http://dx.doi.org/10.5755/j01.eee.19.8.5407 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 19, NO. 8, 2013

An Optimal Sink Nodes Number Estimation for Improving the Energetic Efficiency in Wireless Sensor Networks

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***Abstract*—The paper is dedicated to the issue of reducing the energetic consumption by nodes of a wireless sensor network, by means of deliberately choosing an optimal number of sink nodes in the network. It is shown that an optimal choice of the sink may halve the total number of hops needed for the information from each node to reach it, relative to the sink of the worst choice. Similar research performed on networks with multiple sinks has led to the formulation of a concise formula which allows calculating an optimal number of sinks in an *N*-populated WSN such that a trade-off is met between the energetic and economical savings.**

***Index Terms*—Hop, lifetime, planar, WSN.**

I. Introduction

A Wireless Sensor Network (WSN) starts with an unorganized deployment of physical sensors connected to transmit/receive modules. Such a system of sensors can be discussed in terms of a network only if logical and physical connections are established between these modules (see Fig. 1) – a process called forth – the network spanning.

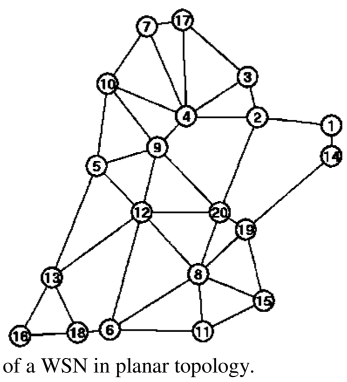

Fig. 1. Example of a WSN in planar topology.

A distributed wireless sensor network (WSN) is a set of line.sensors scattered on a given area, which functionality sensors scattered on a given area, which functionality must not only be limited to merely sensing capabilities but they are also expected to have a transceiver module and a power-supply source (most often – a battery). Its main purpose is to gather information from that area and transport it, via multihop transmissions, to an end-device (a sink) where it will be subject to storage and processing [1]–[3]. Such a procedure requires considerable traffic to be carried by intermediate nodes, which exploit their already limited (i.e. battery-powered) energetic resources. Therefore, in large networks consisting of multiple sensor modules a reasonable solution to this problem is to increase the number of sink nodes whose accumulators can be periodically recharged or some other form of power supply can be provided (such as solar panels). In practical situations these sink nodes can be implemented in the form of a cellular modem (capable of communicating with ZigBee devices [4]) to carry the sensor information over the backbone network to the storage-and-processing center. In this way the number of hops in WSN will decrease and so will the global energy consumption in the whole network since there is now less amount of transit traffic to be conveyed by intermediate nodes.

The purpose of this paper is to demonstrate the amount of savings expected from a smart choice of the sink nodes and their number. It is assumed throughout the article that: firstly, the WSN topology is planar [4], [5] and, secondly, nodes create connections with those counterparts to which the radio signal attenuation (i.e. the pathloss) is the least. This latter feature prevents links to be created between distant nodes (and thus energetically inefficient) in favor of those lying in proximity to each other. Another virtue of this principle is the reduced level of interference in the WSN, since lower transmit powers are now required from the sensor modules to reach their neighbors.

Certainly, the approach of breaking a sensor network up into smaller pieces (clusters) is not a novelty, as in [6], where this idea laid a foundation for a Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol or a similar attempt, known as Power Aware Multi-Access protocol with Signalling (PAMAS), analyzed in [7]. Other approaches for energy saving are studied in [8]–[10] where the impact of multiple static sinks on the network performance was analyzed, with no emphasis however placed on the selection of the candidates for the sink nodes, which – as will be presented herein – may have a remarkable impact on the final energy efficiency. Other noteworthy sources of information on the subject, including discussion on interference inside a WSN can be found in

Manuscript received December 29, 2012; accepted May 5, 2013.

[11]–[15].

II. THE SIMULATION ENVIRONMENT

For the purpose of network simulations a software simulator has been developed comprising two components:

- Matlab scripts performing the network spanning algorithms and building routing tables for the generated random scenarios of nodes distributions;

- a C++ Builder application used for: a) generating random node distribution scenarios (10 scenarios for each number of nodes *N*, where *N* was varied from 10, 20 up to 100) to be fed into the Matlab scripts and b) calculating the total number of hops in the network needed to reach the sink (or sinks) from every individual node.

