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Энергетически сбалансированное погружение узла, располагающегося в беспроводной сенсорной сети, с использованием элементарной модели

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В данной статье предлагается новая модель беспроводной сети датчиков и ее применение для оптимизации энергопотребления сети за счет оптимизации структуры связей между узлами, учитывающая ёмкость источника питания узла, объём собираемой и передаваемой узлом информации, а также энергетическую возможность связи между узлами и её количественную оценку. Данная модель может быть использована для оптимизации структуры энергопотребления в беспроводной сети с целью повышения времени автономной работы сети (времени до первого отказа узла сети из-за исчерпания ресурса источника питания). Обосновывается актуальность задачи. Модель приводится в терминах теории графов. Производится детальная постановка задачи по оптимизации энергопотребления сети для увеличения времени автономной работы и описывается подход к ее решению на основе решения соответствующей задачи линейного программирования. Описывается одна из реализаций решения в виде программы для ЭВМ. Приводятся результаты компьютерного моделирования, даются выводы, касающиеся применимости таких технологий на практике.

Ключевые слова: беспроводные сети датчиков, беспроводные сенсорные сети, БСС, оптимизация энергопотребления, энергетическая балансировка.

Energy balanced sink node positioning in a wireless sensor network using a simple model

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The paper presents a new model of a wireless sensor network and its application for the optimization of network power consumption due to the optimization of connections between the units, taking into account the capacity of the power supply unit, the amount of information collected and transmitted by the unit, as well as the unit power capacity between the units and its quantitative estimate. The model can be used to optimize the energy consumption structure in a wireless network in order to increase the network off-line operation time (that is the time until the first unit failure happens because of battery exhaustion). The urgency of the problem is proved. The model is given in terms of graph theory. The detailed description of the task to optimize the network energy consumption for its longer off-line operation time is given; the approach to dealing the problem, based on the solution of the corresponding linear programming task, is described. The implementation of the solution in the form of a computer program is provided. The results of computer simulations are shown, and the conclusions regarding the applicability of the technology in practice are given.

Keywords: wireless networks of sensors, wireless sensor networks, WSNs, energy optimization, energy balancing.

Introduction

Versatility and ease of operation of wireless detector elements networks or wireless sensor networks (WSN) resulted in their great attraction for researchers worldwide. Among the most acute problems emerging in regard with their use [1], one can note energy efficiency and fault tolerance issues. Self-contained supply is at the same time both one of the main advantages of WSN and a serious problem. This is a consequence of necessity to change batteries regularly. Part of the problem is solved with an approach called Energy Harvesting – conversion of side mechanical, thermal or electromagnetic radiation energy into electric current to power the device. Widespread application of EnergyHarvesting is a feature of devices developed under the trademark of EnOcean.

On the one hand self-contained supply of sensor network components is a serious problem since lots of special sensors (such as gas sensors) are characterized by high energy consumption in the context of systems development for monitoring industrial facilities sensor network components. On the other hand, Energy Harvesting can be successfully applied with regard to a high level of electromagnetic and heat noise and vibrations produced by industrial equipment. The possibility of transforming vibration into electric current to supply a unit of a sensor network is shown, for example, in article [2].

It should be noted that the energy security issue of the network requires monitoring of current power status of all components in the network with the account for data paths and the physical location of components. The latter is required to maintain constant availability of all network components. This problem is investigated among others in [3-4].

Energy balancing problem

One of the practical problems which are directly related with energy efficiency issues and stability of WSN is the increase of battery life of the network. Technologically, this can be achieved by

1. Improving power supply.
2. Application of Energy Harvesting approach.
3. Optimization of network power consumption.

Let us consider the latter.

Energy consumption in WSN depends on the following factors: distance and obstructions between different components (i.e. their location in space relative to each other), amount of information and frequency of its transmission; power consumption of integrated circuits, sensors and other electronic components used in nodes, logical structure of network comprising paths of data transfer from a node to a node.

Varying each of the parameters, the structure of energy consumption in the network and power consumption of each component will change. Energy optimization in this case is called energy balancing. An up-to-date overview of approaches to solving this problem is presented in [5].

