The Effect of Overhead Energy to the Lifetime in Wireless Sensor Networks

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ABSTRACT

Although the transmitter energy is one of the major factors of total energy dissipation in a sensor node, neglecting the overhead energy in energy aware routing decisions could result in suboptimal energy usage. Routing algorithms should be concerned about the overhead energy which is wasted at each hop of data transfer. When only the transmission energy is considered as the communication cost, using shorter multi-hop links seems to be more advantageous. However, due to other energy consuming activities on the sensor nodes, such as reception of relayed messages, sensing and computation tasks, a considerable overhead energy might be dissipated while forwarding a message. Therefore, multi-hopping becomes not always advantageous in wireless sensor networks. In this work, we investigate the use of multi-hop communication links and compare the amount of energy gain acquired by correct routing energy calculations. We show that neglecting the overhead energy and overemphasizing the importance of power adjustable transmitter circuitry could result in considerable energy loss.

I. INTRODUCTION

The design of energy efficient routing algorithms is important in ad hoc networks, since mobile nodes operate on stand alone battery power. In traditional ad hoc networks, the packet transmission energy is much larger than the packet reception energy and the idle energy. The path loss exponent α has a great impact on energy dissipation, since the transmitter energy is proportional to d^{α} where d is the range of the radio signals [1]-[6]. However, in sensor networks, the communication distance is very short due to the dense deployment and stringent power limitations of sensor nodes. The required energy for packet reception is at the same order as the energy for packet transmission using state of the art hardware technology [7].

There has been several works on developing energy efficient routing algorithms in traditional ad hoc networks. In [2], a minimum energy connection protocol based on the distributed Bellman-Ford algorithm is investigated. The effect of mobilization is also analyzed. In [3], a power-aware routing algorithm is presented, which helps to minimize the transmission power needed to forward data packets. In [4], directional antennae are used to construct the minimum energy tree. Here again, the cost of a link is assumed to consist of only the dominant component, i.e., the transmitter energy. Energy efficiency on constructing multicast trees on wireless networks is considered in [6], where the energy gain is focused on transmitter energy.

When only the transmission energy is considered, using shorter multi-hop links seems to be more advantageous. However, due to other energy consuming activities on the sensor nodes, such as reception of relayed messages, sensing and computation tasks, a considerable overhead energy might be dissipated during forwarding a message. Therefore, multi-hopping is not always advantageous in wireless sensor networks.

In this paper, we try to investigate the effect of the overhead energy dissipation at the sensor nodes to the overall network lifetime. We focus on uniformly deployed sensor nodes, each having identical communication capabilities. The sensor nodes are assumed to be able to adjust their transmission power. Therefore, each sensor consumes only the amount of energy that will suffice to reach for the transmitted radio waves to the destined receiver antenna. A similar transmitter model is proposed in [8].

The remainder of the paper is organized as follows. In the next section we introduce the network and power model that we use in the paper. These models are applicable to most of the applications where a random deployment strategy is used. In Section 3, we provide a simple network to explain the importance of overhead energy on network topology. Section 4 presents experimental results which are derived using simulations. We conclude the paper in Section 5.

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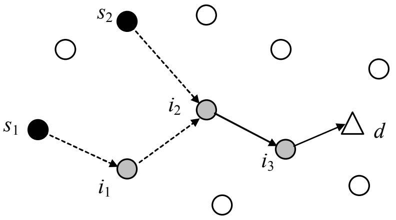


Fig. 1. Data delivery from source to the destination using intermediate nodes.

