Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Computer Networks 46 (2004) 465–478

COMPUTER NETWORKS

www.elsevier.com/locate/comnet

Overhead energy considerations for efficient routing in wireless sensor networks ☆

E. Ilker Oyman *, Cem Ersoy

Computer Engineering Department, Boğaziçi University, 34752 Istanbul, Turkey

Received 23 November 2003; received in revised form 25 February 2004; accepted 18 April 2004

Responsible Editor: R. Sivakumar

Abstract

Energy is the most critical resource in the life of a wireless sensor node. Therefore, its usage must be optimized to maximize the network life. It is known that for higher path loss exponent values, utilizing shorter communication links reduces the transmitter energy, whenever the radio equipment has power adjustment capability. Although the transmitter energy is one of the major factors of total energy dissipation, neglecting the overhead energy could result in suboptimal energy usage. Routing algorithms should also be concerned about the overhead energy which is wasted at each hop of data transfer. In this paper, we investigate the use of multi-hop communication links and compare the amount of energy gain upon alternative routes using analytical techniques. We show that employing multi-hop links does not always result in energy gain, and try to quantify situations when it is advantageous. The analytical results are used in routing decisions and their effect in energy efficiency is validated using simulations. Moreover, we also quantify the gain achieved in terms of lifetime by considering overhead energy on power adjustable sensors for different environmental conditions. We show that the network lifetime can dramatically decrease, if the overhead energy component is neglected during routing decisions.

Keywords: Wireless sensor networks; Energy saving; Multi-hop

1. Introduction

Industrial sensors are responsible to perceive a physical phenomenon in the environment. Thereafter, the data gathered through the sensors has to be forwarded to a control center for further processing. Advances in technology enabled construction of small, low-cost, low-power electronic devices coupled with sensing and wireless communication capabilities. These sensor elements can easily build a self-organizing network for

---

☆ This work was supported in part by the State Planning Organization of Turkey (DPT) under the grant number DPT98K120890, and by Opnet Technologies, Inc. through "Teaching with OPNET" program.

* Corresponding author. Tel.: +90-216-410-5701; fax : +90-216-410-5735.

E-mail addresses: oymani@boun.edu.tr (E.I. Oyman), ersoy@boun.edu.tr (C. Ersoy).

1389-1286/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.comnet.2004.04.004

information propagation [1,2]. There are several surveys providing with in-depth background research on sensor networks [3–6].

Power is one of the most important design constraints in wireless sensor network architectures [7]. The life of each sensor node depends on its energy dissipation. In applications where the sensors are not equipped with energy scavenging tools like solar cells, sensors with exhausted batteries cannot operate anymore. Moreover, since sensor nodes behave as relay nodes for data propagation of other sensors to sink nodes, network connectivity decreases gradually [8]. This may result in disconnected subnetworks of sensors, i.e., some portions of the network cannot be reachable at all. Therefore, the level of power consumption must be considered at each stage in wireless sensor network design.

Sensor nodes have a short transmission range due to their limited radio capabilities. Therefore, the data must be relayed using intermediate nodes towards the sink. In addition, it may be more advantageous to use a multi-hop path to the sink node consisting of shorter links rather than using a single long connection. The energy consumption at the transmitter is known to be proportional to d^{α} where d is the range of the radio signals and α is the path loss exponent [8–12]. In [9], a minimum energy connection protocol based on the distributed Bellman–Ford algorithm is investigated. The effect of mobilization is also analyzed. In [10], a power-aware routing algorithm for wireless ad hoc networks is presented, which helps to minimize the transmission power needed to forward data packets. In [11], 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 [13], where the energy gain is focused on transmitter energy.

There are also different studies for energy based optimizations. In [14], optimum one-hop transmission distance is calculated that will minimize the total system energy. In this work, it is assumed that each node is communicating with its next hop node in a linear network topology. In [15], a communication protocol for wireless sensor networks is proposed, based on energy efficiency. Here, only free space propagation model is assumed and the effects of different path loss exponent values are not investigated. A different minimum energy routing model is proposed in [16], where the effects of shadowing and fading is also considered. Although the importance of the receiver energy is not opposed, this factor is neglected in detailed analysis.

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. 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 [17]. 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, when the usage of an intermediate node results in energy gain. We analyze the amount of energy gain using multi-hop links to construct a communication path. 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 [18].

The remainder of the paper is organized as follows. In the next section we provide a simple network to explain the importance of overhead energy on network topology. In Sections 3 and 4, we introduce the network and power model that we use in the paper. These models are applicable to

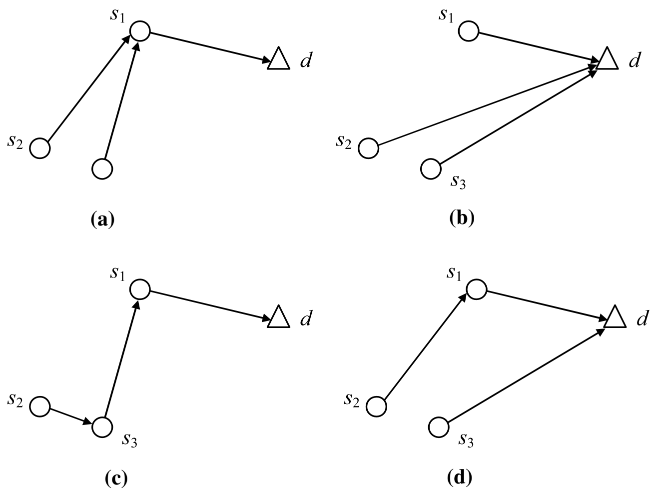

Fig. 1. A sample network representing different topology alternatives for different path loss exponent α and overhead energy τ values. (a) $\alpha = 2$, $\tau = 0$ mJ, (b) $\alpha = 2$, $\tau = 20$ mJ, (c) $\alpha = 3$, $\tau = 0$ mJ, (d) $\alpha = 3$, $\tau = 20$ mJ.

most of the applications where a random deployment strategy is used. The analytical results for energy saving are presented in Section 5. Section 6 presents experimental results which are derived using simulations. We conclude the paper in Section 7.

