear* its packet transmissions even if they are not the intended recipients of these transmissions. Reception of these transmissions can result in unnecessary expenditure of battery energy of the recipients. In this paper, we investigate the impact of overhearing transmissions on total energy costs during data gathering and dissemination and attempt to minimize them systematically.

We model the minimum energy data gathering problem as a *directed* minimum energy spanning tree problem where the energy cost of each edge in the wireless connectivity graph is augmented by the overhearing cost of the corresponding transmission. We observe that in dense sensor networks, overhearing costs constitute a significant fraction of the total energy cost and that computing the minimum spanning tree on the augmented cost metric results in energy savings, especially in networks with non-uniform spatial node distribution. We also study the impact of this new metric on the well known energy-efficient dissemination (also called broadcasting) algorithms for multihop wireless networks. We show via simulation that through this augmented cost metric, gains in energy efficiency of 10% or more are possible without additional hardware and minimal additional complexity.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*; G.2.2 [**Mathematics of Computing**]: Discrete Mathematics—*Graph algorithms, Network problems*

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General Terms

Algorithms, Performance

Keywords

Sensor networks, energy efficiency, data gathering, data dissemination/broadcast, overhearing

1. INTRODUCTION

Explosive growth in embedded computing and rapid advances in low power wireless networking technologies are fueling the development of wireless sensor networks. These dynamic and adaptive distributed systems have applications ranging from monitoring wild-life habitats, inventory management, data collection, and military and space applications. Sensor networks are composed of low power sensor nodes capable of sensing particular physical phenomena in their vicinity and communicating among themselves using wireless transceivers. Due to the large number of nodes, their low cost, or the amount of time they are expected to be deployed in a potentially inaccessible area[1], energy-efficiency becomes perhaps the most important design criteria for sensor networking protocols. A majority of sensor networking applications involve data gathering and dissemination; hence energy efficient mechanisms of providing these services become critical.

Numerous researchers have recently suggested a variety of mechanisms for achieving energy-efficiency in sensor networks, namely, in-network processing of sensor data [7], aggregation [10], transmission power control in radios, and periodic cycling of nodes' activity schedules [2]. Typically, the total energy cost of a transmitted bit is computed to be the cost due to transmission over a wireless channel over a certain distance plus the cost due to reception by the destination radio hardware [8]. However, due to the broadcast nature of the wireless channel many nodes in the vicinity of a sender node *overhear* its packet transmissions even if those are not the intended recipients of these transmissions [14]. This redundant reception results in unnecessary expenditure of battery energy of the recipients. Turning off neighboring radios during a certain point-to-point wireless transmission can mitigate this cost [14, 19].

In this paper, we investigate the energy-cost impact of overhearing packet transmissions during data gathering and dissemination in sensor networks. We model the minimum energy data gathering problem as that of computing a *di-*

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[1] Thus, recharging the sensors may not be an option.

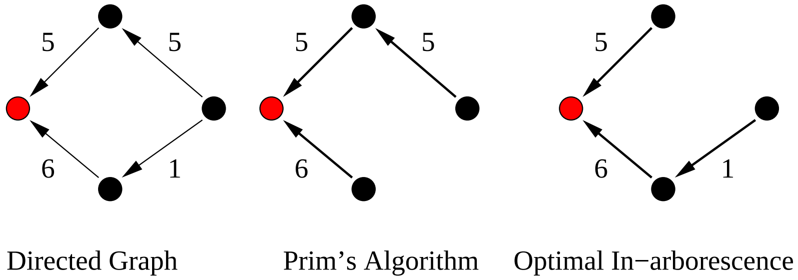

Figure 1: Minimum cost in-arborescence problem: We observe that a greedy algorithm is sub-optimal on directed graphs. In the above figures we are considering the data gathering problem where the left-most node in each subfigure is generating the gathering tree for the other three nodes.

rected minimum energy rooted spanning arborescence of a wireless network where the energy cost of each edge has been augmented by the overhearing cost of the corresponding transmission. We observe that in dense sensor networks, overhearing costs can constitute a significant fraction of the total energy cost and that computing the directed minimum spanning arborescence on the augmented cost metric results in energy savings. We observe a similar phenomenon for the dissemination (also known as broadcasting) scenario.

The rest of the paper is organized as follows: Section 2 introduces the energy models well known in literature; Section 3 introduces the problem of overhearing transmissions; Section 4 describes optimal algorithms for computing rooted arborescences as well as near-optimal heuristics for computing broadcast trees using the overhearing cost metric; Section 5 presents simulation results of the described algorithms; Section 5 concludes the paper.

2. PRELIMINARIES

Sensor networks can be classified into 2 categories: (1) query-driven and (2) event-driven. For the query-driven case, a user submits a query from a base station node (BS) which gets propagated through the network and sensors that can satisfy the query respond to the originator by means of unicast communications. In case of an event-driven system, each sensor sends data to the BS whenever it detects a certain event. This triggered mechanism can be thought of as a response to a long-standing query about that event. Since sending data along individual unicast paths from multiple sensors to the BS is expensive in terms of energy expenditure, researchers have proposed mechanisms to aggregate upstream data as it propagates through the network [10, 20]. Essentially, the sensed data flows back to the base station along the edges of a spanning tree which is constructed during the query dissemination phase. Such trees are referred to as routing trees or gradients. In this context, the principal mechanism of energy minimization is suppression of redundant data packets in the network.

