ENERGY EFFICIENT ROUTING IN WIRELESS SENSOR NETWORKS

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ABSTRACT

Wireless sensor nodes can be deployed on a battlefield and organize themselves in a large-scale ad-hoc network. Traditional routing protocols do not take into account that a node contains only a limited energy supply. Optimal routing tries to maximize the duration over which the sensing task can be performed, but requires future knowledge. As this is unrealistic, we derive a practical guideline based on the energy histogram and develop a spectrum of new techniques to enhance the routing in sensor networks. Our first approach aggregates packet streams in a robust way, resulting in energy reductions of a factor 2 to 3. Second, we argue that a more uniform resource utilization can be obtained by shaping the traffic flow. Several techniques, which rely only on localized metrics are proposed and evaluated. We show that they can increase the network lifetime up to an extra 90% beyond the gains of our first approach.

I. INTRODUCTION

Recently IC and MEMS have matured to the point where they enable the integration of communications, sensors and signal processing all together in one low-cost package. It is now feasible to fabricate ultra-small sensor nodes that can be scattered on the battlefield to gather strategic information [1]. The events detected by these nodes need to communicated to gateways or users who tap into the network. This communication occurs via multi-hop routes through other sensor nodes. Since the nodes need to be unobtrusive, they have a small form-factor and therefore can carry only a small battery. As a result, they have a limited energy supply and low-power operation is a must. Multi-hop routing protocols for these networks necessarily have to be designed with a focus on energy efficiency.

The proposed approaches lean towards localized algorithms [1][2]. Due to the large number of sensors, network-scale interaction is indeed too energy expensive. Moreover, a centralized algorithm would result in a single point of failure, which is unacceptable in the battlefield. In this paper, we propose two options for localized algorithms to increase the sensor network lifetime: (1) minimize the energy consumption of transmissions and (2) exploit the multi-hop aspect of network communications.

The first option is to combine/fuse data generated by different sensors [1][2]. In [3] cluster head selection is proposed to perform this task. However, in section IV, we present a robust way of achieving the same functionality without explicit cluster formation.

The second option focuses on the paths that are followed during the data routing phase. The framework presented in [2] advocates a localized model called ‘directed diffusion’. Other work uses information on battery reserve and the energy cost to find the optimal routes [4]. The routing protocol in [5] is based on the node’s location, transmit energy and the residual battery capacity. In contract to this prior work, we propose a guideline that aims at spreading the network traffic in a uniform fashion. Our spreading ideas, although partly tailored towards the underlying routing algorithm we have chosen, should be beneficial for the energy aware routing protocols mentioned above. We discuss these spreading techniques in section V.

However, before discussing our data fusion and spreading, we first focus on the problem statement: how to increase the lifetime of a network of energy constrained devices. This results in a practical guideline, which considers the energy histogram. All of this is treated in section II.

II. PROBLEM STATEMENT

1. Energy Optimal Routing

Traditional ad-hoc routing algorithms focus on avoiding congestion or maintaining connectivity when faced with mobility [6]. They do not consider the limited energy supply of the network devices. The example of figure 1 illustrates how the limited supply alters the routing issue. Nodes *A* and *E* first send 50 packets to *B*. Afterwards, *F* sends 100 packets to *B*. From a load balancing perspective, the preferred paths are *ADB*, *ECB* and *FDB* respectively.

However, when the nodes are energy constrained such that they can only send 100 packets, these paths are no longer optimal. Indeed, *D* would have used up 50% of its energy

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before it can forward packets from *F* to *B*. In this case, all packets could have been delivered by choosing paths *ACB*, *ECB* and *FDB*. If, instead of *F*, node *C* would have become active, *A* should have used the original path *ADB*.

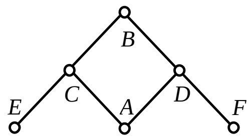

Figure 1: Load versus energy oriented routing

This simple case study highlights the following crucial observation: **optimal traffic scheduling** in energy constrained networks requires future knowledge. In our example, a maximum number of packets can reach *B* only if right from the start we know exactly when (and which) nodes will generate traffic in the future.

2. Energy Efficient Routing

Ideally, we would like the sensor network to perform its functionality as long as possible. Optimal routing in energy constrained networks is not practically feasible (because it requires future knowledge). However, we can soften our requirements towards a statistically optimal scheme, which maximizes the network functionality considered over all possible future activity. A scheme is **energy efficient** (in contrast to 'energy optimal') when it is statistically optimal and causal (i.e. takes only past and present into account).

In most practical surveillance or monitoring applications, we do not want any coverage gaps to develop. We therefore define the **lifetime** we want to maximize as the worst-case time until a node breaks down, instead of the average time over all scenarios. However, taking into account all possible future scenarios is too computationally intensive, even for simulations. It is therefore certainly unworkable as a guideline to base practical schemes on. Considering only one future scenario leads to skewed results, as shown in the example of figure 1.

