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POWER-AWARE METRICS FOR WIRELESS SENSOR NETWORKS

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Abstract

Energy conservation is a critical issue in wireless sensor networks for node and network life, as the nodes are powered by batteries. One way of doing so is to use only local information available to the nodes in the network. This article evaluates a number of power-aware routing protocols based on local information only. The simulation shows that basing the routing decision on the remaining power of neighbouring nodes is not by itself enough. Instead, using the directional value and the sum of power remaining at the next neighbours gives the routing protocol a broader perspective about the condition of the network from a local point of view and enhances the decision process.

Key Words

Sensor networks, topology, routing, power aware

1. Introduction

Wireless sensor networks (WSN) have wide and varied applications. A smart sensor is a collection of integrated sensors and electronics. When these types of sensors are used to form WSN, very powerful, versatile networks can be created and used in situations where traditional wired networks fail. These sensor networks can be used for emission-monitoring systems in the harsh environment of automobile exhaust systems or in large buildings for more consistent climate control. There are also countless medical applications, including health monitors and implantable devices, such as a retinal prosthesis [1]. Research is already being conducted with respect to low-power dissipation for deep space missions [2]. Although the space research has concentrated on direct networks, it is an area where the flexibility of wireless networking would be extremely useful.

Wireless devices must operate for a long period of time, relying on their battery power. Although many developers have looked at extending the life of a wireless system from a hardware point of view, such as directional antennas and improving battery life, power-aware routing is a relatively new concept in wireless networking. Until recently, most routing protocols in wireless networks concentrated mainly on establishing routes and maintaining these routes under frequent and unpredictable changes in network topology. The concept of using routing to minimize power usage has only recently been looked at, and it has been shown to be moderately successful. Researchers have proposed that routing packets in a power-aware method will complement hardware-based methods of extending the network's life. The metrics that have been devised so far to minimize power can be grouped into two main categories: power-aware and cost-aware metrics. Power-aware metrics aim to minimize the total power needed to route a message between two different locations, and cost-aware metrics look at methods that extend the nodes' battery lifetime.

Due to the high cost of communication and low battery power, it is natural to seek decentralized, distributed algorithms for sensor networks. This means that instead of relaying data to a central location that does all the computing, the nodes process information locally. By locally, we mean that the computation of routes should be based on local information that is available to the node from its neighbours only. By doing so we limit the number of messages that need to be sent in the network to discover routes or to make a decision for routing.

Centralized algorithms have the advantages of obtaining global information about the network and obtaining an optimum solution for routing. Due to the limitation of power, the large number of nodes in a sensor network, and the change of power available at the nodes, however, this is not an efficient way of obtaining information, and some of the information, will be outdated.

In this work we focus on designing protocols for stationary regular topologies that increase the life of nodes as well as the overall network. In doing so, we have restricted our protocols to deal with only local information that is available to nodes from their neighbours. The main idea is to request and process data locally and gather information from neighbours on a demand basis. So, a routing protocol for wireless sensor networks should consider the constraints the network will operate under, such as limited power and only local information available to each node in the network. By using local information, we limit the number of messages that the network needs to send to update the changes in the network.

In the next section, we discuss some related work that has been done on power aware metrics. In Section 4

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we introduce some of the assumptions that were used in this article, and in Section 5 explain the routing protocol, directional source-aware routing protocol (DSAP), which is the basic protocol for this work. In Section 6 we discuss different metrics that are tested and our proposed metrics. Section 7 presents the results of our simulations, where we demonstrate the use of new power-aware metrics. Section 8 summarizes the main results and outlines our future research.

2. Related Work

In most routing protocols, the paths are computed based on minimizing hop count or delay. When the transmission power of nodes is adjustable, hop count may be replaced by a power consumption metric. Some nodes participate in routing packets for many source–destination pairs, and the increased energy consumption may result in their failure. A longer path passing through nodes that have plenty of energy may be a better solution [3].