A static sensor network can be represented by a set of nodes V with each sensor node possessing a geographical position attribute. The transmission energy required to transmit a bit of data from node u to v over the wireless channel is dependent upon the RF propagation path loss suffered over the distance d_{uv} between them; it is given by:

$$E_{uv}^{(xmit)} = E_{txelec} + \epsilon_{amp}\, d_{uv}^{\alpha} \qquad \alpha \geq 2.0 \tag{1}$$

Here, α is the path loss exponent and is dependent on the propagation channel and environmental conditions. E_{txelec} is the energy expenditure in the transmitter electronics (per bit) and ϵ_{amp} is a constant that is characteristic of the amplifier in the transmitter. Energy required to receive a bit of data at the receiver is a function of the receiver electronics and is given by:

$$E_{uv}^{(rcv)} = E_{rxelec} \tag{2}$$

Researchers routinely use the above energy model for modeling energy costs of edges in the network graph [8].

The ability to modify transmit power in sensors provides a powerful tool for minimizing energy and is a feature of numerous new sensor systems such as the ARL sensor radio [17]). If we consider arbitrary transmission power control in this model, every pair of nodes in the network will have an edge connecting them and the total energy cost along that edge due to both transmission and reception will be:

$$\begin{aligned} E_{uv} &= E_{uv}^{(xmit)} + E_{uv}^{(rcv)} \\ &= E_{txelec} + E_{rxelec} + \epsilon_{amp}\, d_{uv}^{\alpha} \end{aligned} \tag{3}$$

Note that the energy costs are symmetric in this model, in other words, $E_{uv} = E_{vu}$. Hence an energy efficient mechanism of transmitting a bit of data from all sensors to a base station node is to send and aggregate data along the edges of a minimum energy-cost spanning tree calculated on the entire network graph. Note that the network is represented as a complete graph (clique) under the assumption of arbitrary power control. If the peak transmission power is fixed and the transmitter is allowed to transmit at discrete power levels only, then the resulting graph may not be a clique but the edge costs are easy to formulate. Once the costs are known, the minimum energy spanning trees can be calculated using Kruskal's or Prim's algorithm [4] in $\mathcal{O}(e \log n)$ time. For cliques, a complexity of $\mathcal{O}(n^2)$ can be achieved using efficient priority queue data structures. Each leaf node in the resulting spanning tree transmits its data sample to its parent which aggregates this data with its own and that of other children nodes before transmitting the aggregate in turn to its parent node. This process continues until the base station receives the complete set of aggregates from its children.

3. ENERGY EXPENDITURE DUE TO OVERHEARING TRANSMISSIONS

In this section we demonstrate that the energy model presented in Section 2 is inadequate for dense sensor networks.

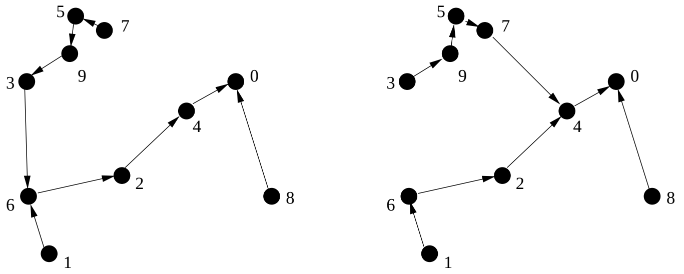

Figure 2: Minimum Energy Directed Spanning Trees (node 0 is the base station): (a) without overhearing cost; (b) with overhearing cost. This network has the ability to be fully connected if nodes use their maximum transmit power.

When a certain node u transmits a data packet for node v using optimal transmit power, all nodes x such that $d_{ux} < d_{uv}$ also receive (or *overhear*) the packet unnecessarily. Hence the reception energy costs increase. This is especially true for dense networks where each node has several neighbors in its close vicinity[2].

In the energy model that incorporates overhearing, the total energy expenditure due to a transmission from node u to v is given by:

$$\begin{aligned} E_{uv} &= E_{uv}^{(xmit)} + E_{uv}^{(rcv)} + E_{uv}^{(ov)} \\ &= E_{txelec} + \epsilon_{amp}\, d_{uv}^{\alpha} + N_{uv}^{(ov)} E_{rxelec}, \end{aligned} \tag{4}$$

where $N_{uv}^{(ov)}$ is the number of nodes within the communicating radius of u when it communicates with v. These are the set of nodes which *overhear* the transmission of the packet from u to v.

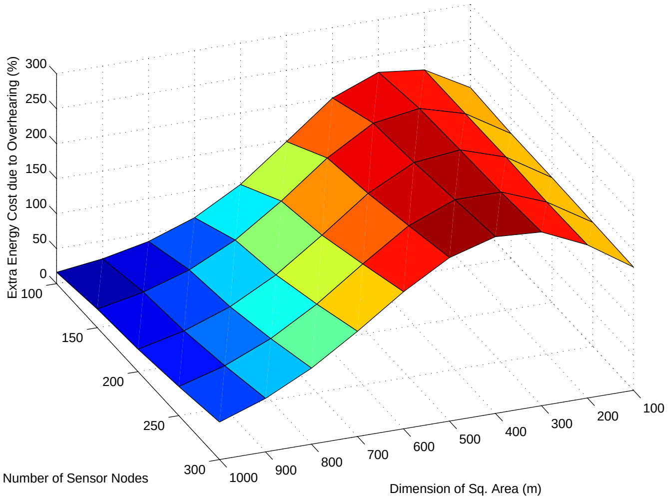

Figure 3: Example of the additional energy cost due to overhearing transmissions along the Minimum Energy Spanning Tree. Simulation parameters including energy costs are the same as those in Table 1 and node locations were generated (uniformly) randomly.

