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TOROSHANKO Yaroslav
State University of Information and Communication Technologies
https://orcid.org/0000-0002-9053-7156
e-mail: toroshanko@ukr.net
TOROSHANKO Oleksandr
Taras Shevchenko Kyiv National University
https://orcid.org/0000-0002-2354-0187
e-mail: toroshanko@gmail.com
OMELCHUK Vadym
State University of Information and Communication Technologies
https://orcid.org/0009-0007-1436-236X
e-mail: v.omelchuk@ukr.net

MANAGEMENT OF INFORMATION EXCHANGE IN WIRELESS SENSOR NETWORKS USING MOBILE AGENTS

The proposed method provides a simple search for the optimal number of routes with energy consumption constraints, as well as minimization of traffic in the network. The delivery speed is regulated by applying controlled Markov processes under the constraints on the required energy consumption of the sensors. When controlled by mobile agents, energy costs for data delivery are reduced, which is especially important for sensor networks with non-renewable energy sources. The control problem is to optimally determine the wear coefficient vector and the diffusion coefficient matrix, which minimize the traffic volume with a limit on energy consumption and taking into account the asymmetry of the communication quality between consecutive nodes.

Keywords: wireless sensor network, mobile agent, Markov process, stochastic optimization, wear factor, radio sensor.

ТОРОШАНКО Ярослав
Державний університет інформаційно-комунікаційних технологій
ТОРОШАНКО Олександр
Київський національний університет імені Тараса Шевченка, Київ
ОМЕЛЬЧУК Вадим
Державний університет інформаційно-комунікаційних технологій

КЕРУВАННЯ ІНФОРМАЦІЙНИМ ОБМІНОМ В БЕЗПРОВОДОВІЙ СЕНСОРНІЙ МЕРЕЖІ З ДОПОМОГОЮ МОБІЛЬНИХ АГЕНТІВ

Розглянутий метод забезпечує простий пошук оптимального числа маршрутів з обмеженням на енергоспоживання, а також мінімізацію трафіка в безпроводовій сенсорній мережі. Проаналізовані обмеження та характерні особливості побудови сенсорних мереж, які обумовлені такими чинниками: здатність до децентралізованої самоорганізації сенсорної мережі, обмежена ємність джерела енергії радіодатчиків, відсутність індивідуальних ідентифікаторів елементів мережі, взаємні завади та спотворення даних, які викликані передачею даних на близьких частотах. Для подолання даних обмежень запропонований метод керування з допомогою мобільних агентів – програмного коду, під час передачі якого вихідний обсяг даних може бути зменшено шляхом ліквідації надлишковості детермінованими методами і методами стохастичної оптимізації. В основі архітектури мережі лежить багаторівнева ієрархія вузлів та пов'язана з нею система мобільних агентів. Мобільні інтелектуальні агенти в умовах безпроводових сенсорних мереж здатні адаптуватися до змінного інформаційного середовища, можуть працювати автономно, зберігати і передавати для оброблення накопичену інформацію. Сформульовано основні принципи колективного керування і мультиагентної взаємодії у групах сенсорів. В якості оптимального керування розуміється дія елемента для досягненні максимально можливого збільшення цільового функціоналу при переході системи з поточного стану в кінцевий. Регулювання швидкості доставки при заданих обмеженнях здійснюється шляхом застосування керованих марковських процесів. При керуванні за допомогою мобільних агентів зменшуються енергетичні витрати на доставку даних, що особливо актуально для мереж сенсорів з невідновлюваними джерелами енергії.

Ключові слова: безпроводова сенсорна мережа, мобільний агент, марковський процес, стохастична оптимізація, коефіцієнт зносу, радіодатчик

1. INTRODUCTION

A wireless sensor network (WSN) consists of a certain number of radio sensors (elements) that can exchange information with each other. As a rule, the number of radio sensors is not determined a priori and can change during the operation of the network. The location of network elements in space (topology) is also random and can change over time. Each radio sensor is a node of a WSN and consists of miniature computing and communication equipment. In addition, the software provides the ability to combine radio sensors into a network, which provides significant advantages over traditional sensor systems [1-6].