Singh *et al.* [3] propose several algorithms for power-aware routing in mobile ad hoc networks. The algorithms in [3] propose to use a function, $f(A)$, to denote node A's reluctance to forward packets and to choose a path that minimizes the sum of $f(A)$ for nodes on the path. This routing protocol [3] addresses the issue of energy-critical nodes. As a particular choice for f, [3] proposes $f(A) = 1/g(A)$, where $g(A)$ denotes the remaining lifetime of the node. The other metrics used in [3] are aimed at minimizing the total energy consumed per packet. However, [3] merely observes that the routes selected when using this metric will be identical to routes selected by shortest hop count routing, as the energy consumed in transmitting (receiving) one packet over one hop is considered constant.

In [4] and [5] the authors describe several localized routing algorithms that try to minimize the total energy per packet and/or lifetime of each node. The proposed routing algorithms are all demand based. These methods use control messages to update the positions of all nodes to maintain the efficiency of the routing algorithms.

We use similar ideas that use power-aware routing, but from a local view of the network, without sending control messages to request information. Each neighbour will gather local information about each neighbour whenever there is communication with its neighbour and will use this information to calculate the possible routes. By doing so, the protocol limits the energy consumption, because energy consumption occurs in three domains: sensing, data processing, and communication. Communication is the major consumer of energy in a WSN; Pottie and Kaiser [6] showed that communication costs significantly more than processing. So, it is possible to make trade-offs between data processing and wireless communication. Hence, local data processing is crucial in minimizing power consumption in a multihop wireless sensor network [7].

3. Problem Statement

Wireless sensor networks typically have power constraints. The absence of wires implies the lack of an external power supply such as battery packs. Although photovoltaic or other passive energy-gathering techniques are possible, these approaches typically provide only a modest amount of operating power. Therefore it is necessary to extend the battery life of individual sensors so that the network can remain functional as long as possible.

Due to the limited power that nodes have, we restrict the routing to the local information available to the nodes from their neighbours only. Consider the following network scenario where all sensors are identical and have the same power. Also, sensors are aware of their neighbours' power and the direction in which to send the message.

From this scenario we want to develop a metric that can be used to route a message from a source to a destination with the aid of local information only. The idea is to evaluate the routing according to this local information without the aid of global information.

In this article we do not consider the effects of communication with a base station. Because the topology is fixed and known, we assume that the base station can be placed at an appropriate position relative to the sensor network.

4. Assumptions

We assume a simple model where the radio dissipates $E_{elec} = 50\,\text{nJ/bit}$ to run the transmitter or receiver circuitry and $E_{amp} = 100\,\text{pJ/bit/m}^2$ for the transmit amplifier to achieve an acceptable E_b/N_0 (see Fig. 1 and Table 1) [8]. To transmit a k-bit message a distance d meters using our radio model, the radio expends:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= E_{elec} \times k + E_{amp} \times k \times d^2 \end{aligned} \tag{1}$$

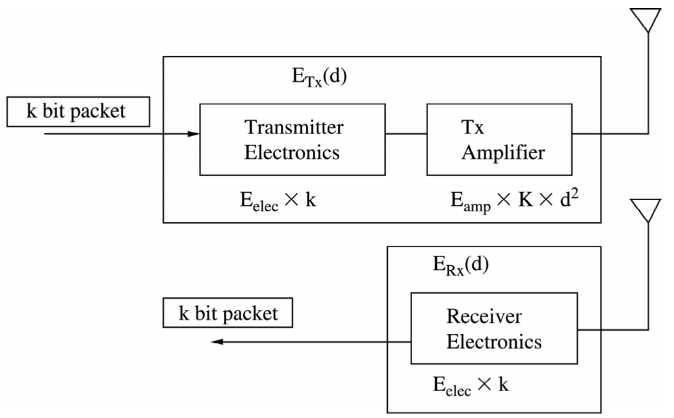

Figure 1. First-order radio model.

Table 1
Radio Characteristics [8]

Operation	Energy Dissipated
Transmitter electronics ($E_{Tx-elec}$) Receiver electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	$50\,\text{nJ/bit}$
Transmit amplifier (E_{amp})	$100\,\text{pJ/bit/m}^2$

To receive this message, the radio expends:

$$E_{Rx}(k) = E_{Rx-elec}(k) = E_{elec} \times k \qquad (2)$$

For these parameter values, receiving a message is not a low-cost operation; the protocol should thus try to minimize not only the transmit distance, but also the number of transmit and receive operations for each message.