2. Motivation for overhead energy considerations

The path loss exponent α has a great impact on energy dissipation at the sensor nodes, since the transmitter energy is proportional to d^{α} where d is the range of the radio signals. On the other hand, the route calculations should also 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. 1. 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. 1(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 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. 1(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 1, the average energy dissipations at sensor nodes are compared for the small sensor network given in Fig. 1. The routing topologies where only the transmitter energy is considered and the overhead energy is not taken into account will cause an obvious energy waste on sensor nodes.

---

[1] For assumptions that are used during energy calculations, the reader should refer to the parameters on Table 2.

Table 1
Average energy dissipation at sensor nodes

Explanation		E (mJ)
$\alpha = 2$	Topology at Fig. 1(a), where τ is neglected	34.28
	Topology at Fig. 1(b), where τ is considered	21.13
	Saving (%)	38.35
$\alpha = 3$	Topology at Fig. 1(c), where τ is neglected	61.80
	Topology at Fig. 1(d), where τ is considered	53.31
	Saving (%)	13.74

In summary, the overhead energy is an intrinsic component of energy dissipation at sensor nodes. Neglecting this important factor during routing decisions may result in worse routing alternatives while promoting meaningless multi-hop communication links and resulting in a significant amount of energy waste.

3. Network model

3.1. 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" or in a shorter notation as n_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 $\langle i, j, \ldots, k \rangle$ 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 $(i, j), (j, \ldots), \ldots, (\ldots, k)$ are in the arc set A. d_{ij} represents the Euclidean distance between n_i and n_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.

3.2. 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. 2, 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.

3.3. 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

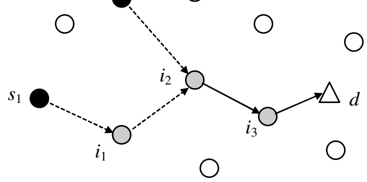

Fig. 2. Data delivery from source to the destination using intermediate nodes.

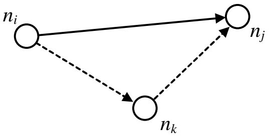

Fig. 3. Using multi-hop links in routing decision.

link from source to destination and a multi-hop link using intermediate nodes, if available. Fig. 3 shows such a subproblem during routing decision. 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 $\langle i, k, j \rangle$.

4. Energy model

4.1. Transmitter power model

As mentioned before, the main concern in wireless sensor network design is power. The underlying architecture must consider power efficiency as a major constraint.

The transmitted power falls as $1/d^\alpha$, where α is the path loss exponent and d is the distance between the two communicating parties. In many sensor applications, it is assumed that α ranges between 2 and 4, since the sensors have short antennae which are very close to the ground.

We also use this power model assuming radio circuitry with power adjustable transceivers. Therefore the transmitter energy is related with the distance between the communicating sensor nodes.

4.2. Energy consumption

Energy consumption in an arbitrary sensor node has in general following components depending on the operations performed within the node:

1. *Sensing energy:* In order to activate sensing circuitry within the node, and gathering data from the environment, an amount of energy must be dissipated, which is called *sensing energy*, E_s. The magnitude of this energy depends on the task that is assigned to the sensor. Different sensors require different level of energy during operation.
2. *Transmitter energy:* Afterwards, this data must be transmitted towards the destination. Therefore, the transmitter circuitry must be operated. For this operation, the *transmitter energy*, E_t must be consumed which depends on the transmitter power, P_t, size of the data packet, and the data transfer rate.
3. *Receiver energy:* As a relay node, a sensor node is also in charge of forwarding data packets of other sensor nodes. For this operation, sensors must be able to receive those data packets. The *receiver energy*, E_r, will be consumed during this operation, which is irrelevant of the distance between nodes. During reception, receiver power, P_r, will be spent during the reception of the data packet with the given data transfer rate.
4. *Computation energy:* To operate these circuitries, sensor's processing unit must be activated. Moreover, whenever data aggregation is performed additional computations must be realized. Compared to the previous items, *computation energy*, E_c, is relatively low [17].

During the life cycle of a typical sensor node, each event or query will be followed by a sensing operation, performing necessary calculations to derive a data packet and transmitting this packet to the destination. In addition, sensor nodes often relay data packets received from other sensors. Thus, the *total energy*, E_{Total}, in an arbitrary active time frame can be presented as the sum of above energy requirements:

$$E_{\text{Total}} = E_t + E_r + E_s + E_c. \tag{1}$$

Efficient sensing circuitries and computation algorithms help to reduce E_s and E_c. The other two components E_t and E_r are dependent on the communication architecture and underlying techniques. Therefore, power aware methods must be employed in order to reduce the energy consumption during communication [17]. In this paper, we focus on the energy gain achieved using shorter multi-hop communication links rather than longer direct links.