III. THE IMPACT OF THE SINGLE NODE SELECTION ON THE NUMBER OF NECESSARY HOPS

As it was already stated, the purpose of the WSN network is to collect sensor readouts, adapt them to a network-specific format, and transfer to the sink node. However, as will be shown in this chapter, the choice of a particular node to be the sink, may have a major influence on the overall power consumption of the whole segment. In a simple experiment, the total number of hops (Σ_h) from all nodes to a singular sink was calculated for each simulated scenario. Every node in the calculations was considered to be the sink once and Σ_h was then calculated to this node. In this way, a series of *N* values (representing the total number of hops needed to reach each temporary sink) was found for all scenarios, which allows observing how Σ_h changes with a selection of a particular sink. The results arranged in an increasing order are shown in grey bundles of curves represent particular scenarios (ten for each number of nodes) while the thick bold line represents their respective average. For example, in scenarios with *N*=120 nodes distributed randomly (the upmost bold curve in Fig. 2) when the most optimal node was chosen, the network needed 566 hops in total to reach it. In the worst case, the sum of all hops equaled 1080, which produces an overall ratio of 1.91 between these cases. Assuming, for simplicity, that the amount of energy per hop is equal for all nodes, this ratio can be regarded as a measure of the overall energetic performance difference between the optimally and not-optimally chosen single sink.

For a better visualization, the differences Δ_h between the minimum and maximum of all average curves, are presented in Fig. 3 (solid triangles). It can be seen that regardless of network population *N*, the ratio between the maximum *MAX(N)* and the minimum *MIN(N)* number of necessary hops, in all cases oscillates around two (1.92 to be exact – represented by the line with empty rhombus markers). As a reminder, the minimum case *MIN(N)* represents the situation where the sink selection is optimal.

It has now become evident that, beside considerations regarding the sole number of sinks, a matter of equal importance is the selection of best candidates for sinks. This can double the energy savings – if optimally chosen or doubling the waste – otherwise

$$MIN(N) = 5.407 \cdot N - 107.42 \qquad (1)$$

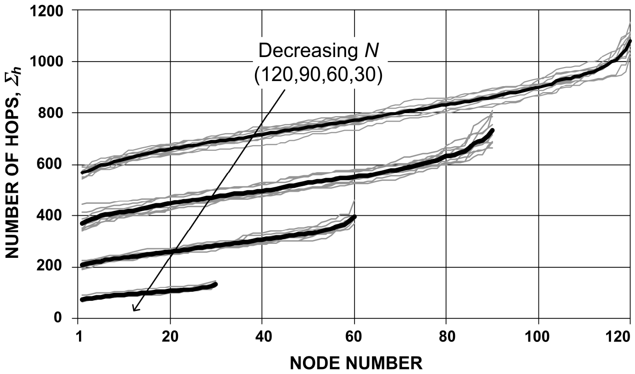

Fig. 2. A total number of hops for all possible selections of the sink.

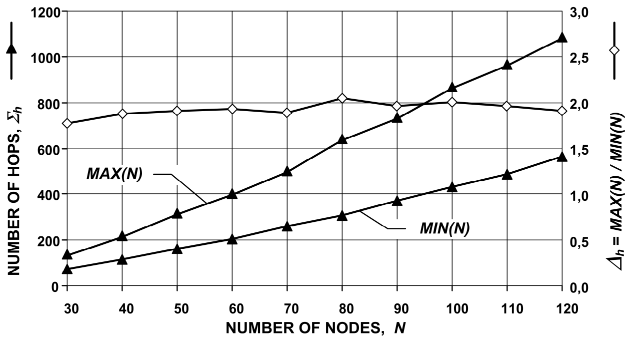

Fig. 3. Averaged maxima and minima of Σ_h for all investigated network populations *N*.

Since the proportionality between the minimum achievable number of hops Σ_h and the total number of network nodes *N* (see *MIN(N)* in Fig. 3) is almost linear, it can be approximated by (1). The determination coefficient R^2 of the best fit equals 0.9936. This formula states how many hops are statistically needed in an *N*-populated planar network to reach the sink node from all other nodes in the network.

IV. THE EFFECT OF MULTIPLE STATIC SINKS ON THE WSN ENERGETIC EFFICIENCY

In this section, the effect of multiple sinks on the WSN energetic performance will be studied. A similar approach was applied in e.g. [8], [9] which give an in-depth discussion on multiple static sinks in general but do not study the impact of particular selection of the sink node(s) on the energy use in the sensor network as is done in this paper.