We assume that the same transmission power is used to reach any neighbouring node and all data packets contain the same number of bits. We assume the following parameters: the maximum transmission range is $d = 0.5$ m and the number of bits transmitted is $k = 512$ bits. The topology that we are going to evaluate is a 10×10 2D mesh with a maximum of eight neighbours (Fig. 2).

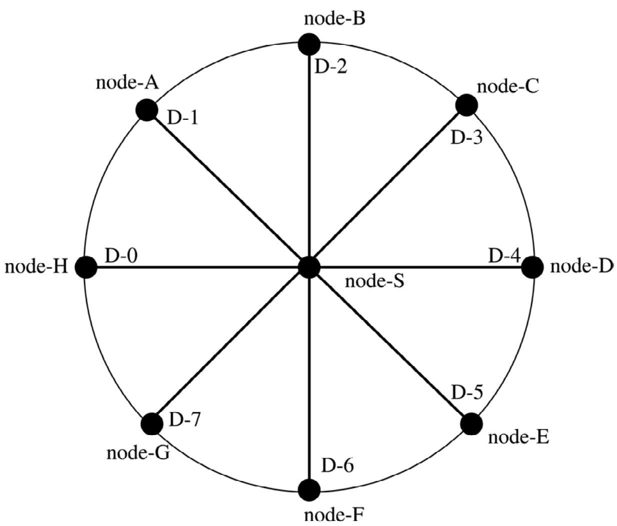

Figure 2. Directional eight-neighbour case.

5. DSAP

The directional source-aware routing protocol (DSAP) [9] incorporates power considerations into routing tables. The routing works by assigning each node an identifier that places that node in the network. Each node has a unique identifier that is called the directional value (DV) [9]. The DV represents the location of each node in the network with respect to its neighbours. These values can be determined in the setup phase of the network. We assume that the setup phase has been done and the DV has been determined. Based on the features of the DV, we use the protocol that was developed in [9]. For example, in the eight-neighbour case shown in Fig. 2, node S would have an identifier of (n_0, n_1, n_2, n_3, n_4, n_5, n_6, n_7). This means that there are n_0 nodes to the edge in direction D-0, n_1 in D-1, n_2 in D-2, and so on.

When transmitting a message, the destination node identifier is subtracted from the source node identifier. This gives at most five positive numbers (for a 2D topology with eight neighbours) that describe in which directions the message needs to move. Negative numbers are ignored. The decision to move in any positive direction is determined by the *directional value* of the nodes in question. Taking each of the neighbour's identifiers and subtracting it from the destination node's identifier computes the DV. These eight numbers are added together, and the one with the smaller number is chosen. If both nodes have the same DV, then one is randomly picked. This is the basic scheme developed for routing messages.

For example, consider the source node $S_{2,2}$ with $DV_{2,2} = (2, 2, 2, 2, 7, 7, 7, 2)$ and destination node $D_{8,8}$ with $DV_{8,8} = (8, 8, 8, 1, 1, 1, 1, 1)$. According to the DSAP algorithm [9], S-D $= (-6, -6, -6, 1, 6, 6, 6, 1)$, which produces D-3, D-4, D-5, D-6, and D-7 as possible positive directions that the message can be forwarded to, then computes the directional value of each positive direction to find which route to take. By doing so, we get the following values for each direction: 37, 36, 34, 36, and 38 respectively.

By choosing the minimum directional value, the message is forwarded in direction D-5, which is obvious from Fig. 3. The protocol repeats until the final destination is reached; that destination will have a DV of 0. In the next section, we will introduce different metrics that can be used to enhance the routing mechanism of DSAP.

6. DSAP and Power Metrics

Using local information that is available to each node limits the resources that are available for the routing protocol. Each node knows its neighbours and their DVs. Each node knows the power available at its neighbours and can calculate the direction of the final destination from the DV. Nodes can calculate the sum of powers from their neighbours and also approximate the number of hops to the destination from the DV.

Considering the above information, we notice that the routing protocol is limited by the choices that are available to decide the next hop to advance the packet. From this local information that is available, we can use power only, DV, DV and power, the sum of power and directional value, the cost of route and number of hops, power sum, and DV.