Only the transmitter energy, E_t, is related with the distance between the communicating sensor nodes. The other components of total energy remain constant with varying distance between communicating pairs. Therefore, we can rewrite (1) as a function of d as follows:

$$E_{\text{Total}}(d) = \kappa d^{\alpha} + \tau, \tag{2}$$

where $\kappa, \tau \in \Re$ are real numbers, κ being a constant multiplier depending on the power model, and $\tau = E_r + E_s + E_c$, the *overhead energy*, which is a constant value with varying d.

5. Energy saving

Routing algorithms in sensor networks should consider communication links with less energy consumption among other alternatives. Suppose that we have two sensor nodes i and j within the sensor field where n_i wants to send a data packet to n_j. This situation is represented in Fig. 4(a). Trivially, n_i should adjust its transmitter circuitry power so that n_j will receive the transmitted signals. Alternatively, the routing algorithm may decide to use an intermediate node k which is lying between both the transmitter and the receiver nodes. Energy saving, δ_E, can be formulated as the difference of total energy consumption between two alternatives

$$\delta_E = E^{(1)}_{\text{Total}} - E^{(2)}_{\text{Total}}, \tag{3}$$

where $E^{(1)}_{\text{Total}}$ and $E^{(2)}_{\text{Total}}$ give the total energy consumption values of these two alternatives, respectively.

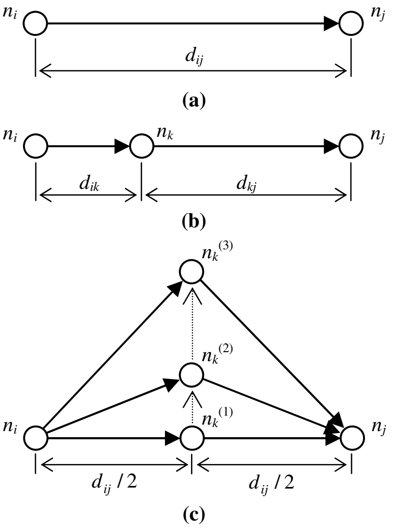

Fig. 4. Routing decision alternatives, (a) direct communication, (b) and (c) using an intermediate node.

Here, we will consider three different scenarios where an intermediate node can be used, and compare the energy saving achieved at each scenario.

5.1. 1-D communication links

In the simplest case, we assume a one dimensional environment. Here, the intermediate node k lies on the line connecting the source and the destination nodes, as given in Fig. 4(b). It is clear that energy loss would occur when n_k would be beyond n_i or n_j. Therefore, we consider $0 \leqslant d_{ik}$, $d_{kj} \leqslant d_{ij}$. Using (2), we have

$$\begin{aligned} E^{(1)}_{\text{Total}} &= \kappa d^{\alpha}_{ij} + \tau, \\ E^{(2)}_{\text{Total}} &= (\kappa d^{\alpha}_{ik} + \tau) + (\kappa d^{\alpha}_{kj} + \tau), \end{aligned} \tag{4}$$

where $E^{(1)}_{\text{Total}}$ gives the total energy consumption when a direct communication link between nodes i and j is established, and $E^{(2)}_{\text{Total}}$ gives the total energy consumption when an intermediate node k is used. Therefore, a two-hop communication path is utilized, the first link connects n_i with n_k, and the second link connects n_k with n_j.

By using (4), energy saving can be found as follows:

$$\delta_E = \kappa[d^{\alpha}_{ij} - d^{\alpha}_{ik} - d^{\alpha}_{kj}] - \tau. \tag{5}$$

Here, using the fact that $d_{ij} = d_{ik} + d_{kj}$, we get

$$\delta_E = \kappa[(d^{\alpha}_{ij} - d^{\alpha}_{ik}) - (d_{ij} - d_{ik})^{\alpha}] - \tau. \tag{6}$$

We keep the distance between n_i and n_j constant and observe the energy saving behavior. An intermediate node k is used that is found on the line between n_i and n_j. For simplicity, we take $\tau = \tau_0$, an arbitrary fixed energy requirement at

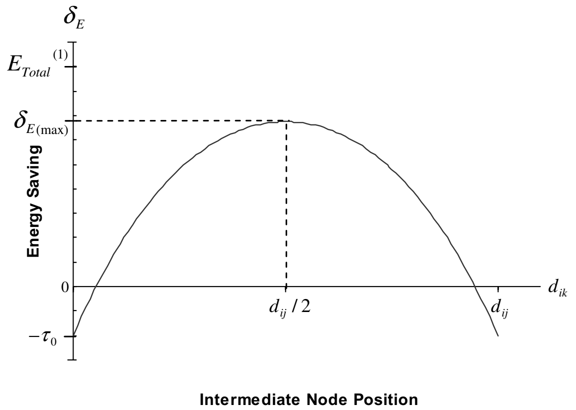

Fig. 5. Energy saving in 1-D communication scenario.

each sensor node. The behavior can be observed in Fig. 5. When n_k is close to the source or the receiver, a significant amount of energy loss occurs. Using an intermediate node becomes only meaningful when this node is distant from both the sender and the receiver. For different values of path loss exponent α, this behavior remains the same. However, the amount of energy that is required for successful data transmission increases exponentially with increasing α.

