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Randomized Algorithms for Energy Balance in Wireless Sensor Networks (2005; Leone, Nikolettseas, Rolim)

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INDEX TERMS: Randomized algorithms, distributed computing, sensor networks, energy balance, lifetime maximization, data flow.

SYNONYMS: Power conservation.

1 PROBLEM DEFINITION

Recent developments in wireless communications and digital electronics have led to the development of extremely small in size, low-power, low-cost sensor devices (often called smart dust). Such tiny devices integrate sensing, data processing and wireless communication capabilities. Examining each such resource constraint device individually might appear to have small utility, however the distributed self-collaboration of large numbers of such devices into an ad-hoc network may lead to the efficient accomplishment of large sensing tasks i.e. reporting data about the realization of a local event happening in the network area to a faraway control center.

The problem considered is the development of a randomized algorithm to balance energy among sensors whose aim is to detect events in the network area and report them to a sink. The network is sliced by the algorithm into layers composed of sensors at approximately equal distances from the sink [8, 4, 5], see Figure 1. The slicing of the network depends on the communication distance. The sink initiates the process by sending a control message containing a counter which value is initially one. Sensors receiving the message assign themselves to slice number corresponding to the counter, increment the counter and propagate the message in the network. A sensor already assigned to a slice ignores subsequent received control messages.

The strategy suggested to balance the energy among sensors consists in allowing a sensor to probabilistically choose between either sending a data to a sensor in the next layer towards the sink or to send the data directly to the sink. The difference between the two choices is the energy consumption which is much higher if the sensor decides to report to the

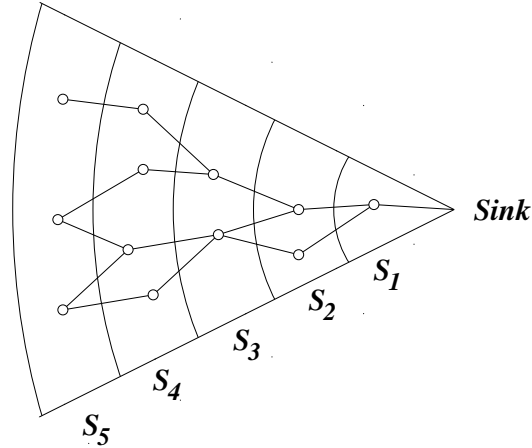


Figure 1: The sink and five slices S_1, \dots, S_5

sink directly. The energy consumption is modeled as a function of the transmission distance by assuming that the energy necessary to send a data up to a distance d is proportional to d^2 . Actually, more accurate models can be considered, in which the dependence is of the form d^α with $2 \leq \alpha \leq 5$ depending on the particular environmental conditions. Although the chosen model determines the parameters of the algorithm, the particular shape of the function describing the relationship between distance of transmission and energy consumption is not relevant except that it might increase with distance. The distance between two successive slices is normalized to be 1. Hence, a sensor sending a data to one of its neighbor consumes 1 unit of energy and a sensor located in slice i consumes i^2 units of energy to report to the sink directly. Small hops transmissions are cheap (with respect to energy consumption) but pass through the critical region around the sink and might strain sensors in that region, while expensive direct transmissions bypass that critical area.

Energy balance is defined as follows:

Definition 1. The network is energy balanced if the average per sensor energy dissipation is the same for all sectors, i.e. when

$$\frac{E[\mathcal{E}_i]}{S_i} = \frac{E[\mathcal{E}_j]}{S_j} \quad i, j = 1, \dots, n \quad (1)$$

with \mathcal{E}_i is the total energy available and S_i the number of nodes in slice number i .

The dynamics of the network is modeled by assigning probabilities λ_i , $i = 1, \dots, N$, $\sum \lambda_i = 1$, of the occurrence of an event in slice i . The protocol consists in transmitting the data to a neighbor slice with probability p_i and with probability $1 - p_i$ to the sink,

for a sensor belonging to slice i . Hence, the mean energy consumption per data unit is $p_i + (1 - p_i)i^2$. A central assumption in the following is that the events are evenly generated in a given slice; then, denoting by e_i the energy available per node in slice i (i.e. $e_i = \mathcal{E}_i/S_i$). The problem of energy balanced data propagation can be formally stated as:

Given $\lambda_i, e_i, S_i, i = 1, \dots, N$, find p_i, λ such that

$$\underbrace{(\lambda_i + \lambda_{i+1}p_{i+1} + \dots + \lambda_n p_n p_{n-1} \dots p_{i+1})}_{=:x_i} \left(p_i \frac{1}{S_i} + (1 - p_i) \frac{i^2}{S_i} \right) = \lambda e_i, \quad i = 1, \dots, N \quad (2)$$

Equations (2) amount to ensure that the mean energy dissipation for all sensors is proportional to the available energy. In turn, this ensures that sensors might, in average, run out of energy all at the same time. Notice that equations (2) contain the definitions of the x_i . They are the one estimated in the pseudo-code in Figure 2, the successive estimations being denoted as \tilde{x}_i . These variables are propotional to the number of messages handled by slice i .