It is easy to see that $E_{uv} \neq E_{vu}$ since $N_{uv}^{(ov)}$ is not necessarily equal to $N_{vu}^{(ov)}$. This results in a directed network graph with asymmetric edge costs, therefore, regular minimum cost spanning tree algorithms are not applicable in this scenario. A minimum cost spanning tree will have to be replaced by a directed minimum cost arborescence R rooted at the base station node such that each node has a valid directed path to the root using the edges of R. Figure 1 illustrates a simple example in which the greedy Prim's algorithm does not yield an optimal rooted arborescence.

This energy model of overhearing assumes that a sensor's receiver circuitry is always awake and can receive and decode all incoming packets. The energy cost of a complete packet reception is greater than the cost of remaining idle [14, 9, 19][3] and is compounded by the need of the receiver to decode the entire packet before determining whether it is the intended recipient. This can indeed be an issue in dense sensor networks where a packet transmission can be overheard by a large number of receivers. Certainly, if the receiver possesses a mechanism of decoding the header of the packet alone and then shutting the radio off for a brief period if it is not an intended recipient, then additional energy savings can be achieved. However, such fine grained scheduling of receiver electronics comes for a high price in terms of hardware complexity and may induce delays in protocol processing at higher layers. We leave this investigation for future research.

Figure 2 illustrates a scenario where ten nodes are sending data towards the base station (node 0) and they are all capable of controlling their transmission power; the intermediate nodes aggregate the data before sending it upstream towards node 0. Figure 2(a) shows the case where data is transmitted along a directed Minimum Energy Spanning Tree or *MEST*. When node 3 forwards a packet to node 6, its transmission is *overheard* by nodes 5, 7 and 9; this results in unnecessary energy expenditure at the latter nodes which cannot be prevented altogether. However, if data is transmitted along a directed Minimum Overhearing Energy Spanning Tree or *MOEST* shown in Figure 2(b), this unnecessary expenditure is minimized. While there are 8 redundant overhearing transmissions in the former case, there are only 5 such transmissions in the latter case. The energy savings due to fewer overhearings in this particular network topology are greater than the extra transmission energy cost, hence the MOEST has a lower total energy expenditure than the MEST.

Figure 3 plots the extra cost of overhearing if data is gath-

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[2] The perfect solution without an overhearing penalty will entail each node having a directional antenna perfectly pointed towards its parent in the spanning tree.

[3] Exact Tx:Rx:Idle power ratios vary depending on the radio hardware.

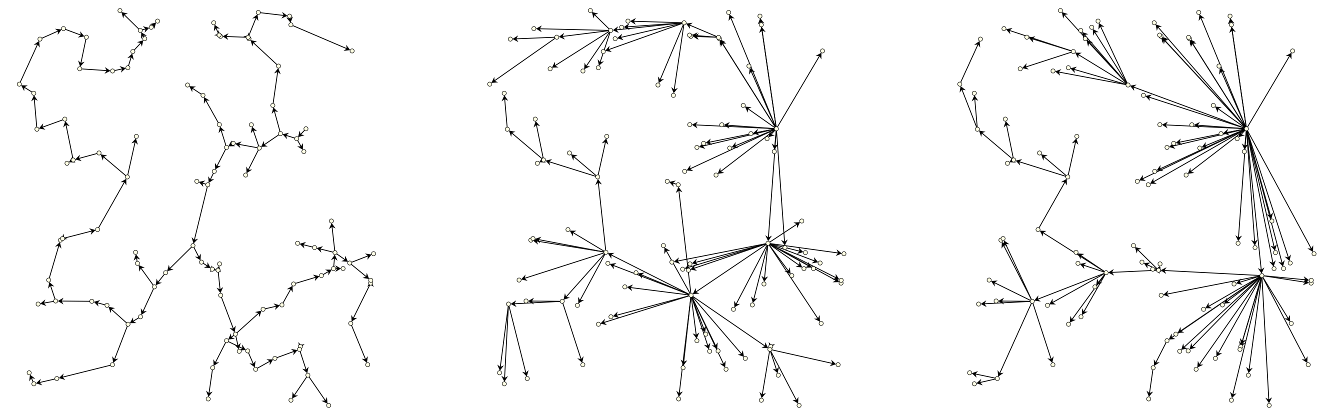

Figure 4: Minimum Energy Directed Broadcast Trees with Wireless Multicast Advantage using Different Energy Cost Models: (a) Tx cost only; (b) Tx plus electronics cost; (c) Tx plus electronics plus overhearing cost. The trees are more *bushy* in (b) and (c) when electronic and receive energy costs are included.

ered from a specified number of sensors towards a base station node along the edges of a minimum energy spanning tree. The additional cost is plotted as a percentage of the base energy cost. The energy cost due to transmission electronics is included in both cases. We observe that the overhearing cost can be very high (up to approximately 300% greater than the base energy cost according to Equation 3 ignoring any idling energy costs) in dense networks for the network sizes plotted in the graph. Hence, algorithms which can minimize this extra cost are necessary. We propose such algorithms in the next section.

