

WAVE LEADER ELECTION PROTOCOL FOR WIRELESS SENSOR NETWORKS

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In this paper we present and analyze a wireless wave leader election protocol (WWLE) for wireless mobile ad hoc sensor networks. We present also a mathematical model for the energy consumption within a sensor node. The capabilities of a node being a leader (like available resources such as battery energy, network capabilities, etc.) are integrated in the algorithm. The simulation results show that this algorithm is efficient in number of rounds and number of messages.

Keywords: leader election protocol, sensor network

1 INTRODUCTION

The vision of ubiquitous computing requires the development of devices and technologies that can be pervasive without being intrusive. The basic component of such a smart environment will be a small node with sensing and wireless communications capabilities, able to organize itself flexibly into a network for data collection and delivery. Realizing such a sensor network presents many significant challenges, especially at the architectural, protocol, and operating system level. Major steps forward are required in the field of communications protocol, distributed data processing, and application support.

In this paper we will deal with an leader election protocol for energy efficient mobile sensor networks in which we take into account irregular topologies and mobility of the nodes. In particular we will look at the performance of the protocol and the energy consumption model. This work is performed within the EYES project [1], which is a European research project (IST-2001-34734) on self-organizing and collaborative energy-efficient sensor networks.

The network has the following characteristics: it is an ad-hoc, multi-hop wireless network in which we assume bidirectional communication (at least at this step in the design and analysis). At a certain moment a node can either transmit or receive information.

This paper is organized as it follows: Section 2 describes the mathematical model of the energy consumption of a sensor node. The next section describes the wave leader election protocol for mobile sensor networks. Section 4 presents several simulations results in order to characterize the algorithm's performances. The paper ends with discussions and directions for future work.

2 MATHEMATICAL ENERGY CONSUMPTION MODEL OF A NODE

In this section we present a basic version of an energy model for a sensor node. The aim of the model is to predict the current energy state of the battery of a sensor node based on historical data, on the use of the sensor node and the current energy state of the battery. The model considers only four components: the radio, the processor, the sensor and the battery.

The base of the model for the energy consumption of a component is the definition of a set S of possible states s_1, \dots, s_k for the component. These states are defined such that the energy consumption of the component is given by the sum of the energy consumptions within the states s_1, \dots, s_k plus the energy needed to switch between the different states. We assume that the energy consumption within a state s_j can be measured using a simple index t_j (e.g. execution time or number of instructions) and that the energy needed to switch between the different states can be calculated on the base of a state transition matrix st , where st_{ij} denotes the number of times the component has switched from state s_i to state s_j . If now P_j denotes the needed power in the state s_j and E_{ij} denotes the energy consumption of switching once from state s_i to state s_j , the total energy consumption of the component is given by

$$E_{consumed} = \sum_{j=1}^k t_j P_j + \sum_{i,j=1, i \neq j}^k st_{ij} E_{ij}. \quad (1)$$

The state sets S are: *off*, *sleep*, *receiving*, and *transmitting* for the radio; *off*, *stand by*, and *active* for the processor; *on* and *off* for the sensor. For the battery only the energy state E_{old} at a time t_{old} in the past is given.

Based on this information an estimate of the current energy state of the battery can be calculated by subtracting from E_{old} the sum of the consumed energy for each component estimated on the base of equation (1).

3 WAVE LEADER ELECTION PROTOCOL (WWLE)

As a first approach to the leader election problem, we have considered a simple wave algorithm [9] specific to static wired networks. We evaluate the protocol for different network topologies, taking mobility into account as well.

The basic wave algorithm was chosen for two additional reasons. First of all, because of its simplicity we can use it to evaluate effects when we modify given wired network algorithms to algorithms specific to wireless networks. The second reason is that it completes in a fixed number of rounds and it involves all the nodes in both transmitting and receiving information operations, so it is a useful tool for testing the lower layers, their protocols and the hardware involved.

3.1 PREVIOUS WORK

For the wireless distributed systems existing results usually cover only particular types of networks and topologies. The main direction in leader election seems to be on randomized algorithms. The first algorithm of this type was described in [3]. It addresses multi-hop static radio networks. In [5] an improved version is described as well as a short survey of the existing protocols in the area. A detailed survey on radio networks algorithms is presented in [4]. Based on these results several improved algorithms were created.