3. Traffic Spreading Rationale

To derive a practical guideline, we start from the following observation: the minimum hop paths to a user for different streams tend to have a large number of hops in common [7]. Nodes on those paths die sooner and therefore limit the lifetime of the network. Figure 2 presents a typical energy consumption histogram at a certain point in time. Some nodes have hardly been used, while others have almost completely drained their energy.

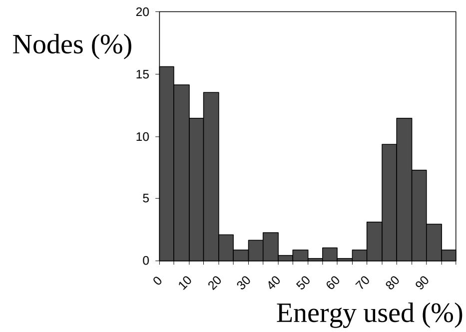

Figure 2: Undesirable energy histogam

As nodes that are running low on energy are more susceptible to die sooner, they have become more critical. If we assume that all the nodes are equally important (we revisit this assumption in section V.2), no node should be more critical than any other one. At each moment every node should therefore have used about the same amount of energy, which should also be minimized. The histogram of figure 3 is thus more desirable than the one of figure 2, although the total energy consumption is the same.

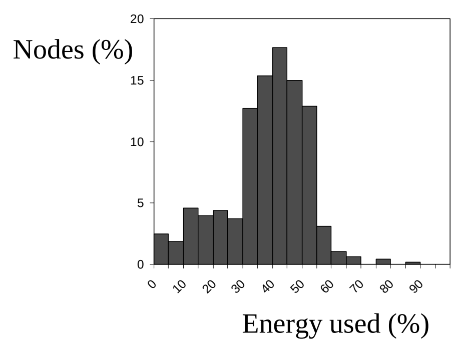

Figure 3: Desirable energy histogram

Striving for a compact energy histogram translates into the guideline that traffic should be spread over the network as uniformly as possible. Since visualizing the histogram over time is hard, we propose to use the root mean square E_{RMS} as an indicator instead (the lower this value, the better). It provides information on both the total energy consumption and on the spread.

III. BASIC ROUTING

As an underlying routing scheme, we base ourselves on the paradigm of directed diffusion [2]. When a user taps into the sensor network, he announces the type of information he is interested in. While flooding this 'interest' possibly using techniques like SPIN [8], gradients are established in each node. These gradients indicate the 'goodness' of the different possible next hops and are used to forward sensor data to the user.

We have opted for a simple instantiation of this paradigm, which we call Gradient-Based Routing (GBR). While being flooded, the 'interest' message records the number of hops taken. This allows a node to discover the minimum number of hops to the user, called the node's **height**. The difference between a node's height and that of its neighbor is considered the gradient on that link. A packet is forwarded on the link with the largest gradient. Although our techniques to increase the network lifetime are built upon GBR, the main principles are general enough to also be applicable to other ad-hoc routing protocols.

IV. DATA COMBINING

1. Data Combining Entities (DCE)

Individual sensor nodes process their sensor data before relaying it to the user [1]. It is advantageous to combine observations from different nodes to increase the resource efficiency. This process reduces not only the header overhead, but also the data itself can be compacted as it contains partly the same information.

Although this combining can be implemented by explicitly selecting a cluster head [3], we present a scheme that is more robust to random node failures. First note that sensor nodes that are triggered by the same event, are typically located in the same vicinity. The resulting cloud of activated nodes is also in close communication proximity. The routes from these nodes to the user merge early on [7]. Nodes that have multiple streams flowing through them can create a Data Combining Entity (DCE), which takes care of the data compaction. Simulations have shown that the DCEs are located inside or very close to this cloud of activated nodes.

This scheme is highly robust. When a node with a DCE dies, the packets automatically take an alternative route and pass through another node that can create a new DCE.

2. Simulations

Figure 4 depicts the effects of our DCE-based data compaction on the total energy consumption. The nodes in this simulation are distributed randomly over a rectangular area with a constant width of 32 m and a linearly increasing length *B*. The radio transmission range *R* is 20 m and the average node density is kept constant at $10^{-2}/m^2$. The nodes at the top of this area sense a target and notify a user that is located at the bottom end (the transmission of one packet takes 5.76 μJ). For our numerical results, we assume that a packet that is combined with another one can be compressed to 60% of its original size. We consider 3 distinct cases: without DCE, with at most one DCE (a compression bit in the packet header signals if the packet has been compressed already) on each route to the user and with no restrictions on the number of DCEs. The reduction in energy consumption is as expected (up to a factor 2 to 3), linearly proportional to the number of bits sent.