The point of maximum energy saving can be found by setting $\delta'_E(d_{ik}) = 0$. The first derivative of energy saving with respect to distance between n_i and n_k can be written as follows:

$$\frac{\mathrm{d}\delta_E}{\mathrm{d}\delta_{ik}} = \alpha\kappa[(d_{ij} - d_{ik})^{\alpha-1} - d_{ik}^{\alpha-1}]. \tag{7}$$

Here, we have $\delta'_E(d_{ik}) = 0$ if $d_{ik} = d_{ij}/2$. In other words, maximum energy saving would be achieved when n_k is exactly on the midpoint between n_i and n_j.

Using this result, we can find the places for an intermediate node where energy is saved when this node is used as a relay node. In other words, we want to find d_{ik}, so that $\delta_E > 0$. Setting $d_{ij} = 2d_{ik}$ in (6), we get

$$\delta_E = 2(2^{\alpha-1} - 1)\kappa d_{ik}^{\alpha} - \tau. \tag{8}$$

Therefore, we can say that $\delta_E > 0$, whenever we have an intermediate node whose distance from the source node is found as follows:

$$d_{ik} > \left[\frac{\tau}{2(2^{\alpha-1} - 1)\kappa}\right]^{1/\alpha}. \tag{9}$$

Eq. (8) provides with another important result. We know from (2) that $E_t(d_{ik}) = \kappa d_{ik}^{\alpha}$. Therefore, we can conclude with an energy saving, whenever the following inequality between the overhead energy τ and transmitter energy E_t holds.

$$\tau < 2(2^{\alpha-1} - 1)E_t. \tag{10}$$

5.2. Isosceles triangular communication links

In the second scenario, we let the intermediate node lie on the top corner of an isosceles triangle whose other two corners are the source and the destination nodes. This scenario is presented in Fig. 4(c). Obviously, the distance between the intermediate node and either the source or the destination cannot be larger than the distance of a direct link between the source and the destination. Therefore, in this case we consider $d_{ij}/2 \leqslant d_{ik}, d_{kj} \leqslant d_{ij}$.

Since the routing triangle is isosceles, we know $d_{ik} = d_{kj}$. Therefore, the energy saving defined in (3) can be represented as follows:

$$\delta_E = \kappa(d_{ij}^{\alpha} - 2d_{ik}^{\alpha}) - \tau. \tag{11}$$

The energy saving with respect to increasing d_{ik} can be seen in Fig. 6. It is monotonically decreasing because the total distance of data links

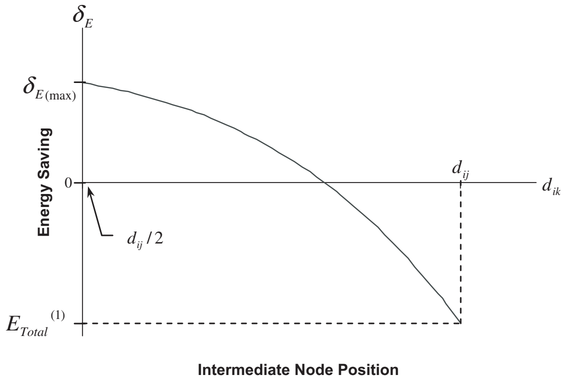

Fig. 6. Energy saving in isosceles triangular communication scenario.

is increasing and more transmitter energy would be necessary to communicate. Maximum energy saving is achieved when the intermediate node k lies on the line connecting n_i and n_j.

In order to find the places where the amount of energy saving is positive, we put $\delta_E > 0$ in (11) and derive the following inequality:

$$d_{ik} < \left[\frac{1}{2}\left(d_{ij}^{\alpha} - \frac{\tau}{\kappa}\right)\right]^{1/\alpha}. \tag{12}$$

5.3. Arbitrary triangular communication links

In real life situations, however, arbitrary triangular routing alternatives will be found, and the routing algorithm has to decide whether to choose the direct link or to choose the multi-hop one. Fig. 7 shows this scenario.

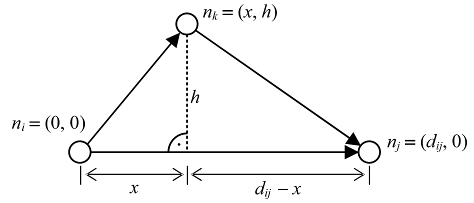

Fig. 7. Arbitrary triangular communication scenario.

Here, we assume that the nodes are lying on a 2-D plane where node i is at the origin, and node j lies on the x-axis with coordinates $(d_{ij}, 0)$. Then, the intermediate node k has coordinates (x, h), where h is the height of the triangle. In this case, energy saving can be found as follows, using $d_{ik}^2 = h^2 + x^2$, and $d_{kj}^2 = h^2 + (d_{ij} - x)^2$:

$$\delta_E = \kappa[d_{ij}^{\alpha} - (h^2 + x^2)^{\alpha/2} - (h^2 + (d_{ij} - x)^2)^{\alpha/2}] - \tau. \tag{13}$$

This equation is plotted in Fig. 8. We have seen this behavior in the first two scenarios. The generalization can easily be reduced to these scenarios by putting $h = 0$ or $x = d_{ij}/2$ for the first and second scenarios, respectively.

5.4. Generalization

Until now, we have presented techniques for two-hop scenarios. However, these techniques can easily be applied recursively on situations where a multi-hop communication link should be considered as an alternative.