For example, [8] describes a uniform leader election protocol that addresses the case of complete radio networks (networks in which each node can communicate directly to any other node, or single-hop networks). The term 'uniform' means that it is assumed that in each time slot every station transmits with the same probability. Other results by the same authors are presented in [7], where they address the case of randomized leader election protocols in the same type of networks. A method of mapping these algorithms to multi-hop wireless networks without collision detection is given in [2].

In [6] the case of networks in which the nodes are aware of their spatial position is discussed. [10] present also two leader election protocols for wireless adhoc networks. They are based on the assumption of the existence of a low-level layer that provides each node with the list of its neighbors.

3.2 OVERVIEW OF THE WWLE ALGORITHM

As we have stated in the introduction, the starting point for our algorithm was an algorithm described in [9]. The main idea consists in assigning unique ID-s from an ordered set to each of the nodes in the network and then elect leader

the node with the minimum ID. Every node maintains a record of the minimum ID it has seen so far (initially its own). At each round, each node propagates this minimum on all of its outgoing edges. After a number of rounds equal to the network diameter, a node elects itself as leader if the minimum value seen in this node is the node's own ID; otherwise it is a non-leader. It is shown in [9] that the number of rounds needed to complete this algorithm is equal to the diameter $diam$ of the network. The number of exchanged messages of the original protocol is $diam \cdot |E|$ ($diam$ is the diameter of the network and $|E|$ is the number of directed edges).

Some nodes might not have enough resources to become leaders. We use *the willingness* of a node to become a leader. A coefficient can be computed locally by each node as a function of the amount of available resources. A low value means high willingness. Other values place the node on lower levels of desire to become leader.

In the following presentation we assume an ideal MAC protocol, that allows the nodes to exchange messages in rounds (for example, something similar to a TDMA scheme). The particular characteristics of the WWLE protocol are:

- a node will transmit the minimum ID only the first time when it learns it (the first round and then only if receiving it from a neighbor);
- a node will decide on the smallest value to transmit immediately as it has received it and not at the end of one round.
- the ID of a node contains also the willingness coefficient of the node (the value is placed in front of the original ID)

4 SIMULATION RESULTS

The number of rounds necessary for the algorithm to complete is related to the diameter of the network. This diameter is not known in most of the cases so we will need an estimation of the maximum number of rounds. For these purpose we have run several simulations for certain degrees of nodes connectivity.

We have used a 2D network of $n=100$ nodes arranged in a 10×10 grid. The results were obtained after 1,000,000 simulations of different ID allocations for the same topology.

Nr. rounds	2	3	4	5	6	7	8	9
Nr. occ.	40	45160	350071	437733	150474	16063	453	6
%	<0.1%	4.5%	35.0%	43.8%	15.0%	1.6%	<0.1%	<0.1%

Table 1: Simulation results for connectivity 3.6

Nr.of rounds	1	2	3	4	5
Nr. of occurrences	311	313414	612890	72645	740
%	<0.1%	31.3%	61.3%	7.3%	< 0.1%

Table 2: Simulation results for connectivity 6.84

4.1 NUMBER OF MESSAGES AND ROUNDS

Due to the nature of the algorithm it is difficult to give an analytical result for the maximum number of rounds needed by the algorithm to complete for an arbitrary topology. The worst case is obtained when the nodes are arranged in a line and they can communicate only with their one hop away neighbors. The maximum number of rounds needed in this case is $n - 1$. The simulation indicates for the used 2D network never more of $diam/2$ rounds were needed and in average the number of used rounds was $diam/4$ (see Table 1).

The first set of results was obtained considering that each node can communicate with the first hop neighbor nodes on horizontal and vertical directions. This gives us an average connectivity of 3.6. Table 1 presents the number of rounds needed for the algorithm to complete. For the algorithm, the maximum number of rounds can be considered 7 with an error of less than 0.1% or even 6 with an error of 1.6%. The average number of rounds is 4.74.

The second step is to extend the connectivity to 6.84 by allowing each node to communicate with the neighbors along the diagonal directions also.

Simulation results for this setting are presented in Table 2. The maximum number of rounds can be considered 4 with an error less than 0.1%. The average number of rounds needed is 2.76.

The medium number of messages exchanged is 245 and respectively 178 messages per total. In the first case, the minimum number of needed messages is 144 and the maximum 426. The exchanged number of messages in the second case lies between 72 and 325.

