Low Energy Adaptive Clustering Hierarchy with Deterministic Cluster-Head Selection

M. J. Handy, M. Haase, D. Timmermann

Institute of Applied Microelectronics and Computer Science
University of Rostock, Richard-Wagner-Str. 31, 18119 Rostock, Germany
matthias.handy@etechnik.uni-rostock.de

Abstract - **This paper focuses on reducing the power consumption of wireless microsensor networks. Therefore, a communication protocol named LEACH (Low-Energy Adaptive Clustering Hierarchy) is modified. We extend LEACH's stochastic cluster-head selection algorithm by a deterministic component. Depending on the network configuration an increase of network lifetime by about 30 % can be accomplished. Furthermore, we present a new approach to define lifetime of microsensor networks using three new metrics FND (First Node Dies), HNA (Half of the Nodes Alive), and LND (Last Node Dies).**

Keywords: microsensors; network; power; energy; clustering; lifetime.

1. Introduction

The vision of Ubiquitous Computing which Mark Weiser described in his 1991 paper [1] is based on the idea that future computers merge with their environment more and more until they become completely invisible for the user. Distributed wireless microsensor networks are an important component of the world of Ubiquitous Computing [2],[3]. Small dimensions are an important design goal for microsensors. The energy supply of the sensors is a main constraint of the intended miniaturization process [4]. It can be reduced only to a specific degree since energy density of conventional energy sources increases slowly [5],[6].

In addition to improvements in energy density, energy consumption can be reduced. This approach includes the use of energy-conserving hardware. Moreover, a higher lifetime of sensor networks can be accomplished through optimized applications, operating systems, and communication protocols. In [7] particular modules of the sensor hardware are turned off when not needed. A low-power MAC-protocol is described in [8]. Rodoplu and Meng propose a new network protocol to reduce energy consumption of wireless networks [9].

This work focuses on LEACH (Low-Energy Adaptive Clustering Hierarchy), a communication protocol for microsensor networks [10],[11],[12]. LEACH collects data from distributed microsensors and transmits it to a base station. LEACH uses the following clustering-model: Some of the nodes elect themselves as cluster-heads. These cluster-heads collect sensor data from other nodes in the vicinity and transfer the aggregated data to the base station. Since data transfers to the base station dissipate much energy, the nodes take turns with the transmission – the cluster-heads "rotate". This rotation of cluster-heads leads to a balanced energy consumption of all nodes and hence to a longer lifetime of the network.

This paper proposes a modification of LEACH's cluster-head selection algorithm to reduce energy consumption. For a microsensor network we make the following assumptions:

- The base station (BS) is located far from the sensors and immobile.
- All nodes in the network are homogenous and energy-constrained.
- All nodes are able to reach BS.
- Nodes have no location information.
- Symmetric propagation channel
- Cluster-heads perform data compression.

The energy needed for the transmission of one bit of data from node u to node v, is the same as to transmit one bit from v to u (symmetric propagation channel). Cluster-heads collect n k-bit messages from n adjacent nodes and compress the data to cn k-bit messages which are transmitted to the BS, with $c \leq 1$ as the compression coefficient.

The operation of LEACH is divided into rounds. Each of these rounds consists of a set-up and a steady-state phase. During the set-up phase cluster-heads are determined and the clusters are organized. During the steady-state phase data transfers to the base station occur. This paper presents an improvement of LEACH's cluster-head selection algorithm – the formation of clusters is not the topic of this paper.

We use the same radio model as stated in [10] with E_{elec}=50 nJ/bit as the energy being dissipated to run the transmitter or receiver circuitry and ε_{amp}=100pJ/bit/m² as the energy dissipation of the transmission amplifier. Transmission (E_{Tx}) and receiving costs (E_{Rx}) are calculated as follows:

$$E_{Tx}(k,d) = E_{elec}k + \varepsilon_{amp}kd^{\lambda} \tag{1}$$

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$$E_{Rx}(k) = E_{elec}k \tag{2}$$

with k as the length of the message in bits, d as the distance between transmitter and receiver node and λ as the path-loss exponent ($\lambda \geq 2$).