Considering the situation in Fig. 9(a), when n_i wants to reach n_j, there might be more than one intermediate node, such as nodes k and l. In this case, the underlying routing algorithm should

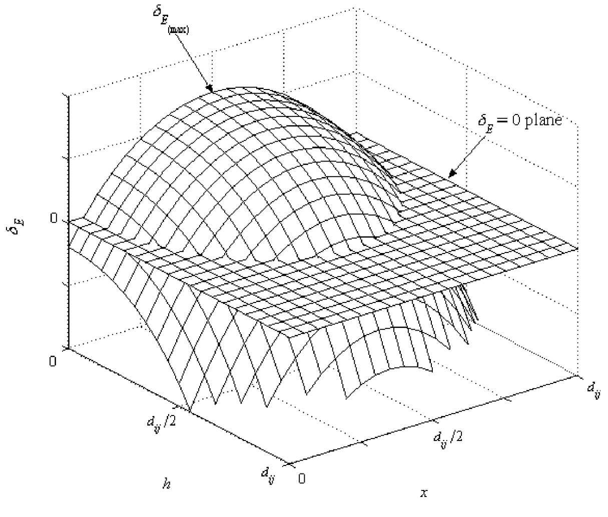

Fig. 8. Energy saving in arbitrary triangular communication scenario.

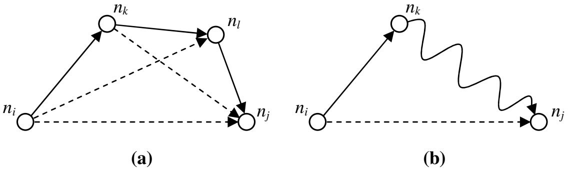

Fig. 9. Generalization into a multi-hop path.

consider the amount of energy saving when nodes k and l are used as relay nodes.

When a distributed routing algorithm is used, n_i will decide on its output power level according to its neighbors. Therefore, n_i will compare the alternatives (i,j) with the path $\langle i,k,j\rangle$ as in Fig. 9(b). n_i is not responsible on the routing decisions of n_k. Therefore, n_k should decide whether to send packets through n_l or sending it directly to n_j.

6. Simulations on overhead energy considerations

In order to validate the effect of utilizing multi-hop communication links in energy saving, we performed simulations using Opnet Modeler v9.1 [19] on different scenarios.

In this work, we monitor 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. This tree is established using the distributed Bellman–Ford algorithm, where the expected energy dissipation that is given in (2) is used as the cost function. The data packets are routed using this minimum energy tree towards the sink node. Thereafter, for each sensor, the communication path from itself to the sink node is traversed, and both the number of hops and the necessary energy is recorded.

6.1. Simulation setup

We focus in our simulations on three different types of sensor nodes varying on their transmission power adjustment capability. The first node type, $P_{\max}$ is unable to make any power control on transmitter circuitry. This type of nodes should always send packets with the maximum transmission power, independent of the distance between source and destination nodes. The second node type, P_3 can adjust its transmission power at three different power levels, whereas the third node type, P_{cont}, has a continuous power level adjustment capability. In simulations, however, we have used 20 discrete power levels instead of a continuous scale. P_3 and P_{cont} type sensors try to change their transmission power to the minimum level that will be sufficient for their radio packets to reach to their destination.

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.

The sensors are assumed to use 800 mW transmission power for a 200 m radio range in open air ($\alpha = 2$). This data is used to calculate the corresponding radio range for each different environment types with different path loss exponent values. These assumptions are summarized in Table 2.

The initial battery capacity of the sensors is chosen to be 200 J. In [20], it is given that for an alkaline-manganese dioxide battery, the typical volumetric energy density is 428 W h/l. In other words, a battery of size one cubic centimeter

Table 2
Simulation parameters

Parameter	Value
Sample transmission power	800 mW
Sample transmission range	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
Default area size (A)	200 m × 200 m
Default path loss exponent (α)	3
Number of sensor nodes	100

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 energy model in (2) is used to calculate the average energy spent at each sensor node for one packet transmission. Here, the overhead energy τ has a typical value of 20 mJ per packet where 400 mW receiver power is assumed, and both sensing and computation energy is neglected. However, we have considered $\tau = 0$–50 mJ to examine the effect of different overhead energy levels. The network lifetime is defined as the length of time until the first battery drainout among all sensor nodes occurs [21].

6.2. Results

In the first experiment, the default simulation parameters are used. The results are presented in Figs. 10 and 11.

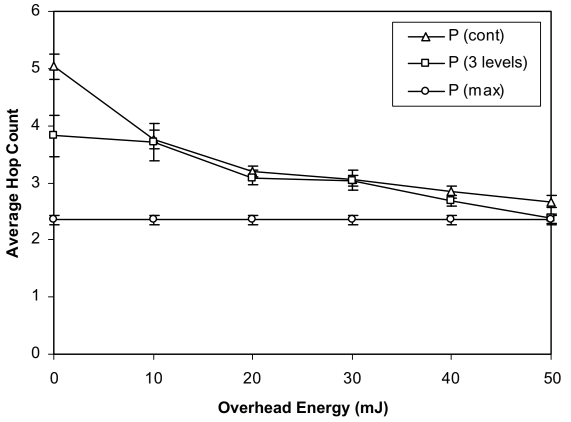

Fig. 10. Average hop count versus overhead energy τ ($A =$ 200 m×200 m, $\alpha = 3$).