II. NETWORK MODEL

A. Definitions

The sensor network is represented by a directed graph $G = (V, A)$ where V, the set of vertices represents the sensor nodes and A, the set of arcs represents valid communication links. A vertex $i \in V$ that is representing a sensor node is referred as "node i." An arc, or a communication link between two nodes i and j is represented as $(i, j) \in A$, where $i, j \in V$. A path is a sequence of nodes $<i, j, \ldots, k>$, where $i, j, \ldots, k \in V$, such that each node is connected to the next node in the sequence. In other words, the arcs (i, j), $(j, \ldots)$, …, $(\ldots, k)$ are in the arc set A. d_{ij} represents the Euclidean distance between nodes i and j.
If the sensors are equipped with undirected antennae then each node is connected to every other node within the transmission range of its radio signals. The sensors are assumed to be identical having the same radio equipment. Therefore, whenever a node u can reach to another node v, it is evident that backward communication is also possible, i.e., node u can be reached by node v.
Routing decisions will dictate sensor nodes with different transmission power levels in order to save energy. Therefore, it may easily happen that node u transmitting with a high power level to reach to a distant node v, and node v transmitting with a lower power level to a closer node w. In this case, it is clear that node v cannot be heard by node u. Therefore, we assume directed edges in the network graph G.

B. Communication Scenario

In general, sensor communication resembles the wireless ad hoc network architecture. The communication takes place between the sensor nodes and the sink node.
Each node generates a small data packet containing the knowledge gathered from the environment. This data packet is sent to the sink using the underlying routing method with the help of intermediate sensor nodes. In Fig. 1, sensor nodes s_1 and s_2 transmit data packets simultaneously. Their packets are routed to the destination node d through intermediate nodes i_1, i_2 and i_3. The underlying routing method may choose to merge the data packets into one packet on the way to the destination, which is not done in our simulations. All other nodes in the environment may stay idle during this communication.

C. Multi-Hop Links

During selection of the most energy effective route, alternative links must be considered. In the simplest case, one has to choose between a direct link from source to destination and a multi-hop link using intermediate nodes, if available. A communication request between nodes i and j may trivially result in a direct link (i, j) between those two nodes, whereas a "good" alternative would be found by using the intermediate node k resulting in the path $<i, k, j>$.

D. Energy Model

We can write the total energy dissipation e_j^T of the sensor node j as a function of distance d as follows

$$e_j^T(d) = \kappa d^{\alpha} + \tau \qquad (1)$$

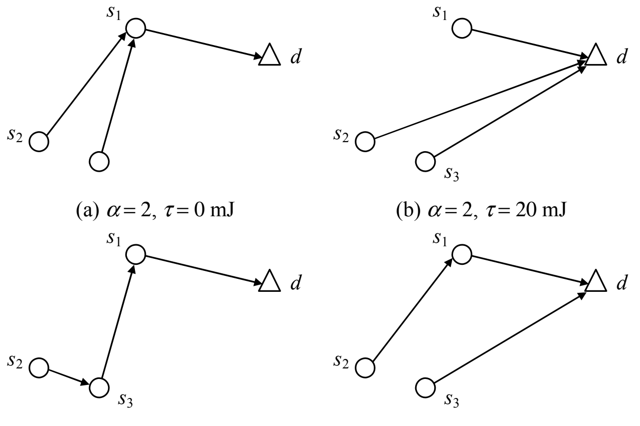
where $\kappa, \tau \in \Re$ are real numbers. τ is the *overhead energy*, representing the sum of the receiver, sensing and computation energy which is a constant value with varying distance d. This energy model is very simple in the sense that it does not provide details on attenuation, fading, and multi-path propagation. The reader may refer to [9] if more detailed empirical and semi-empirical path loss power models are needed.
Whenever a sensor node acts as an intermediate node which only forwards the data packets, then this node does not perform sensing tasks, hence no sensing energy should be dissipated. Therefore, it seems that the "sensing energy" may not be a part of the overhead energy.
On the other side, there might be applications, where the intermediate nodes might choose to piggyback their sensing results into the data packet, rather than sending another individual data packet. In this case, the sensing energy should be considered as a parameter within the overhead energy.

E. Network Lifetime

In this work, the network lifetime is defined as the length of time until the first battery drain-out among all sensor nodes occurs [10].

$$T = \min_j \left\{ \, t : e_j(t) = 0, t \in \Re \, \right\} \qquad (2)$$

where the sensor's energy reserve $e_j(t)$ is defined as a monotonically decreasing function of time. In [11], several other criteria are considered to define network lifetime, such as the ratio of the uncovered area to the total area, or the reliability of the data retrieved from the environment.