4. ENERGY-EFFICIENT DATA GATHERING AND DISSEMINATION ALGORITHMS

4.1 Data Gathering Problem

As mentioned in the previous section, the energy-efficient data gathering problem can be optimally solved by computing the minimum cost arborescence rooted at the base station node. The problem can be posed formally as follows – find arborescence R that satisfies the following:

- $\sum_{(u,v)\in R} E_{uv}$ is minimum; E_{uv} is given by Equation 4.
- $R = (V, E)$ is a directed subgraph of $G = (V, V \times V)$ without self-loops and possesses $|V| - 1$ edges.
- R has exactly one root node r ($outdegree(r) = 0$) and it is connected, i.e., there is exactly one directed path from each node $w \in V - \{r\}$ to r.
- $\forall w \in V - \{r\} : outdegree(w) = 1$.

The last two conditions impose additional constraints on the computation of the directed spanning tree that make the problem different from the regular minimum cost spanning tree problem. Edmonds proposed an efficient algorithm for finding optimum branching (rooted forests) with maximum cost on arbitrary directed graphs [6]. He pointed out that optimal arborescences (rooted trees) can be computed with very minor modifications to the branchings algorithm if the directed graph is strongly connected. Tarjan proposed an efficient implementation of Edmond's branching algorithm in $\min\{\mathcal{O}(e \log n), \mathcal{O}(n^2)\}$ time using efficient priority queue and set union/find primitives [16].

We implemented Tarjan's algorithm and trivially adopted it to solve the minimum cost case instead of the maximum cost case as was done in both [6] and [16]. This was done by replacing original costs by their negative values and then invoking the maximum branching algorithm. Since our graph is strongly connected, it is guaranteed to have an arborescence (and not just a branching) and then the above step works.

The salient steps of the algorithm to find the max-cost spanning in-arborescence are outlined below. We first reverse the directions of the edges, compute an out-arborescence (by Tarjan's scheme), and then reverse the edge directions again.

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1: Construct complete graph $G$ – the edge cost between every pair of nodes $u, v$ is a function of their positions as given by Equation 4. Initialize subgraph $G(H) \leftarrow (V, \phi)$.
2: Reverse the directions of all edges and replace the costs by their negative values. Remove all *incoming* edges into root node $r$.
3: Choose a root component $S$ in subgraph $G(H)^4$.
4: Select the max-weight edge $e = (u, v) \in V \times V$ incoming into $S$. If $u \in S$ discard edge $e$ and goto step 3; otherwise goto step 5.
5: If $u$ and $v$ do not belong to the same weakly connected component of $G(H)$, add $(u, v)$ to $H$ and goto step 3; otherwise goto step 6.
6: Find the sequence $\{S_i, (x_i, y_i), \ldots\}_{i=1}^{k}$ of strongly connected components $S_i$ and edges $(x_i, y_i) \in H$; $y_i \in S_i, x_i \in S_{i+1}, S_k = S, (x_k, y_k) = (u, v), x_k \in S_1$. Find min-cost edge $(x_j, y_j)$ among $(x_i, y_i)$.
7: Redefine the cost of unexamined edges of the form $(x, y)$, $y \in S_i$ as follows:
       $c(x, y) := c(x, y) - c(x_i, y_i) + c(x_j, y_j)$
8: Add $(u, v)$ to $H$ thus combining $S_i$'s to one strongly connected component. If all nodes in $G$ have been selected,
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[4] If S is such that no edge $(u_1, u_2) \in H$ satisfies $u_2 \in S$ and $u_1 \in V \setminus S$, then S is a root component of $G(H)$.

goto step 9; otherwise, goto step 3.

9: Find the shortest path tree T on H rooted at r.

10: Reverse the directions of edges in T and restore the original positive costs; R is the resultant minimum cost gathering arborescence.

We implemented the above algorithm using efficient data structures such as priority queues as suggested in [16]; since there are $\binom{n}{2}$ edges in G, the time complexity is $\mathcal{O}(n^2)$. We simulated the above algorithm for sensor networks of various sizes at different node densities; both MEST and MOEST were simulated and the results of comparison have been presented in Section 5.

4.2 Data Dissemination Problem

Energy-efficient data dissemination in wireless networks has been a hot topic of interest in the research community recently [18, 1]. The objective is to develop algorithms that consume the minimum amount of energy for broadcasting a bit of data to all nodes in the network. The broadcasting (or dissemination) problem in wireless networks is different from its point-to-point wired counterpart because the wireless channel has inherent broadcast capability; hence a node can send a packet to all its neighbors with just one broadcast. Wieselthier et al. coined the term "wireless multicast advantage" (WMA) for this phenomenon. In [18] they developed energy-efficient broadcasting protocols which exploit the WMA.

Cagalj et al. showed that the wireless broadcast (or dissemination) problem is NP-complete and developed approximation algorithms as well as a heuristic called EWMA (Embedded WMA) [1] whose salient steps are outlined below:

1: Construct a feasible solution for broadcast. e.g., we start with a Minimum Energy Spanning tree as an initial broadcast tree.