We now describe the paths chosen by the corresponding localized routing algorithms. To illustrate this, a sample has been taken at round 4,000 as shown in Fig. 3 to compare the different routes each method will take.

6.1 Power Only

In Fig. 3, DSAP first calculates the DV to determine the positive directions, and then the packet is forwarded to the node with the maximum power available at that node. As shown in the figure, this routing method may take longer paths because of the power and may even loop in the network without reaching the final destination. To avoid looping, the algorithm keeps track of the neighbour that forwarded the packet to it and tries to avoid that node.

6.2 Directional Value Only

In this approach, the algorithm considers only the DV of its neighbours with respect to the final destination. The only information that is available to the source is the IDs of its neighbours. From this information the source can

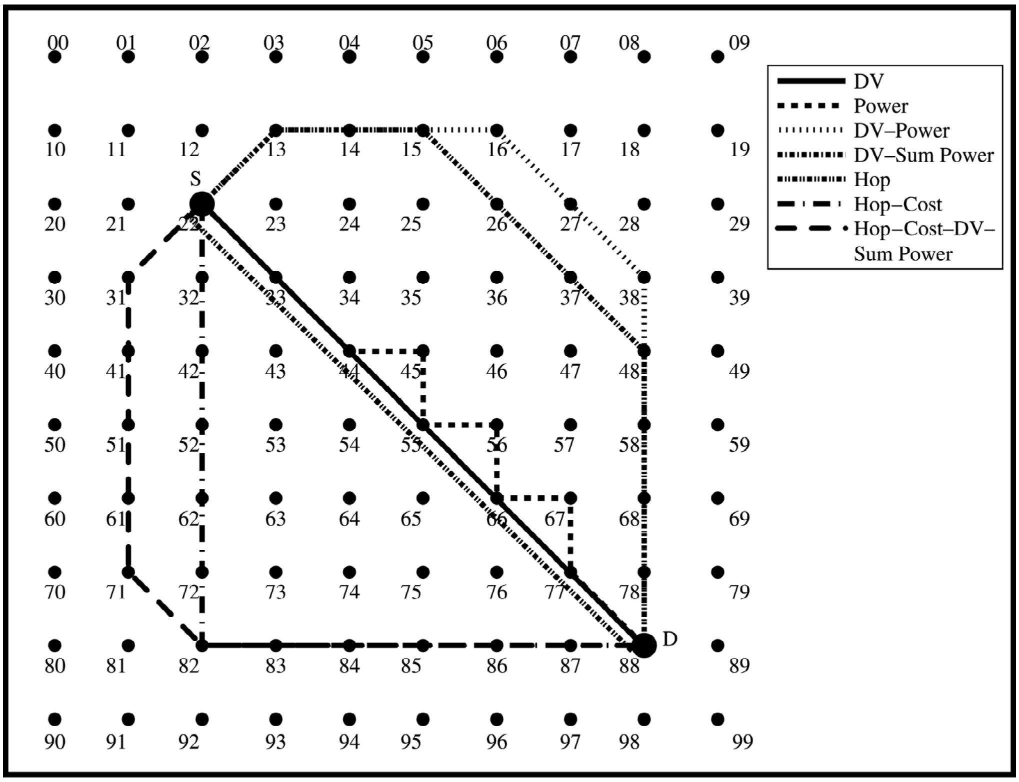

Figure 3. Routing using different metrics at round 4,000.

calculate the DV of its neighbours with respect to the final destination. The message will be forwarded to the node with the minimum value. As shown in Fig. 3, node $(2, 2)$ takes the direct path to node $(8, 8)$ without considering the power available at those neighbours. So it may take the shortest path, but it may be a costly path that is taken.

6.3 DV and Power

In this approach, the algorithm incorporates energy efficiency. This was achieved by considering the maximum available power and minimum DV when picking which node route to take. Instead of picking the node with the lowest DV or the maximum power, the DV is divided by the power available at that node. The smallest value of this power-constrained DV is the path that is chosen. This allows for a least-transmission path that is also cognizant of power resources, although in some cases a longer path may be chosen if the available power dictates that choice. As shown in Fig. 3, the path from source $(2, 2)$ to destination $(8, 8)$ is longer than the path taken by using the DV metric only.