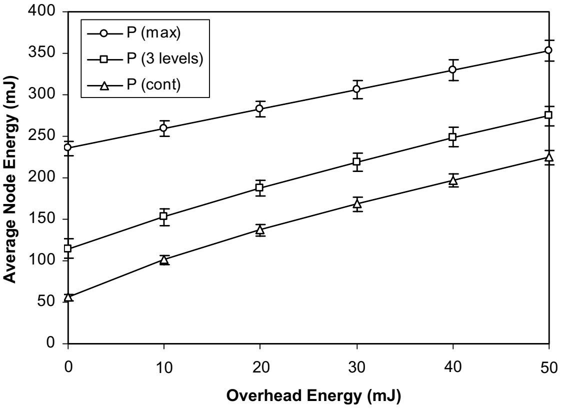

Fig. 11. Average node energy versus overhead energy τ ($A = 200$ m×200 m, $\alpha = 3$).

Multi-hop communication paths are utilized whenever the overhead at each hop is small. Therefore, at higher overhead energy values, direct links are preferred to multi-hop paths. When the sensors are communicating with the maximum transmission power, then the resulting routing tree will be independent of the overhead energy, i.e., each sensor will try to communicate with the one that is furthest away from itself. Hence, we have a constant average hop count for $P_{\max}$ nodes. Since P_{cont} nodes can make a finer power adjustment than P_3 nodes, this optimization results in a higher average hop count.

It is evident that average node energy should increase when the overhead energy increases (see Fig. 11), since this is a constant added to the total energy of every node. The increase in the total energy, however, is more than the additional overhead. The reason for this is that the tendency to direct links increases as the overhead energy increases, which require more energy than multi-hop paths consisting of shorter links. As the amount of power adjustment levels increases, the energy spent at each node decreases. In other words, sensor nodes can use their energy more effectively. As an example, for the typical case where $\tau = 20$ mJ, $P_{\max}$ nodes spend on the average $E_{\text{Total}} = 282$ mJ, whereas P_{cont} nodes spend on the average $E_{\text{Total}} = 137$ mJ. This results in an improvement of more than 50% energy saving, which doubles the lifetime of each sensor node.

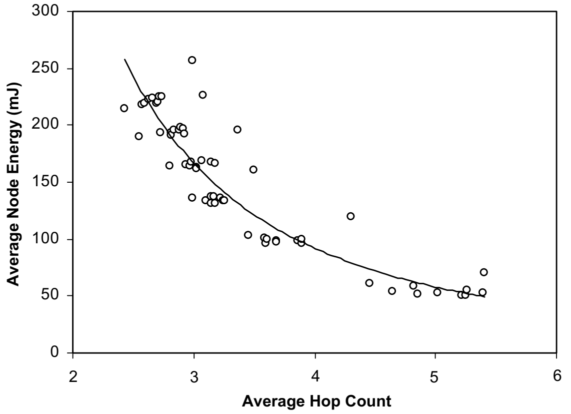

Fig. 12. Average node energy versus average hop count ($A = 200$ m×200 m, $\alpha = 3$, only P_{cont} nodes are used).

In Fig. 12, we consider only the P_{cont} nodes. Here, the results of all experiments with different overhead energy values are plotted. The trendline indicates clearly that whenever the network is able to use multi-hop links, average node energy decreases. The usage of multi-hop links, however, is determined by considering the amount of the overhead energy, as we have seen in Fig. 10.

In the second experiment, the effect of sensor density is analyzed. Therefore, the area size is increased to 400 m×400 m while the number of sensors is kept the same. As shown in Fig. 13, the network shows the same behavior as in the dense scenario, with a difference that the average node energy requirement becomes larger. This is because the average distance between each sensor node has been increased. For our typical case where $\tau = 20$ mJ, the improvement achieved by using P_{cont} nodes instead of $P_{\max}$ nodes is found as 42%, which again approximately doubles the lifetime of each sensor node.

The third experiment focuses on different environmental conditions by varying path loss exponent α. In this experiment, only P_{cont} nodes are used which are proven to provide with the most efficient energy management scheme.

We know that in urban areas or in more obstructed environments, the value of α increases. Therefore, radio transmission range decreases for the same transmission power values. As a result, the sensor nodes can be connected to the sink node

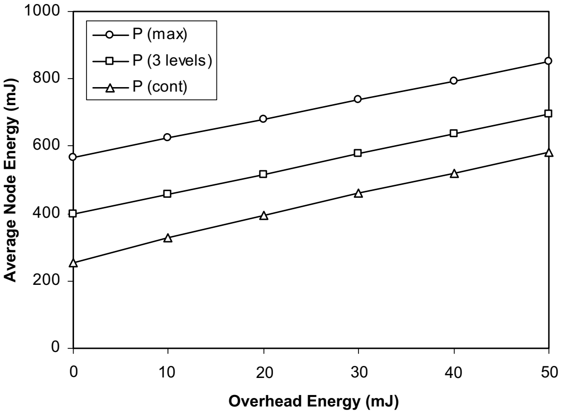

Fig. 13. Average node energy versus overhead energy τ ($A = 400$ m×400 m, $\alpha = 3$).