The rest of the paper is organized as follows. Section 2 shows that a stochastic cluster-head selection can theoretically lead to a three times higher energy consumption during the set-up phase than deterministic cluster-head selection. Three new metrics are introduced to define the lifetime of a microsensor network. Additionally, clustering algorithms similar to LEACH are briefly reviewed in section 2. In Section 3 a modification of LEACH's cluster-head selection algorithm is proposed. Simulation results comparing stochastic and deterministic cluster-head selection are presented in section 4. Section 5 concludes the paper and discusses possible future research directions.

2. Preliminaries

2.1. *Problem formulation*

LEACH cluster-heads are stochastically selected. In order to select cluster-heads each node *n* determines a random number between 0 and 1. If the number is less than a threshold *T(n)*, the node becomes a cluster-head for the current round. The threshold is set as follows:

$$T(n) = \frac{P}{1 - P \times \left(r \bmod \frac{1}{P} \right)} \qquad \forall n \in G \tag{3}$$

$$T(n) = 0 \qquad \forall n \notin G \tag{4}$$

with P as the cluster-head probability, r as the number of the current round and G as the set of nodes that have not been cluster-heads in the last 1/P rounds. This algorithm ensures that every node becomes a cluster-head exactly once within 1/P rounds.

Looking at a single round of LEACH, it is obvious that a stochastic cluster-head selection will not automatically lead to minimum energy consumption during data transfer for a given set of nodes. All cluster-heads can be located near the edges of the network or adjacent nodes can become cluster-heads. In these cases some nodes have to bridge long distances to reach a cluster-head. However, looking at two or more rounds it could be assumed that a selection of favourable cluster-heads results in an unfavourable cluster-head selection in later rounds since LEACH tries to distribute energy consumption among all nodes. As an example, consider the case of Fig. 1. In the bad-case-scenario cluster-heads are selected unfavourably near the edges, in round 0 on the right-hand-side and in round 1 on the left-hand-side of the network. Using Eq. (1) and (2), the accumulated transmission energy of all nodes over both rounds – excluding the transmission to the base station – accounts for 321,5 nJ/bit. In the good-case-scenario cluster-heads are not distributed optimally across the network, however, better than in the bad-case-scenario. The accumulated transmission energy of all nodes over both rounds now accounts for 90,5 nJ/bit. The next paragraph shows that a selection of favourable cluster-heads will not automatically lead to a higher energy consumption in later rounds.

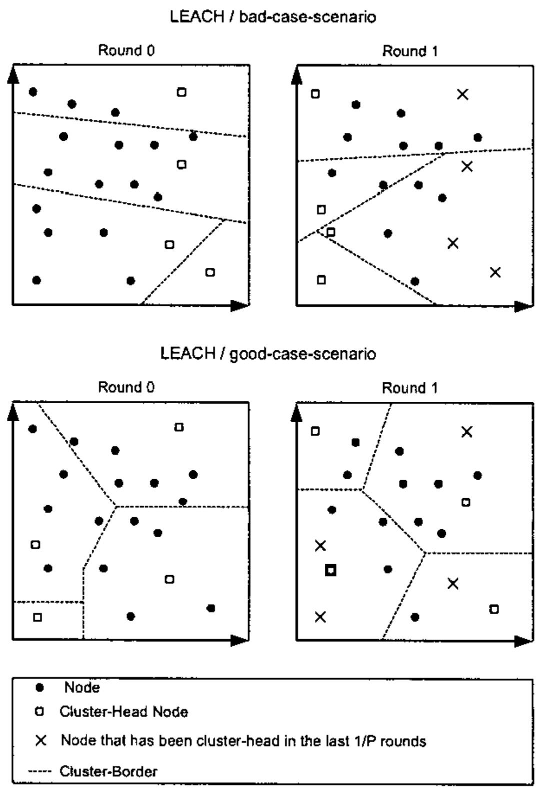

Fig. 1. LEACH-Network with P=0.2; n=20; network dimension: 100x100m. Above, cluster-heads are placed in proximity to each other and near the edges. This leads to high energy consumption since nodes have to transmit over long distances. Below, energy is saved by uniformly distributing cluster-heads over the network. Notice that the set of nodes that have not been cluster-heads in round 0 and 1 is equal for both cases.