Given the above, additional requirements and limitations arise when building a wireless sensor network [1, 4, 7, 8], namely:

– due to the limited capacity of the energy source, each network element has low computing and communication resources, i.e. the ability to process and transmit a relatively small amount of data;

– the algorithmic support must provide for the possibility of decentralized self-organization of the network. This requirement is due to the random nature and possible uncontrolled changes in the network topology, as well as the tendency of unattended network elements to fail;

– the absence of individual identifiers of the sources of the received information, which complicates the task of determining the location of the radio sensor-sender;

– the need to take into account the influence of mutual interference and data distortion caused by the operation of radio sensors at close frequencies.

2. PROBLEM STATEMENT

An effective way to control the WSN with the above limitations is to use mobile agents (MA), which allows reducing the amount of data transmitted by eliminating redundancy using deterministic methods and stochastic optimization methods [4, 8, 9]. The task of data transmission based on the mobile agent method is as follows. The transmission of the results of observations (measurements) obtained by the sensor is carried out to point A via a digital radio channel. In most cases, due to the limited bandwidth of the channel, the measurement result cannot be transmitted in full. For this purpose, a certain part of the data (C bits) is selected from the measurement result obtained at time t and sent via the communication channel. This function is performed by the computing component of the element. That is, the data arrives at point A in an encoded and truncated form. Accordingly, a software module is required that performs the function of decoding and, based on the encoded data, obtaining the estimated value $bx(t)$ of the quantity $x(t)$.

The mobile agent method is based on a multi-level network hierarchy and multi-agent interaction of communication nodes, which is based on the following principles of collective network management [1, 2, 10].

1) Each mobile agent, as a member of the group team, independently forms its control functions (determines its actions) in the current situation, depending on the value of its own internal data and input arguments. In this case, only the collective goal is taken into account, events in the network in the previous period of time are taken into account, as well as the current actions of other mobile agents and communication nodes as members of the team. The collective goal of the mobile agent system is to choose the optimal data transmission route from the sender to the final recipient.

2) The optimal control (action) of each member of the team in the current situation is understood as an action that makes the maximum possible contribution to achieving the general (collective) goal. In other words, each member of the team gives the maximum possible increase in the target functionality when the "team – environment" system transitions from the current state to the final one. Optimal control is implemented by mobile agents in the nearest current time interval and then a new control function is determined.

3) A team member is allowed to refuse actions that are maximally acceptable for a given network element if these actions bring insignificant benefits or even harm to the network as a whole. This means making compromise decisions that best ensure the achievement of the collective goal: determining the optimal data transmission route, minimal energy consumption for transmission, maximum reduction in the volume of measurement information.

4) Mobile intelligent agents work autonomously in the event of a loss of communication with other network elements and. When the connection is restored mobile intelligent agents transmit the accumulated information for their intended purpose. This function is of particular importance in solving the problem of adaptation to the changing information environment of wireless sensor networks.

3. INFORMATION EXCHANGE MANAGEMENT BASED ON THE MOBILE AGENT METHOD

Collective multi-agent control systems are characterized by relatively low computational complexity of data processing algorithms. In conditions of randomly changing situation and a priori uncertainty of the topology and structure of a wireless sensor network this allows to quickly make close to optimal decisions.

As a model of the mechanism of stochastic optimization of data transmission redundancy in a dense network of radio sensors is used a controlled diffusion Markov process $\xi = \xi(t)$, the transition probability density $p(t.x)$ of which in the ε-vicinity of each internal point satisfies the inverse Kolmogorov equation [4, 11-13]:

$$\frac{\partial}{\partial t}L(p),\ L = \frac{\partial}{\partial x}\mathbf{A}(x) + \frac{\partial^2}{\partial x^2}\mathbf{B}(x),\ \mathbf{B}(x) = \frac{1}{2}\mathbf{R}(x). \qquad (1)$$

In the above expression (1) the following notations are adopted:

– $\mathbf{A}(x)$ is a vector of wear coefficients of dimension K;
– $\mathbf{B}(x)$ is a matrix of diffusion coefficients of dimension $K \times K$;
– $\mathbf{R}(x)$ is a correlation matrix of dimension $K \times K$;
– K is a number of radio sensors (source nodes).