The ultimate goal of power consumption optimization is to improve self-contained network battery life. Let us consider what we understand as this notion. In the context of practical application, the most logical definition for time of self-contained network operation is mean-time-to-first-failure of any of its components due to exhaustion of a battery power source. This approach is widely used in studying the problem of energy balancing [5-8].

Model of functioning of a wireless sensors network

Power consumption optimization of the network requires an adopted model of its operation. There is a number of fairly complex models, for example [9], that take into account specific features of interaction protocols between components of the sensor network, their vulnerability. However it is enough to consider a simpler model described below in order to optimize power consumption of a fixed network.

Each network component may be connected to various sensors for the measurement of various parameters of the environment and the operation of industrial facilities respectively. Let us assume that a component transfers data about results of measurements at certain regular intervals T_C (data transfer period). The duration of data transfer t_c is constant at every session (it characterizes amount of data transferred). The model is vividly depicted in Figure 1. Gray color indicates time moments when a data transfer takes place.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

Figure 1. Model of information transmission by a network node during the time $t = 30$ *s at* $T_c = 10$ s, $t_c = 2$ s.

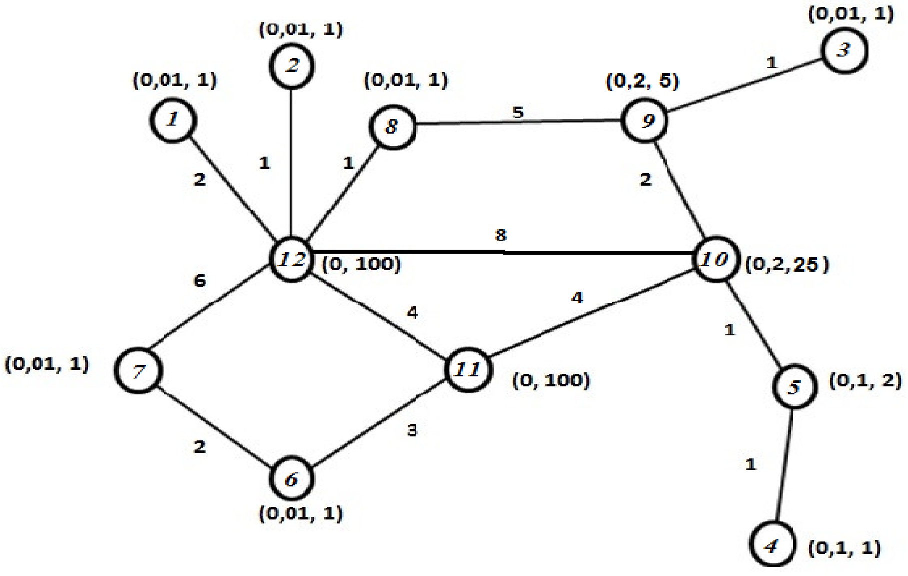

Figure 2. Graph for a sample wireless sensor network.

In this model, time required to transfer data in the component during a time period t is calculated by the formula

$$T_{per} = ([(t - t_c)/T_c]+1)\cdot t_c$$

(brackets show an operation of retrieving the integer part).

For the purposes of this article we should consider the following simplified assessment:

$$t_{\text{per (avg.)}} = t_c \cdot t \;/\; T_c$$

In order to finally characterize a component, let us introduce one value – transfer time ratio $k_{t\ \text{per.}}$. (i.e. time portion required to transfer data from a component)

$$k_{t\ \text{per.}} = t_c \;/\; T_c$$

Obviously, power consumption of a component in data transfer depends on power that runs the transmitter and duration of its operation (as described above). Modern transmitters control power to ensure reliable data transmission to a component with minimum power consumption. Thus, the connection between two components is characterized with power of a transmitter of a node P_{per} where it is possible. This index depends in its turn on various factors where the essential one is the signal level at the receiving component, which directly influences the mutual placement of nodes.

A component is also characterized by power capacity C_P of a self-contained power supply (in $W{*}s = J$).

A set of components of metering and wireless data transfer which is described by the abovementioned parameters can be represented with the following graph (Figure 2). Each vertex corresponds to a couple of values ($k_{t\ per}$, C_P) and each edge to a P_{per} value. In practice sometimes there can be occasions when P_{per} for data transfer may differ for two different directions, but in this article we will not consider them.