2: Exchange some edges of this tree with new edges in order to systematically reduce the total energy cost. This reduction is referred to as *gain*. At the expense of increase in a certain node v's transmission energy, significant gain can be achieved by excluding several nodes from the broadcast tree. In this step, one has to ensure that the node v should be able to reach nodes which were previously reachable only through a subset of the excluded nodes in the broadcast tree.

3: Iterate the previous step until no nodes can be excluded from the broadcast tree and all nodes in the network are covered.

In this section we investigate how overhearing energy cost models affect the total energy savings. Figure 4 illustrates the effect of using different energy cost models on the structure of the broadcast tree generated by EWMA. The inclusion of the transmission electronics cost (E_{txelec}) causes EWMA to reduce the number of transmitting nodes since a large number of transmissions is deemed expensive in this model. This results in some nodes having to increase their transmission power and *cover* the excluded nodes, and hence giving the tree a *bushy* appearance.

When the overhearing cost is included in the energy model, we observe that the tree is bushier near the root node but less so at forwarding nodes at lower levels. The reason behind this is intuitively clear: having a number of low degree forwarding nodes at lower levels of the tree results in lesser expenditure of energy due to overhearing than if the forwarding nodes at all levels have similar degree (which is the case for Figure 4(b)). This non-uniform degree structure for case in Figure 4(c) minimizes the redundancy of overhearing at other nodes. We show by simulations in Section 5 that the total energy cost can be minimized by incorporating overhearing cost into the energy model.

Table 1: Simulation Parameters

Parameter	Value
P_{txelec}	50 mW
P_{rxelec}	50 mW
B (data rate)	1 Mbps
E_{txelec}	$\frac{P_{txelec}}{B} = 50$ nJ/bit
E_{rxelec}	$\frac{P_{rxelec}}{B} = 50$ nJ/bit
$P_{rxthresh}$ (Rx sensitivity)	-72 dBm
h (antenna height)	1.5 m
ν (frequency band)	916 MHz
λ (RF wavelength)	c/ν
$e_{amp}(\alpha = 2)$	$\frac{16\pi^2 P_{rxthresh}}{B\lambda^2}$ J/bit/m^2
$e_{amp}(\alpha = 4)$	$\frac{P_{rxthresh}}{Bh^4}$ J/bit/m^4
d_{xover} (crossover)	$\frac{4\pi h^2}{\lambda} \approx 86$ m

4.3 Discussion

Since idle listening on a wireless channel is a significant source of energy consumption, researchers have proposed a multitude of schemes for mitigating this problem. Preamble sampling [5], PAMAS [14] and wake-on-wireless [13] are representative of such schemes. In the first scheme, a sensor node goes into fine-grained periods of sleep and wakes up periodically[5] to sample the channel, and it keeps awake if it sees a preamble transmitted by the sender. The receiver may still incur the overhearing energy cost since it has to decode the entire packet before ascertaining whether it indeed is an intended recipient of the transmission. Both PAMAS and wake-on-wireless schemes advocate the separation of signaling and data channels to achieve greater power efficiency.

In wake-on-wireless, a low-power radio that consumes only 2mW of power listens to incoming transmissions and wakes up the main radio when it detects a valid incoming packet. Although this technique mitigates the overhearing cost in point-to-point transmissions (as in the data gathering case), it may not be able to do so in the network-wide data dissemination scenario[6] Arguably, more sophisticated protocols can be developed that can save energy in this situation, but we leave that for future investigation.

While minimizing total energy is always a desirable goal in the data dissemination application, the choice of the broadcast transmission strategy should be made only after evaluating all the trade-offs appropriately. For example, if reliability in broadcast is more desirable than total energy savings, a sparse tree can be more suitable than a bushy one. We leave the study of such trade-off for future research.

We note that these algorithms require knowledge of the state of all links in the network. Such algorithms can be implemented without modification in networks that use dis-

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[5] The radio is turned on for $30\mu s$ in every $300\mu s$ instead of $10s$ in every $100s$.

[6] The low-power radio will always wake up the main radio upon the arrival of a broadcast packet even if that packet is redundant from a dissemination standpoint.

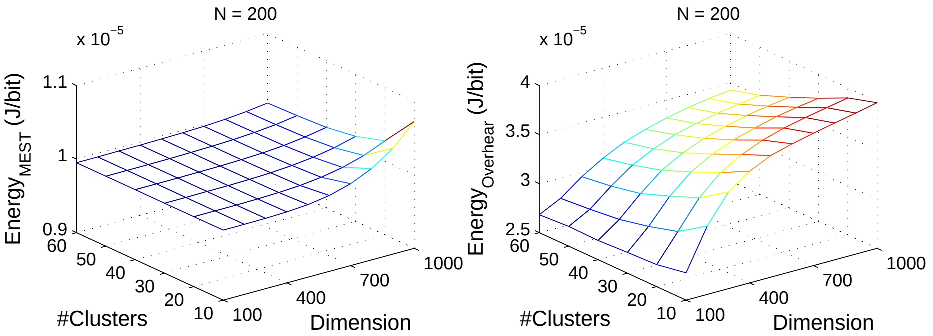

Figure 5: Total Energy vs. Degree of Clustering and Area: (a) Cost of the gathering tree MEST without overhearing cost; (b) Cost of overhearing along edges of MEST (Cluster radius = 20 m)