Coefficients $a_i(x)$ of the vector $\mathbf{A}(x)$ and $b_{ij}(x)$ of the matrix $\mathbf{B}(x)$ are uninterrupted, and $b_{ij}(x)>0$, $(i,j=\overline{1,K})$.

The control task is to optimally choose the values of $\mathbf{A}(x)$ and $\mathbf{B}(x)$ in formula (1), which minimizes the traffic volume to simply find the optimal number of routes with a power consumption constraint and taking into account the asymmetry of the communication quality between successive nodes. In the case of a dense distribution of sensors on a surface or in space, a random process $\xi(t)$ can be considered as a process governed by a stochastic vector differential equation of the form

$$d\xi(t)=\mathbf{A}[\xi(t)]dt+\mathbf{R}[\xi(t)]d\eta(t). \quad (2)$$

In the expression (2) the following notations are adopted:

– $\eta(t)=\frac{\xi(t)-\xi(t)-[\mathbf{A}(t)-\mathbf{A}(t_0)]}{\sqrt{|D(t)-D(t_0)|}}$;

– $|D(t)-D(t_0)|=\int_{t_0}^{t}\|B(\tau)\|d\tau$ – the process of Brownian motion;

– $|\cdot|$ is a matrix norm.

Therefore, the transmission process is essentially a directed diffusion process controlled by mobile agents.

The control task is to choose the values of $\mathbf{A}(x)$ and $\mathbf{B}(x)$ in such way that minimizes the amount of traffic transmitted along the optimal number of routes with a constraint on energy consumption and taking into account the asymmetry of the quality of communication between successive nodes. The results of the calculations are substituted into the correlation matrix $\mathbf{R}(x)$, which is used in the diffusion process control problem (2).

The wear coefficient in this problem plays the role of the average deviation of the process from the desired data propagation trajectory from the source-sender to the source-receiver, which in a wireless sensor network is the point of collection and processing of observation results

Fig. 1 shows the most typical examples of the wear factor on the optimal information transmission route in a wireless sensor network.

Example 1. The optimal route between the sender node 1 and the receiver node 5 is the trajectory T_1 (chain 1-2-3-4-5). The trajectory T_2 illustrates the wear factor effect on the entire route between the specified end nodes (chain 1-6-7-8-9-10-5). The trajectory T_3 illustrates the wear factor effect on the route starting from the intermediate 3-rd node of the optimal route (chain 1-2-3-11-12-13-5).

Example 2. The optimal route between the sender node 14 and the receiver node 19 is the trajectory T_4 (chain 14-15-16-17-18-19). The trajectory T_5 illustrates the wear factor effect on the entire route, but through one of the elements (the 15th node) of the optimal route between the specified end nodes (chain 14-19-15-20-21-22-23-19).

As can be seen from Fig. 1, the wear effect can lead to an increase in the route, in some cases to a significant one. However, the route formed as a result of the wear effect will have the same number of transit nodes as the optimal route. That is, in each specific case, there may be several equivalent optimal routes.