Let G_0 be the set of nodes that have not been cluster-heads before round 0 and let G_0=N with N as set of all nodes of the network, thus

$$G_i = G_{i-1} - R_{i-1} \qquad \forall \quad 1 \le i \le \frac{1}{P};\, i \in \aleph \tag{5}$$

where R_i is the set of nodes that have been cluster-heads in round *i*. Moreover, Figure 1 shows that

$$G_{2\_good\_case} = G_{2\_bad\_case} \tag{6}$$

the set of nodes that have not been cluster-heads before round 2 is equal for both cases. Thus it appears that a selection of favourable cluster-heads in earlier rounds does not result in an unfavourable cluster-head selection in later rounds. Therefore, energy savings of earlier rounds will not consumed by a higher energy dissipation in later rounds. Regarding energy consumption, a deterministic cluster-head selection algorithm can outperform a stochastic algorithm.

This paper presents a deterministic cluster-head selection algorithm with reduced energy consumption.

2.2. *Lifetime of a Microsensor Network*

The definition of the lifetime of a microsensor network is determined by the kind of service it provides. Hence, three new approaches of defining lifetime are proposed. In some cases it is necessary that all nodes stay alive as long as possible, since network quality decreases considerably as soon as one node dies. Scenarios for this case include intrusion or fire detection. In these scenarios it is important to know when the first node dies. The new metric *First Node Dies* (FND) denotes an estimated value for this event for a specific network configuration. Furthermore, sensors can be placed in proximity to each other. Thus, adjacent sensors could record related or identical data. Hence, the loss of a single or few nodes does not automatically diminish the quality of service of the network. In this case the new metric *Half of the Nodes Alive* (HNA) denotes an estimated value for the half-life period of a microsensor network. Finally, the metric *Last Node Dies* (LND) gives an estimated value for the overall lifetime of a microsensor network

For a cluster-based algorithm like LEACH the metric LND is not interesting since more than one node is necessary to perform the clustering algorithm. Hence, we limit the discussion of algorithms in this paper to the metrics FND and HNA.

2.3. *Related Work*

In [12] each node computes the quotient of its own energy level and the aggregate energy remaining in the network. With this value each node decides if it becomes cluster-head for this round or not. High-energy nodes will more likely become cluster-heads than low-energy nodes. The disadvantage of this approach is, that each node has to estimate the aggregate remaining energy in the network since this requires additional communication with the base station and other nodes.

LEACH-C (LEACH-Centralized), also described in [12], uses a centralized algorithm to form clusters. A nonautonomous cluster-head selection is again the main disadvantage of this algorithm. Moreover, LEACH-C requires location information of all nodes of the network. However, location information in mobile wireless networks is only available through GPS or a location-sensing technique, such as triangulation which requires additional communication among the nodes.

Lindsey *et al.* present an interesting chain-based algorithm to solve the problem of collecting data from a microsensor network [13]. This algorithm also assumes that every node has location information which is not applicable for our assumptions about a wireless microsensor network.

3. Deterministic Cluster-Head Selection

A first approach increasing the lifetime of a LEACH network is the inclusion of the remaining energy level available in each node. It can be achieved by reducing the threshold *T(n)*, denoted in Eq. (3), relative to the node's remaining energy. Therefore, *T(n)* is multiplied with a factor representing the remaining energy level of a node:

$$T(n)_{new} = \frac{P}{1 - P\left(r \bmod \frac{1}{P}\right)} \frac{E_{n\_current}}{E_{n\_max}} \tag{7}$$

where $E_{n\_current}$ is the current energy and E_{n_max} the initial energy of the node.

Our simulations show that such a modification of the cluster-head threshold can increase the lifetime of a LEACH microsensor network by 30 % for FND and more than 20 % for HNA.

Nevertheless, a modification of the threshold-equation by the remaining energy has a crucial disadvantage: After a certain number of rounds the network is stuck, although there are still nodes available with enough energy to transmit data to the base station. The reason for this is a cluster-head threshold which is too low, because the remaining nodes have a very low energy level.