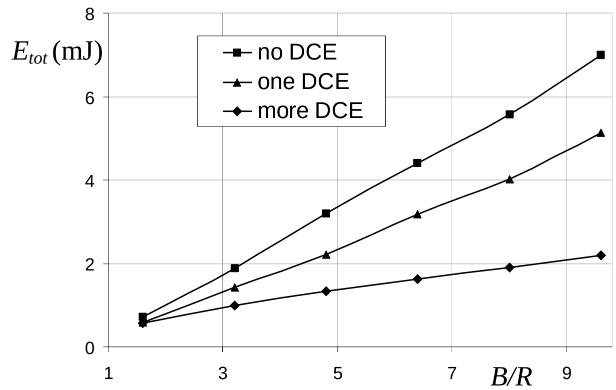

Figure 4: Energy comparison for DCE

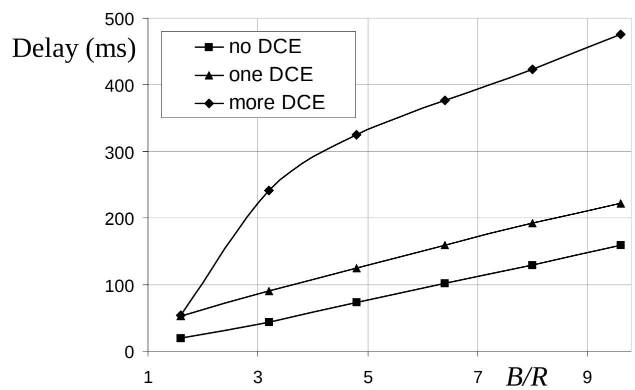

Figure 5: Delay comparison for DCE

The flip side is the average delay per packet, which is presented in figure 5. Since DCEs have to buffer data for a while, the packet delay will increase with the number of combining stages applied. Whether or not this is acceptable depends on the application.

V. NETWORK TRAFFIC SPREADING

1. Spreading Techniques

Stochastic Scheme: Using a rationale similar to the one of [9], each node can select the next hop in a stochastic fashion. More specifically, when there are two or more next hops with the same lowest gradient, a random one is chosen. This does not increase the length of the path followed, but nonetheless contributes to spreading the network traffic.

Energy-based Scheme: When a node detects that its energy reserve has dropped below a certain threshold (50% in our simulations), it discourages others from sending data to it by increasing its height. This may change a neighbor's height (since a node's height is one more than that of its lowest neighbor). It in turn informs other nodes and these updates are propagated as far as is needed to keep all the gradients consistent.

Stream-based Scheme: The idea is to divert new streams away from nodes that are currently part of the path of other streams. A node that receives packets tells all its neighbors except to the one from where the stream originates, that its height has increased. Again, other nodes must make sure the gradients remain consistent. As a result of this scheme, the original stream is unaffected, since those nodes have not updated the height of the next hop. New streams of packets, however, will take other paths as the height of the nodes on the first path has apparently increased.

2. Simulations

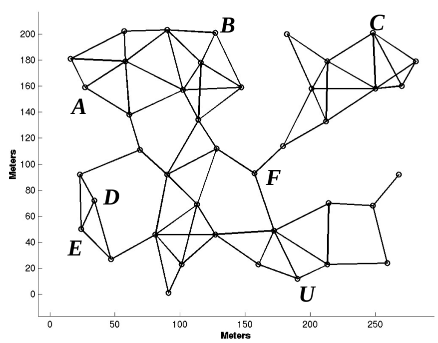

Figure 6: Wireless sensor network topology

Scenario 1: Nodes *A* and *B* (see figure 6) detect a different target and send packets to the user at regular intervals. After generating 100 packets each (this takes 11.8 seconds), these targets disappear and both nodes become inactive again. At this time, no node has been drained yet completely and the network connectivity is still fully intact. We have assumed a node has only 0.76 mJ of energy at its disposal (which is enough to send about 140 packets). The results can readily be scaled towards more realistic scenarios. Figure 7 shows the evolution of E_{RMS} as a function of time, for 5 different schemes. The unenhanced GBR is called 'standard'. Besides the three schemes discussed in V.1, we have also studied a combination of the stochastic and energy-based one.