Table 2: Overhearing Energy Costs for Data Gathering in Random Topologies (nodes uniformly distributed in a 0.25 km^2 area; cost in J/bit)

N	Cost(MEST)	Cost(MOEST)	% Gain
50	0.66288×10^{-5}	0.64324×10^{-5}	2.96
100	1.34579×10^{-5}	1.29657×10^{-5}	3.66
200	2.71298×10^{-5}	2.61901×10^{-5}	3.46
300	4.07797×10^{-5}	3.92669×10^{-5}	3.71
400	5.4402×10^{-5}	5.24448×10^{-5}	3.60

tributed databases of topology information such as link state style protocols [3, 11], or can be implemented with modification and some loss of performance in protocols which distribute more limited sets of network information such as HSLS [12].

5. SIMULATION RESULTS

We simulated the optimal minimum energy spanning tree algorithm for two dimensional sensor networks. The radio parameters used for simulation have been listed in Table 1 (most parameters have been taken from [8]).

5.1 Data Gathering Results

First, we present simulation results for the data gathering problem. We simulated Tarjan's algorithm for energy models both with and without overhearing cost. We began our investigation with randomly (2D uniform distribution) distributed topologies. Table 2 presents a snapshot of the results. The costs presented therein correspond to the total energy expenditure (transmission, electronics and overhearing reception) for MEST and MOEST style tree construction. While the former method ignores the overhearing cost during tree calculation, the latter factors that in. We observe that the gains are modest (less than 4%) in the uniform density case for several values of N. Hence we decided to investigate whether the gains are higher for non-uniform network topologies.

We simulated non-uniform topologies in the following manner: first k points are generated with coordinates drawn from a uniform distribution; these points correspond to the k clusters in the network and a number of points (total of N) are randomly generated within a certain radius of these cluster centers (20 m, in our simulations). For low values of k the network is highly non-uniform but as k approaches N, the non-uniformity vanishes.

Figure 5 plots the variation in the total cost of MEST with area and clustering for $N = 200$. Both base and overhearing costs are plotted. We observe that the increase in area is more gradual for high k than for low values of k (high degree of clustering). At low k, the distance between clusters increases more rapidly with increase in area and the propagation cost along edges connecting the clusters starts dominating.

When the network is very dense (200 nodes in a $0.01 km^2$ area), radio electronics tend to dominate the energy cost and hence $cost(MEST)$ is unaffected by a variation in k. However when the area is increased, the cost of edges connecting the k clusters tends to dominate the electronics cost. It is known that the cost of the minimum spanning tree of random graphs with power-weighted edges[7] diminishes as N increases [15]. Hence, as k increases the sum of costs of the long edges connecting the k clusters decreases and thus $cost(MEST)$ decreases as well[8]. For similar reasons we observe that the overhearing cost increases with both area and degree of clustering.

In Figure 6 we compare the total energy expenditure (transmission, electronics and overhearing reception) due to MEST and MOEST. Representative results for 500×500, 600×600, and 700×700 areas have been shown. We observe that MOEST outperforms MEST in this metric in all scenarios. Gains up to almost 10% are observed. While this may not be a very large value, it is not insignificant for low power sensor networks which need to operate as long as possible. For all N, the absolute gains (not relative gains) of MOEST over MEST are maximum for low k and diminish gradually as k increases. This is because there is a greater degree of overhearing for highly clustered networks and hence it pays to consider that into the cost model.

From Figure 7 we observe that the source to sink path lengths are not affected much by incorporating overhearing cost in the cost model. In fact, on several occasions (low k), MOEST gives shorter average path lengths than MEST. This means that the aggregated packets will not suf-

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[7] This refers to the case where the edge cost is of the form of r^β where r is the euclidean length of the edge and β is a quantity greater than 1.

[8] This is because the cost of edges connecting the k clusters dominates the total cost.

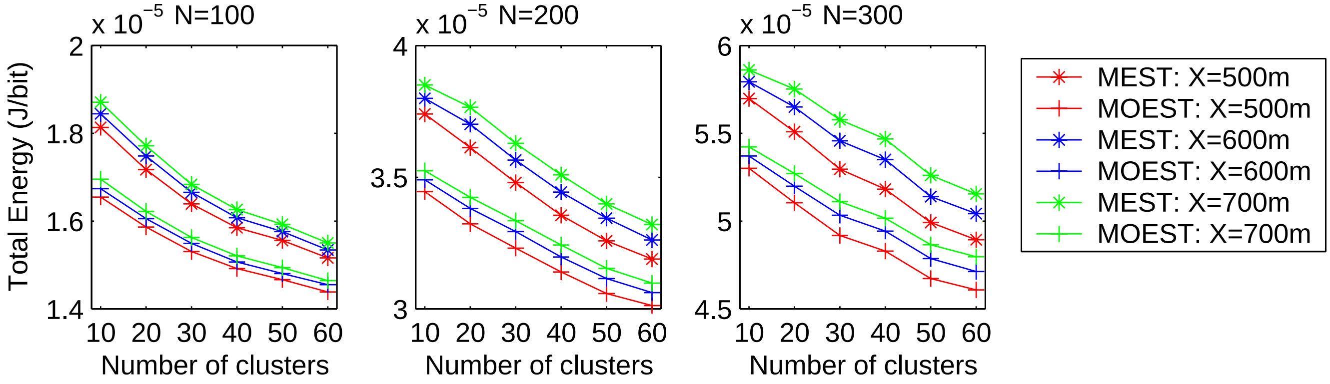

Figure 6: Simulation Results for Clustered Topologies: Total Energy Consumption vs. Number of Clusters: Lines exist in pairs for each area and they correspond to the manner of tree construction for data gathering. The Y-axis however, represents the total energy consumed in the overhearing energy cost model for each of these trees.