(a) $\alpha = 2$, $\tau = 0$ mJ (b) $\alpha = 2$, $\tau = 20$ mJ

(c) $\alpha = 3$, $\tau = 0$ mJ (d) $\alpha = 3$, $\tau = 20$ mJ

Fig. 2. A sample network representing different topology alternatives for different path loss exponent α and overhead energy τ values.

III. MOTIVATION FOR OVERHEAD ENERGY CONSIDERATIONS

The route calculations should consider the *overhead energy dissipation* at the sensor nodes, which include the receiver energy, the computation energy, and the sensing energy. These overhead energy requirements and path loss exponent values may result in different minimum energy tree structures, consequently different routing topologies.

Consider a small wireless sensor network with three sensor nodes s_1, s_2, s_3 and one destination node d whose layout is given in Fig. 2. Even in such a small network, we can see that routing decisions based on energy calculations may result in different routes depending on the assumptions about the underlying model. Fig. 2 (a) and (c) shows the minimum energy routing tree where the overhead energy τ is neglected during routing calculations assuming $\tau = 0$ mJ, for different environmental situations with $\alpha = 2$ and $\alpha = 3$ respectively. In real world sensor nodes, however, we must not forget the overhead energy which is dissipated at each hop of data transfer. Assuming a realistic[1] overhead energy value with $\tau = 20$ mJ, different routing topologies would be found which are presented in Fig. 2 (b) and (d). These alternatives show that the actual minimum energy routes are different from the initial ones. The most important point is that, neglecting the significance of the overhead energy dissipation would result in a considerable amount of energy waste.

In Table I, the average energy dissipations at sensor nodes are compared for the small sensor network given in Fig. 2. The routing topologies where only the transmitter energy is considered and the overhead energy is ignored will cause an obvious energy loss on sensor nodes.

TABLE I
AVERAGE ENERGY DISSIPATION AT SENSOR NODES

Explanation		E (mJ)
$\alpha = 2$	Topology at Fig. 2 (b), where τ is considered	21.13
	Topology at Fig. 2 (a), where τ is ignored	34.28
	Energy loss (%)	62 %
$\alpha = 3$	Topology at Fig. 2 (d), where τ is considered	53.31
	Topology at Fig. 2 (c), where τ is ignored	61.80
	Energy loss (%)	16 %

IV. SIMULATIONS

In order to visualize the effect of neglecting the overhead energy parameter during routing calculations, we performed simulations using Opnet Modeler [12]. We have implemented two similar minimum energy tree construction algorithms based on the Distributed Bellman-Ford Algorithm. In the first case, the "*Ignore*" algorithm (IA) considers only the transmitter energy and tries to establish connections between nodes where the transmission power is minimized, while ignoring the overhead energy dissipation at each hop. In the second case, the "*Consider*" algorithm (CA) considers the total energy cost as given in (1) while constructing the routing tree. For the implementation details the reader may refer to [11].

A. Simulation Setup

The sensor nodes are assumed to be capable of adjusting their transmitter power to the minimum required level that will be sufficient for their radio packets to reach to their destination. In simulations, however, we have used 20 discrete power levels instead of a continuous scale.

For each experiment, 10 different random sensor networks are generated. The graphs are plotted using the average values derived from these networks, with a 95% confidence interval.

Each sensor network consists of one sink node and 100 sensor nodes. The sink node is located in the middle of the area, whereas the sensor nodes are distributed uniformly. We have also considered locating the sink node to one of the corners of the area, which did not change the overall behavior of the system.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Sample transmission power	800 mW
Sample transmission range in open air (α=2)	200 m
Data rate	20 kbps
Packet size	1024 bits
Minimum transmission power	100 mW
Maximum transmission power	2,000 mW
Initial battery capacity	200 J
Area size (A)	200 m x 200 m
Path loss exponent (α)	3
Number of sensor nodes	100