2 KEY RESULTS

In [4, 5] similar recursive equations as (2) are suggested and solved in closed form under adequate hypotheses. The need for a priori knowledge of the probability of occurrence of the events, the λ_i parameters is considered in [7] in which these parameters are estimated by the sink based on the observations of the various paths the data follows. The algorithm suggested is based on recursive estimation, is computationally not expensive and converges with rate $\mathcal{O}(1/\sqrt{n})$. One might argue that the rate of convergence is slow, however, it is numerically observed that relatively quickly compared to the convergence time, the algorithm finds out an estimation close enough to the final value. The estimation algorithm ran by the sink (which has no energy constraints) is given in Figure 2.

Results taken from [4, 5, 7] all assume the existence of an energy balance solution. However, particular distributions of the events might prevent the existence of such a solution and the relevant question is no longer the computation of an energy balance algorithm. For instance, assuming that $\lambda_N = 0$, sensors in slice N have no way of balancing energy. In [9] the problem is reformulated as finding the probability distribution $\{p_i\}_{i=1,\dots,N}$ which leads to the maximal functional lifetime of the networks. It is proved that if an energy balance strategy exists, then it maximizes the lifetime of the network establishing formally the intuitive reasoning which was the motivation to consider energy balance strategies. A centralized algorithm is presented to compute the optimal parameters. Moreover, it is numerically observed that the inter-slice energy consumption is prone to be uneven and a spreading technique is suggested and numerically validated as being efficient to overcome this limitation of the probabilistic algorithm.

The communication graph considered is a restrictive subset of the complete communication graph and it is legitimate to wonder whether one can improve the situation by extending it. For instance by allowing data to be sent two hops or more away. In [1, 6]

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Initialize  $\tilde{x}_0 = \lambda, \dots, \tilde{x}_n$ 
Initialize NbrLoop=1
repeat forever
  Send  $\tilde{x}_i$  and  $\lambda$  values to the stations which compute their  $p_i$  probability
  wait for a data
  for  $i=0$  to  $n$ 
    if the data passed through slice  $i$  then
       $X \leftarrow 1$ 
    else
       $X \leftarrow 0$ 
    end if
    Generate  $R$  a  $\tilde{x}_i$ -Bernoulli random variable
     $\tilde{x}_i \leftarrow \tilde{x}_i + \frac{1}{NbrLoop}(X - R)$ 
    Increment  $NbrLoop$  by one.
  end for
end repeat

```

Figure 2: Pseudo-code for estimation of the x_i value by the sink

it is proved that the topology in which sensors communicate only to neighbor slices and the sink is the one which maximizes the flow of data in the network. Moreover, the communication graph in which sensors send data only to their neighbors and the sink leads to a completely distributed algorithm balancing energy [6]. Indeed, as a sensor sends a data to a neighbor slice, the neighbor must in turn send the data and can attach information concerning its own energy level. This information might be captured by the initial sensor since it belongs to the communication range of its neighbor (this does not hold any longer if multiple hops are allowed). Hence, a distributed strategy consists in sending data to a particular neighbor only if its energy level consumption is lower, otherwise the data is sent directly to the sink.

3 APPLICATIONS

Among the several constraints sensor networks designers have to face, energy management is central since sensors are usually battery powered making the lifetime of the networks highly sensitive to the energy management. Besides the traditional strategy consisting in minimizing the energy consumption at sensor nodes, energy balance schemes aim at balancing the energy consumption among sensors. The intuitive function of such schemes is to avoid energy depletion holes appearing as some sensors that run out of their available energy resources and are no longer able to participate to the global function of the networks. For instance, routing might be no longer possible if a small part of sensors run out of their energy leading to a disconnected network. This has been pointed out in [3] as well as the

need to develop application specific protocols. Energy balancing is suggested as a solution in order to make the global functional lifetime of the network longer. Earliest development of dedicated protocols ensuring energy balance can be found in [2, 10, 11].

A key application is to maximize the lifetime of the network while gathering data to a sink. Besides increasing the lifetime of the networks, other criteria have to be taken into account. Indeed, the distributed algorithm might be as simple as possible due to limited computational resources, might avoid collisions or limit the total number of transmissions, and might ensure a large enough flow of data from the sensors toward the sink. Actually, maximizing the flow of data is equivalent to maximizing the lifetime of sensor networks if some particular realizable conditions are fulfilled. Besides the simplicity of the distributed algorithm the network deployment and the self realization of the network structure might be possible in realistic conditions.

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