If data is transferred from one component to others, then corresponding factors of transferring components are summed with its $k_{t.per}$ factor (let us denote the result as $k_{t.\text{per.sum}}$).

Average power consumption of a component e_{avg} (J) for time t is

$$E_{\text{avg}} = \underline{P}_{\text{per}} \cdot k_{t.\text{per.sum}} \cdot t.$$

If we assume that the capacity of a power supply at all components is the same the problem transforms into how to build a network so that each node $k_{t.per.sum}$ would differ from the average in the network as low as possible. However this formulation does not quite match with practice and common sense: retranslation components should be equipped with batteries of higher capacity to transfer greater amounts of information.

Therefore, the model needs also to take into account the capacity of the self-contained power supply of each component. Naturally, the practical use of the model will require corrections because of power consumption of data transfer.

It is assumed that a component can receive data from several components but can transfer data to an only one component, i.e. the network is a tree. In this model, there is a one sink node and it is the root of the tree.

Average time of self-contained operation of a component can be found if we equate e_{avg} and C_P:

$$C_P = P_{per} \cdot k_{t.per} \cdot t_{aut}$$

$$T_{aut} = C_P/(P_{per} \cdot k_{t.per})$$

Then this problem reduces to finding a tree on the graph of network component connections such that minimum t_{aut} would be the greatest among all possible values. At that, the condition $k_{t.per.sum} <= 1$ must be fulfilled for every component.

This problem can be solved with a computer.

Solution of the problem by using the exhaustive search

For this we consider all possible spanning trees. We shall use the following algorithm for finding them:

1. Construct a random spanning tree *G'* using any graph traversal algorithm G.
2. Choose a random edge *e* in tree *G'*:
3. Remove edge *e* from tree *G'*. Thus, it splits into two trees: G''_1 и G''_2.
4. Among all edges *G*, not included in the tree *G'*, choose those that connect trees G''_1 и G''_2. As a result, each of them forms a new spanning tree.
5. Repeat steps 3-4 for next edge *e* and wood *G'* until all the edges be considered.

This algorithm is illustrated in Figure 3.

Each spanning tree should be evaluated by the lower battery lifetime of node. To determine this moment, it is necessary to know the direction of the network traffic. In a sensor network, data flows to the sink node. Let us suppose that the sink is selected from existing nodes in the graph.

For each spanning tree obtained by using this algorithm, we determine the best position for the sink node in case of when it will be located in place of one of the network nodes, using the following algorithm:

1. Match each node with a number *l*, initially equal to the number of connections with other nodes.
2. For all nodes that have $l = 1$, calculate the battery life, after which set $l := 0$ for them and $l := l - 1$ for a neighbor node.
3. After that, all nodes will have $l = 0$. Last node for which battery life has not been calculated, we assume to be a sink node.

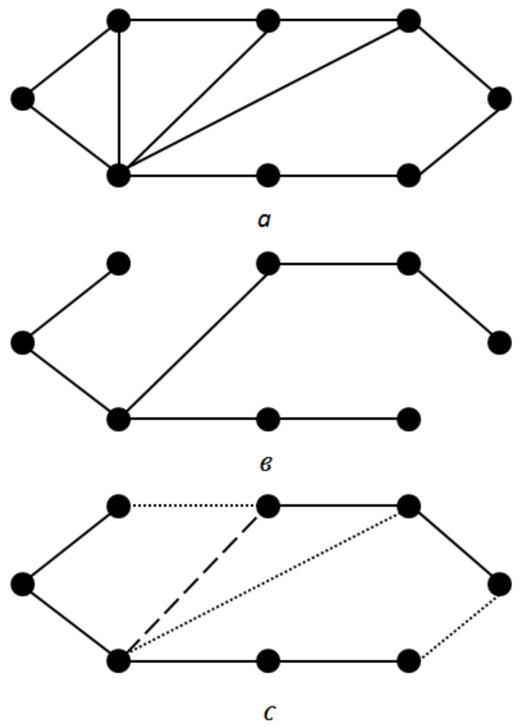

Figure 3. Illustration of algorithm for enumeration of possible spanning trees: a) initial network, b) some spanning tree, c) if we remove the edge of the tree b (dashed line), it is possible to restore the connection enabling one of the other edges of the original network (the dotted line).