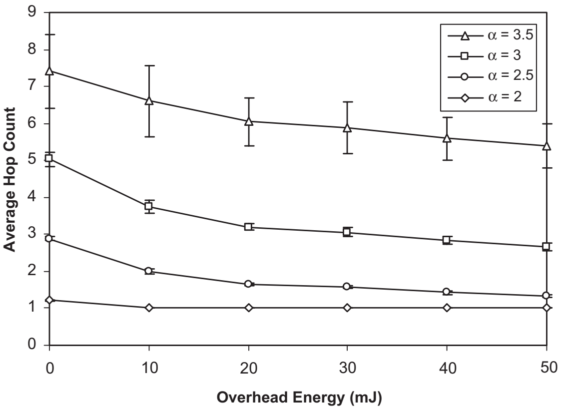

Fig. 14. Average hop count versus overhead energy τ ($A = 200$ m×200 m, only P_{cont} nodes are used).

only with shorter links, and therefore using more hops (see Fig. 14). Moreover, we can clearly observe that the degree of multi-hopping reduces when the overhead energy at each sensor node increases. This shows that the nodes prefer rather direct links than multi-hop paths. For α values greater than 4, even the maximum transmission power that our sensor nodes are capable becomes insufficient to form a connected network. In rural areas ($\alpha = 2$), however, the sensors can be more densely deployed, as the radio range is higher. In our experiment, each sensor node starts to communicate via a direct link with the sink node, as the overhead for using a multi-hop link is relatively high. Only for the case where the overhead is omitted ($\tau = 0$ mJ), some multi-hop links are established. In Fig. 15, we observe that the energy dissipation of each sensor node is exponentially related with the path loss exponent. Therefore, in more obstructed environments, one must expect shorter sensor lifetime which is exponentially related with α.

An interesting result is that, the average hop count is also exponentially related with path loss exponent. The typical case with $\tau = 20$ mJ is shown in Fig. 16. Here, we have a larger confidence interval for larger α values, since interconnection degree of the network decreases, which results in more deviated values. However, the exponential trend can easily be seen, since we use a logarithmic scale. Therefore, the degree of multi-hopping increases with increasing path loss exponent exponentially, which is increases the end-to-end delay and packet loss rate, but decreases the total energy dissipation.

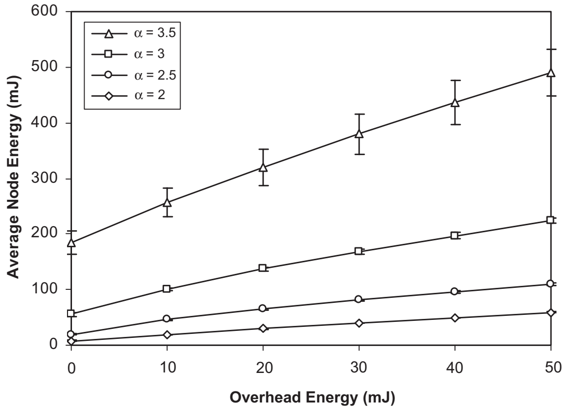

Fig. 15. Average node energy versus overhead energy τ ($A = 200$ m×200 m, only P_{cont} nodes are used).

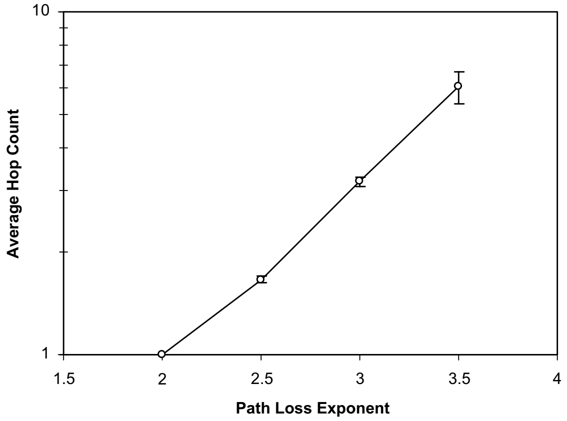

Fig. 16. Average hop count versus path loss exponent α ($A = 200$ m×200 m, $\tau = 20$ mJ, only P_{cont} nodes are used).

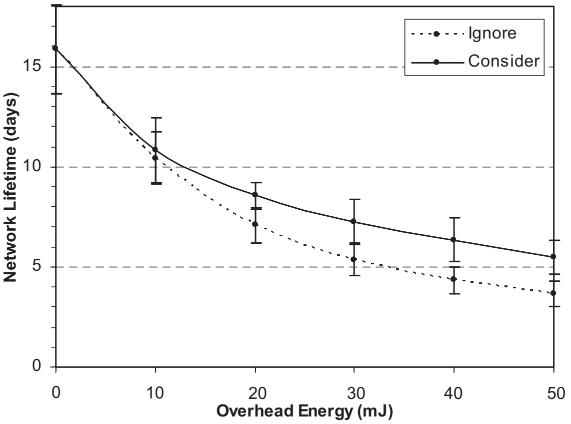

Fig. 17. Network lifetime versus overhead energy τ.

In Fig. 17, the change in 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 ignoring the overhead energy. At the same overhead energy level, more efficient routing trees could be created when the overhead energy is considered in energy calculations, where the lifetime would increase up to 5.5 days, with a gain of more than 50%. For larger overhead energy values, we have observed larger gains in network lifetime up to 65%.

7. Conclusion

In order to maximize the network lifetime, energy resources of each individual sensor node must be consumed effectively. Using multi-hop paths that consist of shorter links instead of one long link might result in considerable energy gain. In this paper, we proposed a new analytical approach to quantify energy saving using multi-hopping and power level adjustments. We have studied different multi-hop communication scenarios and calculated the energy saving in each scenario. We have also expanded these scenarios to general cases. The generalization can be applied into any arbitrary triangle and can be used in energy optimized route calculations. We also tried to quantify the effect of path loss exponent α, and overhead energy τ on energy saving. These analytical methods can be used for developing faster power aware routing algorithms. We have also validated our analytical study using simulations.