fer greater delays if one decides to include overhearing cost into the energy equation.

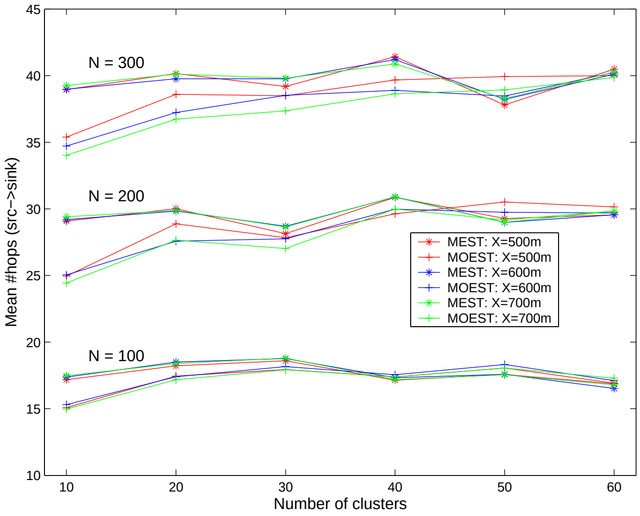

Figure 7: Simulation Results for Clustered Topologies: Average Hop Counts for Minimum Energy Spanning Trees. The average source to sink path lengths are not affected much by the cost model.

5.2 Data Dissemination Results

Here we present the simulation results for the energy-efficient data broadcast algorithm due to Cagalj et al. [1] as mentioned in Section 4.2. A random (uniform) distribution of nodes was assumed in both dense and sparse topologies. In Figure 8 we simulate and plot the total energy consumed to broadcast a bit of data for 3 different energy cost models for $N = 100, 200, 300$. We observe that graphs for all these cost models are *wavy* in general shape, i.e. they have regimes of sharp increase followed by gentle increase and then sharp increase again. For the densest networks (dimension around $100m$) the electronics cost dominates the energy equation and the depth of the broadcast tree is 1 for energy models 2 and 3; hence the curves are mostly flat. As the network gets slightly sparser (dimension between $500m$ and $1000m$, the depth of the EWMA increases to a few hops and that results in a sharp increase in energy costs of models 2 and 3. This is the regime where overhearing starts to become a major factor.

As the network becomes sparser (dimension between $1000m$ and $3000m$), electronics and overhearing costs are comparable to the propagation energy costs and the trees are less bushier. Hence a slight increase in area does not result in a significant increase in energy. However there is a sharp increase in costs as the network becomes very sparse ($3000m$-$5000m$) because the propagation cost is the dominant factor in that regime, not the electronics or overhearing cost. The broadcast trees are not at all bushy for such sparse networks.

The gains of using electronics and overhearing cost models are maximum for dense networks and these increase in absolute value as N is increased. This is because for dense networks, all nodes can be "covered" with only a few broadcasts. See Figure 10 shows how the number of forwarding nodes increases with the area in each case.

The gains of using the overhearing cost model over the other two models which do not capture that cost can be seen in Figures 8 and 9. The highest percentage gains can be observed around the 1 km^2 region. We see that incorporating overhearing as well as electronics cost into the energy equation can save as much as 45% energy in those regimes. We also observe that energy model 3 (overhearing cost) yields gains of over 10% above energy model 2 in dense networks ($N = 300$; dimension around $1000m$).

These energy gains come in at the expense of other metrics. The trees are likely to be very bushy and thus less reliable and the burden of forwarding the packet is shared by only a small fraction of the nodes (see Figure 10). It is the duty of the system designer to analyze the requirements of the task and balance these trade-offs.

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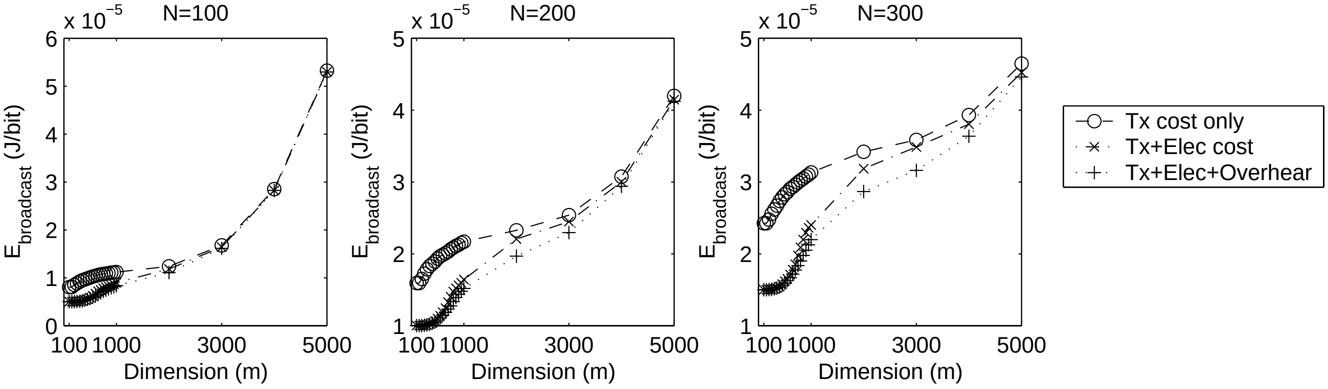