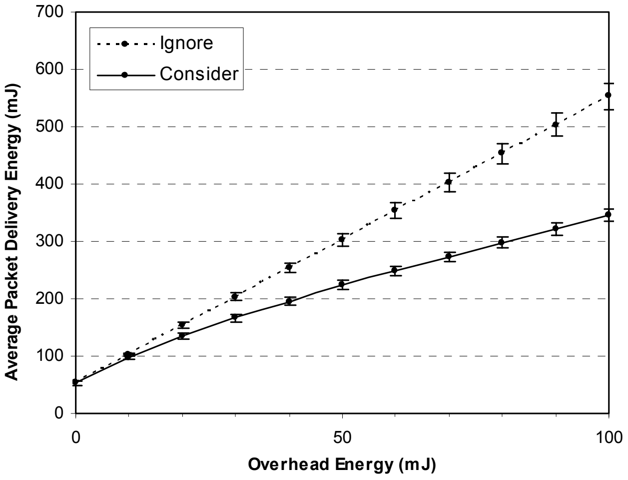


Fig. 3. Average packet delivery energy versus overhead energy.

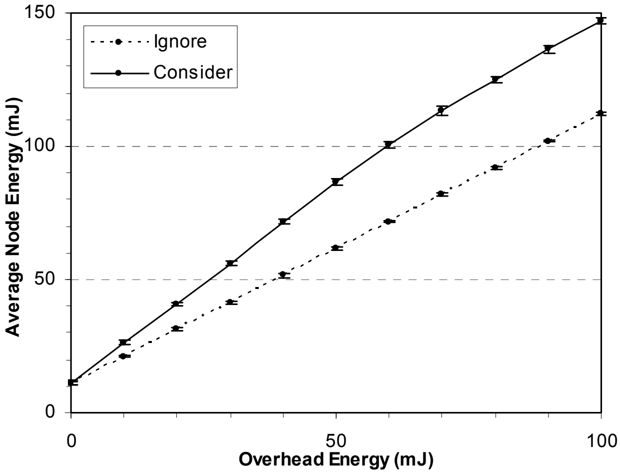


Fig. 4. Average node energy versus overhead energy.

The sensors are assumed to use 800 mW transmission power for a 200 m radio range in open air ($\alpha = 2$). These values are chosen, as they are very close to the Berkeley/Crossbow Mica Motes' specifications [13]. However, we have scaled the radio range for our simulation environment where we used a constant path loss exponent value with $\alpha = 3$.

The initial battery capacity of the sensors is chosen to be 200 J. In [14], it is given that for an alkaline-manganese dioxide battery, the typical volumetric energy density is 428 Watt hour per liter. In other words, a battery of size one cubic centimeter would have the capacity 1540 J. However, we have chosen a smaller value to shorten the simulation time. The behavior of the simulations will not change, since the battery capacity only causes the results to appear earlier.

The sensors are assumed to perform independent readings, and therefore independent packet generations. The packet generation process is assumed to be a Poisson process with rate $\lambda = 1$ packets per hour, where we assume a continuous monitoring application. Nevertheless, here a periodic process could also be chosen where the sensors are polled with a predefined frequency. The data rate of the communication channel is chosen to be 20 kbps, and a fixed packet size of 1024 bits is used. These simulation assumptions are summarized in Table II.

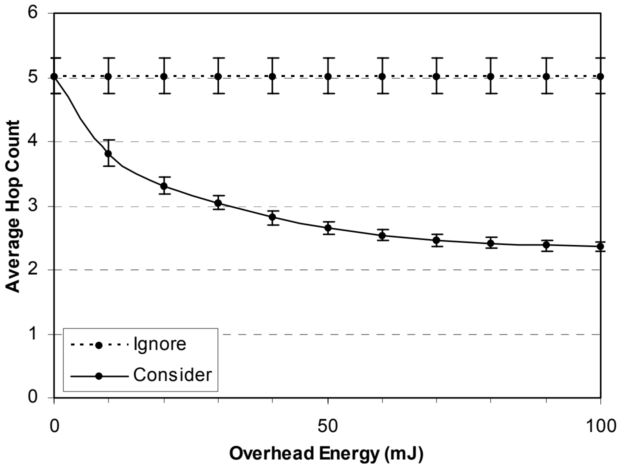


Fig. 5. Average hop count versus overhead energy.