Although the transmitter energy reduces by using multi-hop communication links, we have shown that the total communication energy might increase depending on the overhead energy that has to be dissipated at every hop in the network. Therefore, the degree of hopping should decrease whenever higher overhead energy values are under consideration. We have compared the effect of overhead energy with average hop count and with average node energy per packet on different scenarios. It is shown that the sensor lifetime can easily be doubled using power adjustable transmitter circuitry.

The overhead energy is an intrinsic component of energy dissipation at sensor nodes. Neglecting this important factor during routing decisions may result in worse routing alternatives while promoting meaningless 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.

References

[1] G.J. Pottie, W.J. Kaiser, Wireless integrated network sensors, Communications of the ACM 43 (5) (2000) 51–58.

[2] J.M. Kahn, R.H. Katz, K.S.J. Pister, Next century challenges: mobile networking for smart dust, in: Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM '99), Seattle, WA, August 15–20, 1999, pp. 271–278.

[3] S.S. Iyengar, L. Prasad, H. Min, Advances in Distributed Sensor Integration: Application And Theory, Prentice-Hall, Englewood Cliffs, NJ, 1995.

[4] H. Qi, S.S. Iyengar, K. Chakrabarty, Distributed sensor networks—a review of recent research, Journal of the Franklin Institute 338 (2001) 655–668.

[5] D. Ganesan, R. Govindan, S. Shenker, D. Estrin, Wireless sensor networks, ACM Mobile Computing and Communications Review 5 (4) (2001).

[6] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, Computer Networks 38 (2002) 393–422.

[7] P.J.M. Havinga, G.J.M. Smit, Design techniques for low-power systems, Journal of Systems Architecture 46 (2000) 1–21.

[8] W.H. Yuen, C.W. Sung, On energy efficiency and network connectivity of mobile ad hoc networks, in: Proceedings of the 23rd International Conference on Distributed Computing Systems (ICDCS 2003), Providence, RI, May 19–22, 2003.

[9] V. Rodoplu, T.H. Meng, Minimum energy mobile wireless networks, IEEE Journal on Selected Areas in Communications 17 (8) (1999) 1333–1344.

[10] J. Gomez, A.T. Campbell, M. Naghshineh, C. Bisdikian, Conserving transmission power in wireless ad hoc networks, in: Proceedings of the 9th International Conference on Network Protocols (ICNP 2001), Riverside, CA, November 11–14, 2001.

[11] R. Wattenhofer, L. Li, P. Bahl, Y. Wang, Distributed topology control for power efficient operation in multi-hop wireless ad hoc networks, in: Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2001), Anchorage, AK, April 22–26, 2001, pp. 1388–1397.

[12] K. Kar, M. Kodialam, T.V. Lakshman, L. Tassiulas, Routing for network capacity maximization in energy-constrained ad hoc networks, in: Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003), San Francisco, CA, April 1–3, 2003.

[13] J.E. Wieselthier, G.D. Nguyen, A. Ephremides, On the construction of energy-efficient broadcast and multicast trees in wireless networks, in: Proceedings of the 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2000), Tel-Aviv, Israel, March 26–30, 2000, pp. 585–594.

[14] P. Chen, B. O'Dea, E. Callaway, Energy efficient system design with optimum transmission range for wireless ad hoc networks, in: Proceedings of the 2002 IEEE International Conference on Communications (ICC 2002), New York, April 28–May 2, 2002, pp. 945–952.

[15] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, in: Proceedings of the Hawaii

International Conference on System Sciences, Maui, HI, January 4–7, 2000.

[16] A. Catovic, S. Tekinay, T. Otsu, Reducing transmit power and extending network lifetime via user cooperation in the next generation wireless multi-hop networks, Journal of Communications and Networks 4 (4) (2002) 351–362.

[17] V. Raghunathan, C. Schurgers, S. Park, M.B. Srivastana, Energy-aware wireless microsensor networks, IEEE Signal Processing Magazine 19 (2) (2002) 40–50.

[18] J. Monks, J.P. Ebert, W.M.W. Hwu, A. Wolisz, Energy saving and capacity improvement potential of power control in multi-hop wireless networks, Computer Networks 41 (2003) 313–330.

[19] Opnet Technologies, Inc., Opnet Modeler Home Page, Available from <http://www.opnet.com/products/modeler/home.html>, 2002.

[20] Duracell, Alkaline-Manganese Dioxide Technical Bulletin, Available from <http://www.duracell.com/oem/Pdf/others/ATB-full.pdf>, 2003.

[21] J. Chang, L. Tassiulas, Energy conserving routing in wireless ad-hoc networks, in: Proceedings of the 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2000), Tel-Aviv, Israel, March 26–30, 2000, pp. 22–31.

E. Ilker Oyman received the B.Sc. degree in Computer Engineering and Mathematics, the M.Sc. and the Ph.D. degrees in Computer Engineering, Boğaziçi University, in 1993, 1996 and 2004, respectively. He is a co-founder and software manager of Gordion Software, Ltd., since 1995. His academical research interests include wireless sensor networks, ad hoc networks and multicast communication techniques.

Cem Ersoy received his BS and MS degrees in electrical engineering from Boğaziçi University, Istanbul, in 1984 and 1986, respectively. He worked as an R&D engineer in NETAS A.S. between 1984 and 1986. He received his PhD in electrical engineering from Polytechnic University, Brooklyn, New York in 1992. Currently, he is a professor in the Computer Engineering Department at Boğaziçi University. His research interests include performance evaluation and topological design of communication networks, wireless communications and mobile applications. Dr. Ersoy is a Senior Member of IEEE.