Figure 8: Effect of Overhearing Transmission on Dissemination Algorithms: Each of the 3 lines in every subplot represents the particular manner of construction of the broadcast tree although the Y-axis represents the total energy consumed in the overhearing energy cost model alone. We can observe that the gains of using the overhearing energy cost model for tree construction improve as N increases. For each N the gains over the "transmission cost only" model are maximum for the densest scenarios.

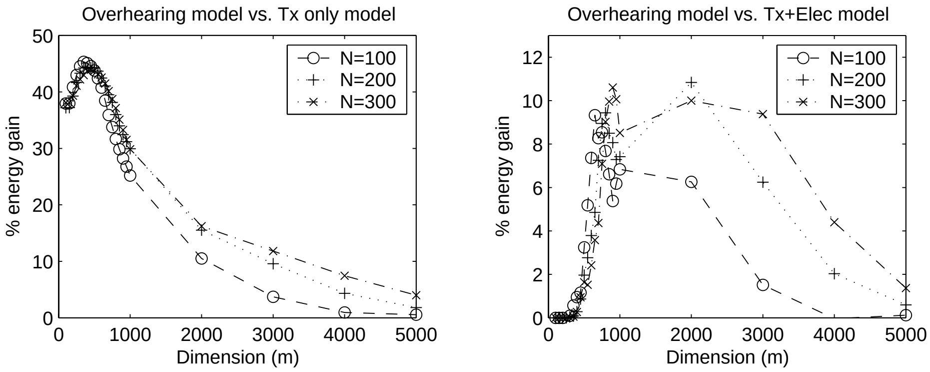

Figure 9: Energy Gain due to use of the Overhearing Cost Model: (a) Gains over transmission cost model; (b) Gains over transmission and electronics cost model

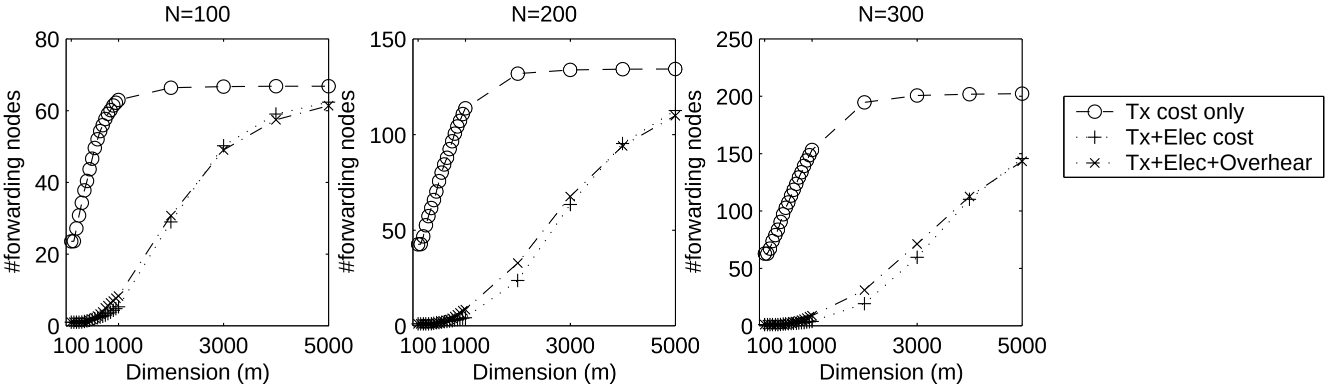

Figure 10: Number of Nodes Forwarding Packets in the Broadcast Tree: Much lesser number of nodes participate in forwarding broadcast packets if electronics and/or overhearing cost is included in the model. There are a few more forwarding nodes in the overhearing cost model than in the electronics cost model.

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6. CONCLUSIONS AND FUTURE WORK

In this paper we showed that in dense sensor networks, packet overhearing at receivers be a significant additional energy expenditure during data gathering and dissemination. We argued that overhearing cost should be incorporated into the energy equation while calculating the best data gathering and broadcast trees. We also showed that traditional minimum energy spanning trees are inadequate due to the asymmetric nature of the overhearing cost and we described briefly how Tarjan's minimum branching/arborescence algorithm can be utilized to do the job. We demonstrated by simulations that incorporating overhearing cost into the energy model can result in close to 10% energy savings in both data gathering and broadcast scenarios.

In future, we plan to investigate the impact of overhearing on data dissemination and gathering applications under more complex and detailed energy models and channel access schemes, especially the ones involving intelligent cycling of low-power sensor radios to save energy.

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