In the experiment, in each WSN scenario, the total number of hops was examined for groups of *M* optimal sink nodes (as opposed to a single sink in the previous section, where *M*=2,3,4 and so forth. For each *M*, a brute-force algorithm was applied to find the most optimal candidates to be sinks (a time-efficiency was not an issue here), i.e. all permutations of *M* sinks in an *N*-large network were compared to each other with respect to the total number of hops Σ_h they required. The group that produced the smallest Σ_h was selected as the optimal group of *M* sinks in the *N*-node network. As is shown in Fig. 4, there is an exponential rate at which the number of hops decreases with the number of sinks

$$\Sigma_h(M,N) = a(N) \cdot M^{b(N)}, \qquad (2)$$

where $a(N) = 4.1433 \cdot N - 42.763$, $b(N) = 0.0024 \cdot N - 0.6452$.

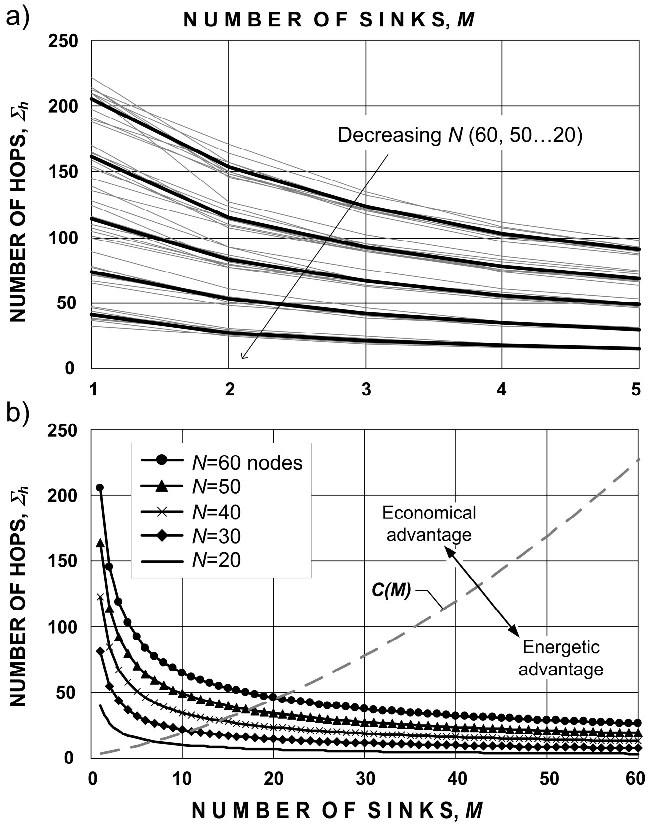

Fig. 4. Averaged of hops in the network as a function of sinks: a) simulated, b) exponential best-fit.

Since the number of network nodes N causes a regular, almost linear shift along the vertical axis, a general formula for the whole family of curves can be derived for Σ_h as a function of N. It is given by (2) and is drawn – separately for different N in Fig. 4b. It can be regarded as an extension of (1), applicable to many sink nodes instead of a single one.

V. An Optimal Number of Sinks in a WSN

In this section we will look for an optimal number of sink nodes in a given planar N-node WSN. It is assumed that the functionality of sink nodes is restricted only to transmissions (i.e. they have no sensing capabilities). The minimum number of hops $\Sigma_{h|min}$ is therefore achieved when the ratio of $\Sigma_h(M,N)$ and the number of all network nodes N is kept at minimum, which is expressed more formally by (3). In the most desirable case, being also the energetically most optimal one, each node needs to make only one hop in order to reach the nearest sink. It is exemplified in Fig. 5 where nine nodes (out of 11 in total) are served by two sinks in an optimal fashion, i.e. each node is just one hop away from the sink, therefore (3) yields 9/11. However, it should also be kept in mind that an increase in the number of sinks – desirable as regards the energetic consumption – may be economically unjustified as it also multiplies the net cost of modems (refer to Section I). Thus, instead of tending towards an absolute fulfillment of the 'one-hop-to-sink' condition (3), the authors recommend looking for such M at which the $\Sigma_h(M,N)$ curve achieves its greatest curvature. Before this point the rate of decrease in the number of hops still outperforms the rate of growth in the number of sinks. Behind this point the situation reverses and the addition of further sinks may no longer be reasonable since their number increases at a greater pace than the gradient of decrease in Σ_h. The grey dashed line $C(M)$ in Fig. 4b represents the connected maximum curvature points of all five $\Sigma_h(M,N)$ curves shown there. $C(M)$ also divides the solution space into two regions. Namely, values of M lying on the left of $C(M)$ bring the network closer to the economic advantage by requiring less sinks at the expense of more hops Σ_h. Values of M on the right of $C(M)$ bring the network towards the energetic advantage but increase costs. The number M of sinks which lies directly on the intersection of $C(M)$ and $\Sigma_h(M,N)$ will be referred to as an optimal M (or M_{opt}). It defines a trade-off between the economical and energetic aspects.