6.4 DV and Sum of Power

In this approach the algorithm incorporates energy efficiency from a different point of view; it uses the DV and the power available at the surrounding neighbours. Instead of looking at the power at the neighbours of the source, it looks one hop beyond these neighbours. This is accomplished by getting the sum of power at a node's neighbours from each neighbour. By doing so, the protocol may have a better choice in picking the next route. The route can be different from that chosen in the previous section, as shown in Fig. 3.

6.5 Number of Hops Only

This algorithm uses only the number of hops, which can be calculated from the DV. The number of hops for each direction will give a minimum and maximum number of hops. The algorithm will use the average of those two numbers to make a choice on routing the packet. The packet will be forwarded to the neighbour with the minimum number of hops. From Fig. 3, we see that for this sample the route is the same as for the DV metric.

6.6 Hops and Cost

In this approach, the algorithm uses the number of hops, which can be calculated from the DV, and estimates the cost of routing in each direction. The number of hops for each direction will give a minimum and maximum number of hops. The algorithm will use the average of those two numbers and then take the first hop and multiply it by the number of neighbours for the power received, and for the rest we estimate the maximum number of neighbours for this topology, which is eight neighbours. For each of these hops, a power transmission is added, because one node will transmit. This will give an estimate of the total power needed to transmit the message from the source to the destination. In Fig. 3, we see that the protocol takes a different route as shown.

6.7 Hops, Cost, DV, and Sum of Power

This algorithm takes into consideration all the information that is available to the source and tries to make the decision according to that information. First it calculates the number of hops and estimates the power needed to deliver the packet. Then it calculates the DV and the sum of power at the neighbours. Finally, it takes the ratio between those two values and picks the one with the minimum value. The packet will be forwarded to that neighbour. As shown in Fig. 3, this approach takes the longest path to try to conserve energy.

7. Performance Evaluation

In order to evaluate the performance of DSAP with different metrics, several simulations were run with the various metrics. For each metric that was tested, we used the same 10 randomly generated files that have the requested transmission from source to destination to guarantee the same requests for each different metric. Then, the average of those ten runs was taken to create the tables. For each table we calculate the total power level remaining for the network, the percentage mean of the power remaining, the total number of transmissions and receptions, the standard deviation of the power, the number of rounds after which a certain number of nodes died, and the total number of requests that were dropped because of dead nodes. This explains the status of the network using different routing methods. Finally, we look at the condition of the network at a fixed round to compare the performance of each method.

From Tables 2–8 we observe the following:

1. From Tables 2 and 7 we observe that the first node died in rounds 4,675 and 5,342, and the power remaining in the network is higher than in any other metric. But the standard deviation of the remaining power is also higher than in the other metrics. In Tables 3, 4, 5, 6, and 8 the first node died after round 10,000 and the first two methods mentioned have more than 25 nodes dead. That means that using power or cost only as a metric for routing exhausts the power available at some nodes without trying to distribute the power usage evenly among the rest of the nodes in the network.
2. From these tables, notice the amount of energy lost when the first node dies and the 25th node dies. We see that, when using the power only metric, the total power consumed is higher than with the other metrics. This is because in using power the routing protocol looks for nodes with higher power and tries to exhaust them until they die.
3. From Table 5 note that the number of dropped simulation messages using the DV and sum of power metric is less than that of all other metrics used. This is because

Table 2
Routing Using Power Only

Dead	1	5	10	20	25
Power	18.68	17.46	16.26	13.53	12.67
Mean %	74.72	69.83	65.03	54.12	50.07
Trans.	28053	33965	40142	54762	59597
Recv.	218816	260673	301255	393283	422063
STD	22.20	25.56	28.04	31.39	31.53
Rounds	4675	5546	6281	7796	8234
Drop	0	50	177	727	1059