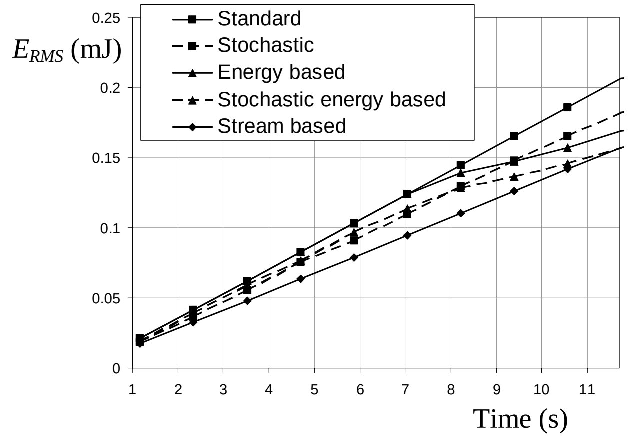

Figure 7: E_{RMS} for scenario 1

It is clear that the stream-based scheme indeed spreads the traffic more uniformly over the network. As soon as the energy of some nodes drops below 50%, the energy-based scheme kicks in. The stochastic routing provides an improvement both on top of the normal GBR and on top of the energy-based scheme.

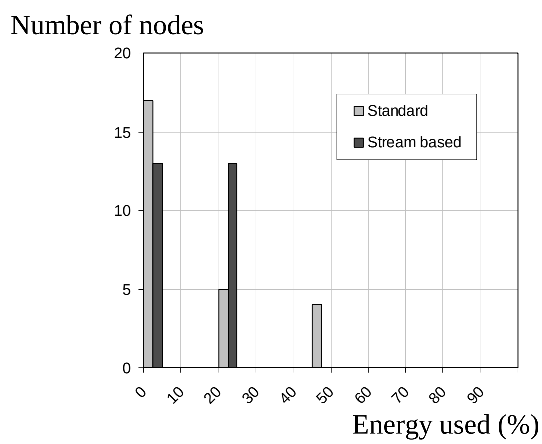

Figure 8: Energy histogram after 6 seconds

To verify that the E_{RMS} captures the relevant information, figure 8 shows the energy histogram for the standard and the stream-based scheme after 7 seconds. It is clear that spreading balances the energy consumption better.

Finally, we would like to show that the improved energy histogram is able to extend the network lifetime for a particular future scenario, although this does not prove anything about other possible futures. After 11.8 seconds node *C* starts forwarding packets to the user. Table 1 shows that the schemes that resulted in better traffic spreading also increase total traffic that reaches the user. We have verified that the time the network remains intact is increased by 90% when using the stream-based scheme.

Scheme	Packets received
Standard	127
Stochastic	133
Energy-based	160
Stochastic energy-based	161
Stream-based	175

Table 1: Packets received for scenario 1

Scenario 2: Nodes *D* and *E* (figure 6) each send 100 packets to the user in 11.8 s. Figure 9 illustrates that our traffic spreading schemes again result in a more uniform utilization of the network resources.

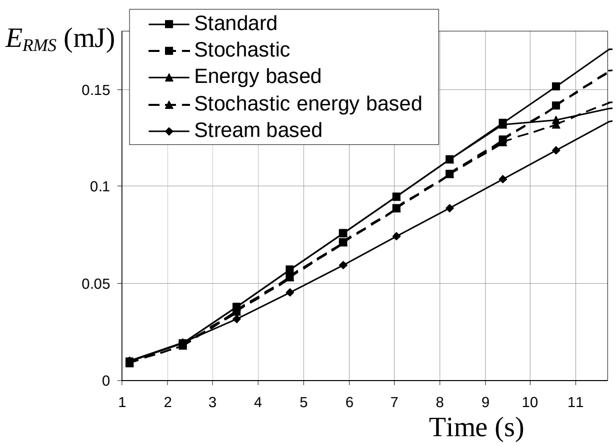

Figure 9: E_{RMS} for scenario 2

As before, we investigate one particular future activity scenario: node *C* becomes active after 11.8 seconds. From table 2, we conclude that spreading the network traffic has a negative effect as fewer packets are received! This is because the route taken by the standard GBR protocol avoids bottleneck node *F*. On the other hand, preading the traffic of *D* and *E* diverts some packets via *F* and therefore already partly drain this node before *C* can use it. This illustrates that spreading might increase the lifetime, although this does improve all possible futures. We observe however that the problems in this case are largely due to the fact that node *F* is critical as it is the only gateway to an entire subnet. Enhanced spreading techniques should therefore try to avoid critical nodes.

Scheme	Packets received
Standard	217
Stochastic	211
Energy-based	193
Stochastic energy-based	193
Stream-based	176

Table 2: Packets received for scenario 2

VI. CONCLUSIONS

In this paper we have argued that optimal routing in sensor networks is infeasible. We have proposed a practical guideline that advocates a uniform resource utilization, which can be visualized by the energy histogram. We acknowledge however that this is only a first cut at tackling this complicated issue. For example, exceptions must be made when nodes are critical in the overall network connectivity. We also propose a number of practical algorithms that are inspired by this concept. Our DCE combining scheme reduces the overall energy, while our spreading approaches aim at distributing the traffic in a more balanced way. We note that although we have started from GBR, our basic ideas and techniques should be able to enhance other routing protocols as well.

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