The next step is to increase the matrix dimension while maintaining the same number of nodes. In this way we allow different asymmetric topologies while still maintaining low connectivity. The results are presented in Table 3.

Matrix dimension	15x15	20x20	50x50
Average connectivity	5.3	5.12	4,89
Average nr. of messages	328.5	353.2	385.8
Average nr. of rounds	4.9	5.5	6.75

Table 3: Extended matrix simulation result

Probability of topology change	static	10%	20%	30%
Nr. of rounds	2.96	1.976	1.967	1.970
Nr. of messages	178	134.78	132.29	132.09

Table 4: Mobility simulation results

4.2 MOBILITY ISSUES

In our sensor network there can be both fixed and mobile nodes. The fixed sensors are larger and better equipped and are better candidates to become the leader. In the next setup we will simulate these two distinct kind of nodes, in which the mobile nodes have smaller resources and will participate in the leader election algorithm just to forward data and to learn the new leader.

We consider that half of the network will be made up of static nodes and half of mobile nodes. We allow only the static nodes to be possible candidates for the leader election. This can be done by imposing distinct willingness coefficients to both mobile and static nodes. It is interesting to notice that the results obtained by simulations are almost identical with the previous case (the same exact number of rounds and only slight modifications in the number of exchanged messages).

To address topology changes we have modified slightly the algorithm by forcing each node to transmit the minimum value each time it is its turn (not only when it first learns about a minimum value). Simulations were performed assuming different probabilities of topology change occurring in each time slot for the mobile nodes. The results are presented in Table 4, in which the network has connectivity of 6.84. An improvement in medium number of rounds and messages is achieved when compared to the static network. There is no significant difference between the degrees of mobility.

4.3 ENERGY CONSUMPTION ISSUES

The main reduction in energy consumption is caused by the small number of messages exchanged and the small size of each message. The mathematical model for the energy consumption presented at the beginning of the paper can be used to determine exactly how much energy is spent during this process. However, for

	$P_j(mW)$	tr matrix(μs)				
j			S1	S2	S3	S4
S1	0	S1	...	...	...	...
S2	0.15	S2	...	...	288	720
S3	14.4	S3	...	158	...	...
S4	36	S4	...	396	720	...

Table 5: Radio characteristics

a detailed characterization one has to take into consideration the MAC protocol used, since this has a major impact.

As an example, let us assume the case of 100 nodes and a TDMA scheme. We assume data packet of 1000 bits, the header (that contains the routing information, data format, time information, etc.) occupies 100 bits. The ID that needs to be transmitted has 11 bits (4 describing the disponibility of a node and 7 identifying the node). The maximum transmission speed of the TR1001 is 115.2 kilobits per second.

First step of this analysis is to identify the power consumption in each of the states for the radio and also the time spent in each of the states (see Table 5). The four states are, in order: off (S1), sleep (S2), receive (S3) and transmit (S4).

Formula (1) gives some partial results based on the previous data. So, when a node acts like a transmitter inside a time slot it needs $37\mu J$ to transmit the minimum ID it knows. To receive an ID it needs $14.5\mu J$. So, for the case of 4 rounds of messages in which 178 messages are transmitted we have a energy consumption of 584mJ (assuming that all of the nodes are listening when not transmitting). In the worst case in which all the nodes will transmit full length packets at their time we have an energy consumption of 699,8mJ. If all the network is in the sleep mode, then the energy consumption will be of only $0.13\mu J$.

The small difference between the results appears due to the assumption that the nodes are listening all the time. Once again, the previous computation is just an example and the real results can be obtained only after analyzing the MAC protocol used.

5 CONCLUSIONS

In this paper we presented and simulated an efficient leader-election protocol for mobile ad hoc sensor networks.

The results show that the WWLE algorithm is efficient in number of rounds and exchanged messages. Moreover, our protocol takes into account mobility and

network topology, whereas related work merely addresses less general approaches. The development of WWLE algorithm gave us the opportunity of testing and improving the specifications for the lower layers involved in the project.

The simulations were made with the assumption of low network connectivity. However, in practice, the connectivity might be usually larger which would give us better results. In future research we will investigate the influence of different MAC protocols and determine possible interactions. Also aspects of reliability in case of node failure will be studied and integrated in the protocol.

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