$$\Sigma_{h|\min} = \lim_{M \to M_{opt}} \frac{\Sigma_h(M,N)}{N} \to \min \qquad (3)$$

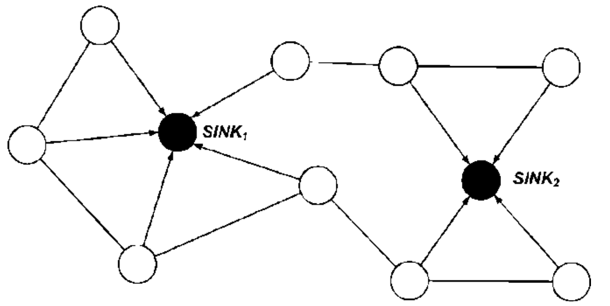

Fig. 5. A WSN example with an optimal number of sinks (one hop per node).

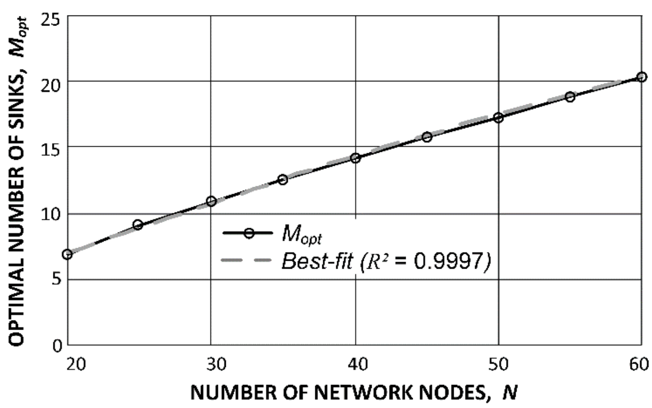

Fig. 6. The plot of an optimal number of sinks (M_{opt}) versus the number of network nodes N.

$$M_{opt}(N) = \left[-0.0014 \cdot N^2 + 0.4466 \cdot N - 1.3199 \right] \qquad (4)$$

For example, in Fig. 4b M corresponding to the greatest curvature of $\Sigma_h(M_{opt},60)$ equals about 21 and results in the total of 45 number of hops. In a network of N=20 nodes, in turn, the transition between both regions occurs at M_{opt}=7, resulting in $\Sigma_h(M_{opt},20)$=11 hops in total. It turns out that $M_{opt}(N)$ can be very accurately approximated by a parabola (4) shown in Fig. 6, as a function of N. For practical purposes, of course, one will only consider integer values of $M_{opt}(N)$.

VI. CONCLUSIONS

The paper was dedicated to evaluating the possibility of increasing the WSN lifetime by implementing techniques for reducing the network overall energy consumption. The energy usage was expressed in terms of the total number of hops required for each network node to reach the sink (or of multiple sinks). In a simple experiment in Section 4 the authors demonstrated that an optimal localization of a single sink node in the network may cut energy costs in the network by the factor of c.a. 2, compared to the worst-case choice of the sink. In Section 5, investigations were carried out with a variable number of sinks for different network populations. Since the obtained curves representing the number of hops were characterized by a regular exponential tendency, a general mathematical model was fitted to the simulations which allowed determining a simple formula for an optimal number of sinks in an *N*-populated WSN, being a trade-off between economical and energetic savings.

VII. AUTHORS' CONTRIBUTIONS

The work presented here was carried out in collaboration between both authors. Kamil Staniec was partially responsible for the introductory part (Section I) and Section II. He is also the sole author of Sections III-VI. Grzegorz Debita was a partial contributor to Section I and Section II (as an author of Matlab scripts for performing the network spanning operations).

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