A possible solution for this problem is a further modification of the threshold equation. It is expanded by a factor that increases the threshold for any node that has not been cluster-head for the last 1/P rounds:

$$T(n)_{new} = \frac{P}{1 - P\left(r \bmod \frac{1}{P}\right)} \left[\frac{E_{n\_current}}{E_{n\_max}} + \left(r_s div \frac{1}{P}\right)\left(1 - \frac{E_{n\_current}}{E_{n\_max}}\right)\right] \tag{8}$$

with r_s as the number of consecutive rounds in which a node has not been cluster-head. When r_s reaches the value 1/P the threshold $T(n)_{new}$ is reset to the value it had before the inclusion of the remaining energy into the threshold-equation. Thus, the chance of node n to become cluster-head increases because of a higher threshold. A possible blockade of the network is solved. Additionally, r_s is reset to 0 when a node becomes cluster-head. Thus, we ensure that data is transmitted to the base station as long as nodes are alive.

4. Simulation Results

For the presented simulations we use our own tool, which simulates energy consumption of microsensor networks [14]. The reference network of our simulations consists of 200 nodes distributed randomly across a plain area of 200x200 meters. The base station is located at position (100,300). Each node is equipped with an energy source whose total amount of energy accounts for 1 J at the beginning of the simulation. Every node transmits a 200-bit message per round to its actual cluster-head. The cluster-head probability P is set to 0.05 – about 10 nodes per round become cluster-heads. The path-loss exponent λ is set to 2 for intra-cluster communication and 2.5 for transmissions to the base station. Cluster-heads compress the collected data to 5 % of its original size.

Fig. 2 illustrates simulation results of our sample network. We compare the original LEACH algorithm with our two optimization steps denoted by Eq. (7) and (8). For FND a 30 % improvement is accomplished comparing the algorithm of Eq. (8) with original LEACH. HNA improves by 21 %. The difference between the lifetime of Eq. (7) and Eq. (8) is not significant and within the standard deviation for both FND and HNA.

Now we change the position of the base station to (100,500). Fig. 3 shows simulation results for this configuration. It can be seen that both HNA and FND decrease compared with the former network configuration. Comparing original LEACH and the algorithm denoted by Eq. (8) for the latter network configuration, FND increases by about 25 % and HNA by about 18 %. Since our simulations only optimize energy consumption of intra-cluster communication, the energy needed to transmit the collected data to the base station is not influenced. The position of the base station has vital impact on the achievable improvements of the discussed algorithms. With a longer distance between the base station and the nodes, energy savings are less since most of the energy is consumed by transmissions from cluster-heads to the base station.

5. Conclusion

This paper has discussed two modifications of LEACH's cluster-head selection algorithm. With these modifications a 30 % increase of lifetime of microsensor networks can be accomplished. Furthermore, an important quality of a LEACH network is sustained despite the modifications: For the deterministic selection of cluster-heads only local and no global information is necessary. The nodes themselves determine whether they become cluster-heads. A communication with the base station or an arbiter-node is not necessary. Additionally, the metrics FNA, HNA and LND which describe the lifetime of a microsensor network have been presented.

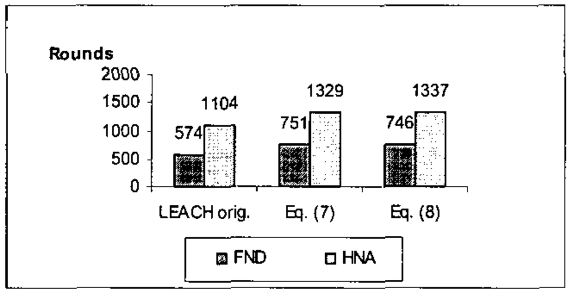

Fig. 2. Simulation results of the sample network with the base station located at (100,300). LEACH's original cluster-head selection algorithm is compared with the modifications denoted by Eq. (7) and (8).

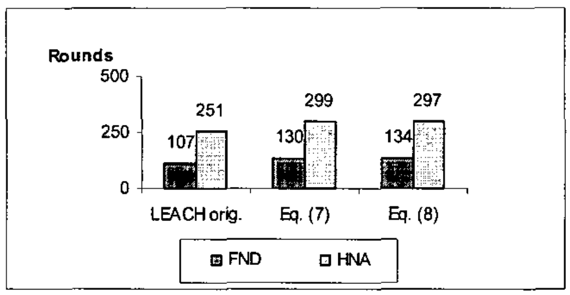

Fig. 3. Simulation results of the sample network now with the base station located at (100,500).

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