Further optimization of the sink position is as follows. We consider the nodes adjacent to the sink. For each node, check what happens to the minimum battery life among all the nodes in the network, if the sink mode is moved to this node's position. If it would not diminish, we continue to move the sink.

Table 1. Runtime nodes before and after optimization

№ node	$k_{t.\text{per}}$	C_P	Before optimization			After optimization		
			P	$k_{t.\text{per.sum}}$	t_{aut}	P	$k_{t.\text{per.sum}}$	t_{aut}
1	0,01	1	2	0,01	50	2	0,01	50
2	0,01	1	1	0,01	100	1	0,01	100
3	0,01	1	1	0,01	100	1	0,01	100
4	0,1	1	1	0,1	10	1	0,1	10
5	0,1	2	1	0,2	10	1	0,2	20
6	0,01	1	3	0,01	33,33333	3	0,02	16,66667
7	0,01	1	6	0,01	16,66667	2	0,01	50
8	0,01	1	1	0,01	100	1	0,01	100
9	0,2	5	2	0,21	11,90476	2	0,21	11,90476
10	0,2	25	8	0,61	**5,122951**	4	0,61	**10,2459**
11	0	100	4	0,01	2500	–	–	–
12	0	100	–	–	–	4	0,03	833,333

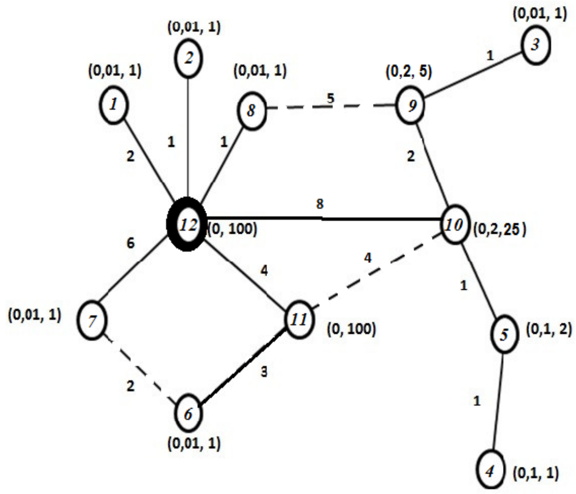

Figure 4. Scheme of the network structure before optimization.

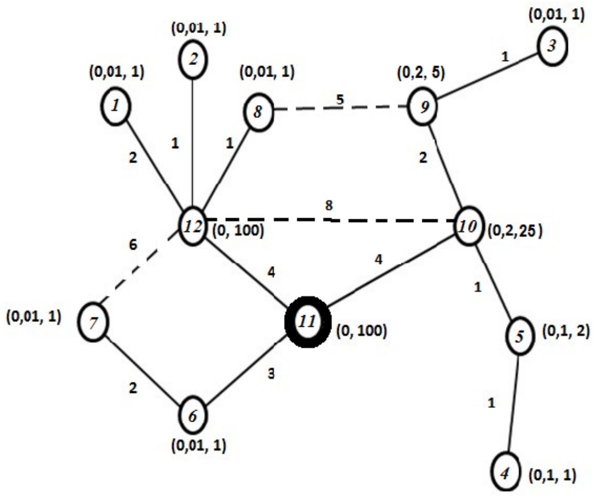

Figure 5. Scheme of the network structure after optimization.

As a result, the interconnection structure of network nodes will be determined, which provides a largest value of minimal battery lifetime of a network node.

This algorithm is implemented as a computer program, which was registered in Rospatent (obtained evidence [10]).

Numerical experiment

Here is an example of the algorithm operation for some network structure shown in Figure 4. Figure 5 illustrates a diagram of interconnections in the network after the optimization carried out by the described algorithm. Table 1 shows the calculated battery life for each node when the network structure is as shown in Figures 4 and 5. The smallest battery life among all the nodes is marked bold. Capacity of the power supply, transmitter power and battery life are given in relative units.

Conclusion

We proposed a new model of the wireless sensor network operation, taking into account the capacity of the power supply unit, the volume of information that was collected and transmitted by node, presence of a link between nodes and its quantitative evaluation in means of energy costs. This model can be used to optimize the structure of energy consumption in a wireless network in order to increase the battery life of the network (time to first node failure due to exhaustion of power supply).

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