The energy model in (1) is used to calculate the average energy spent at each sensor node for one packet transmission. We have considered $\tau = 0$ mJ to 100 mJ to examine the effect of different overhead energy levels.

B. Results

In this work, we monitor the network lifetime, the average hop count and the average energy spent per packet at each node. These values are calculated as follows. After the network setup phase, a communication tree is formed. Thereafter, for each sensor, the communication path from itself to the sink node is traversed, and both the number of hops and the necessary communication energy is recorded. IA generated always the same routing tree in spite of varying overhead energy levels because it ignored the effect of overhead energy during routing tree formation phase. For the effect of other simulation parameters like node density and path loss exponent, the reader may refer to [11].

In Fig. 3, we have compared the average energy load of a packet on the network. For each data packet generated at any sensor node, the total energy dissipation on the path towards the sink node is calculated. The graph shows the average of this total energy over all sensor nodes in the network with respect to increasing overhead energy values. Since IA produced the same routing tree, the average energy dissipation increases linearly. However, CA was able to find more energy efficient routes reducing the total energy dissipation for a packet to reach to the destination.

In Fig. 4, the energy dissipation at each sensor node is compared individually. In this graph, we can clearly see that sensor nodes spend more energy when they are

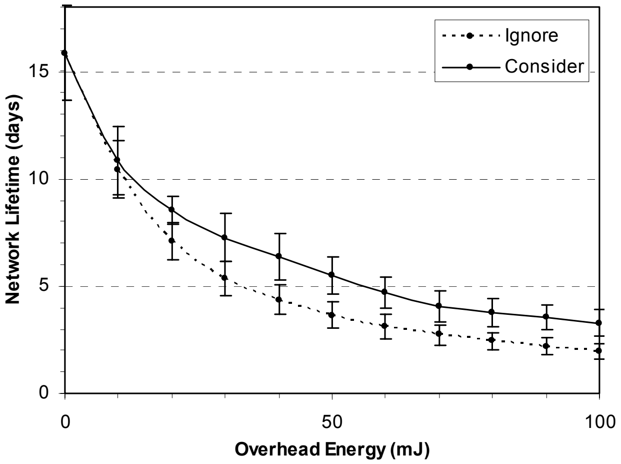


Fig. 6. Network lifetime versus overhead energy.

connected using the routing trees found by CA. Although individual energy dissipation is higher compared to IA, we have seen in Fig. 3 that the total energy dissipation is less. Whenever the overhead energy becomes a significant element in the energy cost, the routing algorithm prevents unnecessary hops and therefore the energy waste because of overhead energy that is spent at each hop. The result can easily be seen in Fig. 5, where the average hop count in the routing trees is compared. The larger the overhead energy that is spent at each hop is the smaller is the average number of hops in the network.

In Fig. 6, the network lifetime is observed. It is obvious that increasing the overhead energy shortens the lifetime, since the energy dissipation at the sensor nodes becomes higher. In addition, we can observe undoubtedly that ignoring the overhead energy parameter in routing calculations result in suboptimal routing trees. As an example, consider $\tau = 50$ mJ. The network would be alive only 3.6 days where the routing tree is constructed using IA. At the same overhead energy level, CA would create a more efficient routing tree where the lifetime would increase up to 5.5 days, with a gain of more than 50 per cent. For a larger overhead energy value with $\tau = 100$ mJ, this gain in network lifetime is nearly 65 per cent.

V. CONCLUSION

The overhead energy is an intrinsic component of energy dissipation at sensor nodes. In this work, we have analyzed the effect of neglecting the overhead energy dissipation in routing decisions. Neglecting this important factor during routing decisions may result in worse routing alternatives while promoting meaningless and uneconomical multi-hop communication links and resulting in a significant amount of energy waste. The network lifetime would decrease significantly if the routing algorithm does not consider overhead energy dissipation.

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