Table 3
Routing Using DV Only

Dead	1	5	10	20	25
Power	13.97	12.95	12.66	10.99	10.58
Mean %	55.89	51.49	50.62	43.94	42.33
Trans.	50557	55405	56877	65634	67911
Recv.	380131	415083	424983	481768	495196
STD	23.43	25.31	25.85	27.32	27.54
Rounds	10804	11537	11721	12663	12867
Drop	0	59	86	472	627

Table 4
Routing Using DV and Power

Dead	1	5	10	20	25
Power	8.11	7.80	7.57	7.16	6.82
Mean %	32.45	31.10	29.98	28.58	27.28
Trans.	83160	84825	86150	88795	91261
Recv.	576461	586990	594737	607999	618842
STD	19.53	19.69	19.63	19.42	18.9
Rounds	15078	15284	15409	15599	15753
Drop	0	10	28	115	242

Table 5
Routing Using DV and Sum of Power

Dead	1	5	10	20	25
Power	7.51	7.32	7.20	6.88	6.59
Mean %	30.06	29.27	28.78	27.52	26.35
Trans.	86166	87236	87952	90009	92031
Recv.	596802	603401	607498	617793	627136
STD	19.30	19.34	19.30	18.87	18.39
Rounds	15720	15852	15919	16072	16203
Drop	0	5	16	82	176

Table 6
Routing Using Number of Hops Only

Dead	1	5	10	20	25
Power	13.23	12.68	11.94	11.06	10.15
Mean %	52.90	50.72	47.78	44.24	40.62
Trans.	54462	57105	60900	65753	70923
Recv.	405459	424099	449042	478724	508945
STD	23.33	24.35	25.57	26.59	26.83
Rounds	11643	12163	12806	13489	14191
Drop	0	30	143	443	967

Table 7
Routing Using Hops and Cost

Dead	1	5	10	20	25
Power	12.25	11.58	10.83	9.97	9.65
Mean %	48.99	46.32	43.30	39.87	38.60
Trans.	58353	61374	64852	68941	70542
Recv.	439782	462771	488786	518249	529081
STD	23.35	24.41	25.20	25.42	25.32
Rounds	5342	5608	5908	6240	6364
Drop	0	14	61	201	293

Table 8
Routing Using Hops, Cost, DV, and Sum of Power

Dead	1	5	10	20	25
Power	8.97	8.56	8.19	7.47	7.16
Mean %	35.90	34.23	32.78	29.89	28.63
Trans.	80195	82326	84196	88131	90078
Recv.	545746	559967	572210	596444	606889
STD	17.52	18.03	18.49	19.25	19.40
Rounds	13159	13436	13651	14038	14172
Drop	0	19	54	203	319

this method uses the sum of power at the neighbours, which gives the method a broader perspective of the power distribution on future paths. This will conserve power at the nodes with lower power.

In Table 9 we compare the behaviour of the network at a fixed round to see the number of dead nodes and the amount of power remaining in the network. We observe the following:

1. DV with power and DV with sum of power have no nodes dead for that round. This is because the power is distributed almost evenly among these nodes using the methods. We can see this from the standard deviation of the power.
2. The number of dead nodes in power only, cost only, and DV is much higher than in the other methods. The standard deviation is also high.
3. The amount of power remaining in the network for all the methods is close to each other, but they differ in the number of dead nodes and the number of dropped messages.

Table 9
Routing Using All Method at 14,000 Rounds

Routing Method	Power Level	Mean %	SD	Dead Nodes	Dropped Packets
Power	8.91	35.64	27.74	40	3693
DV	8.39	33.54	25.70	37	2271
DV–P	9.44	37.76	18.45	0	0
DV–Sum P	9.64	38.55	18.09	0	0
Hop	10.40	41.59	26.80	24	808
Hop–Cost	6.99	27.95	21.47	40	1988
Hop–Cost–DV–Sum P	7.54	30.18	19.15	18	192

8. Conclusion

We have discussed the need to make the routing protocols power aware from a local point of view. Thus, the routing protocol tries to make its decision by what is available from its neighbours only. Basing the decision on the power remaining is not by itself enough. Using the DV and the sum of power remaining at the next neighbours will give the routing protocol a broader perspective about the condition of the network from a local point of view. Our simulations show that using the DV and the sum of power and also using the DV with power extends the lifetime of the network.

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