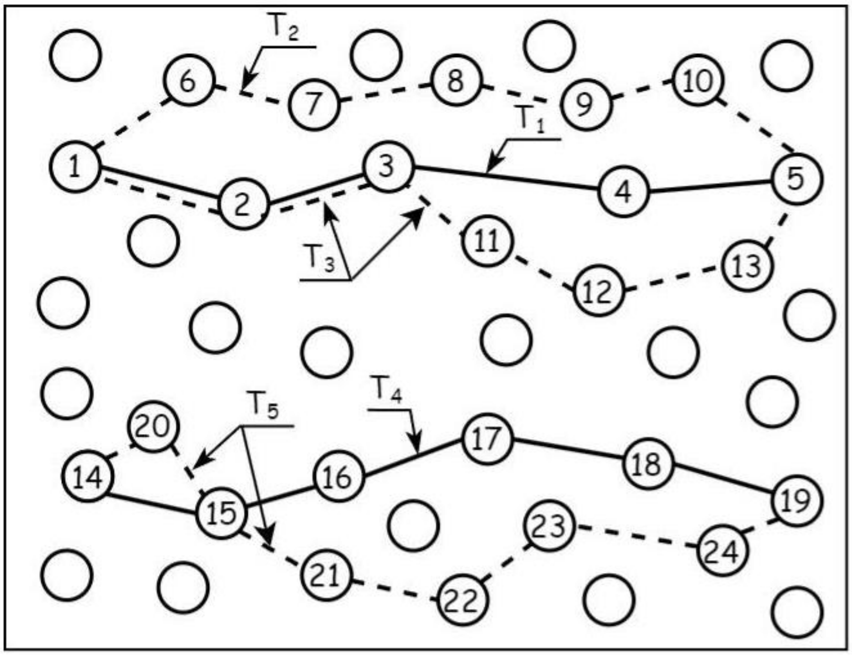

Fig. 1. The impact of the wear effect on the optimal information transmission route in the WSN

The controlled diffusion process (2) is a set of routes that are selected according to many criteria, which are usually contradictory.

Consider the following optimization criteria:

1) Network utilization efficiency η_T is a ratio of the amount of useful traffic to the total amount of traffic in the network;

2) Sensor utilization efficiency η_E is a total number of data packets received by the collection point before any node fails due to a power supply discharge.

The network utilization efficiency is calculated by the formula [9]:

$$\eta_T = \frac{V_d N_{res}}{V_d N_d^{\Sigma} + V_s N_s^{\Sigma}}.$$

In the above expression the following notations are adopted:

– V_d and V_s are an integral volumes of user and proprietary information, respectively;
– N_{res} is a total number of normalized data packets at the collection point;
– N_d^{Σ} and N_s^{Σ} are a total number of normalized data packets and signal packets.

Each transmitted through a transit node packet is counted separately. So, if a packet is transmitted to the data collection point through one transit node (two hops), we consider that two data packets are transmitted in the network - a “useful” packet and a retransmission packet.

Therefore, the larger the value of η_T, the more efficiently the routing protocol uses the bandwidth of the communication channel. For simplicity, we assume that all data and signal packets have fixed sizes, which are set in the parameters of the network model.

In an ideal communication channel N_d^{Σ} and N_s^{Σ} include only “useful” data packets and retransmission packets.

In a real communication channel N_d^{Σ} and N_s^{Σ} include packets that are retransmitted due to delivery losses.

Let us define the average delivery delay from the source to the collection point for the cases of conventional directional diffusion (DD) τ_{dd} and directional diffusion with mobile agents (DDMA) τ_{ma}. Taking into account all possible delays in data propagation to the collection point

$$\tau_{dd} = \frac{\tau_e}{n_p} + \left(\frac{S_d + S_h}{d_{MAC}} + \tau_c + \tau_a\right)(N_h + n_h)\,, \tag{3}$$

In the expression (3) the following notations are adopted:

– τ_e is an average time of delivery trajectory generation;
– n_p is a number of packages to be delivered;
– S_d and S_h is a size of the data in the packet and the size of the packet header;
– d_{MAC} is a data delay at the level of access to the environment;
– τ_c and τ_a is an average control and access delays, respectively;
– N_h is number of transitions along the optimal trajectory with a minimum of nodes;
– $N_h + n_h$ is an average number of transitions along all valid trajectories.

If the number of packages delivered to the collection point is much larger than one, expression (3) is simplified:

$$\tau_{dd} \approx \left(\frac{S_d + S_h}{d_{MAC}} + \tau_c + \tau_a\right)(N_h + n_h). \tag{4}$$

When delivering data using mobile agents, the expression for the delivery delay is

$$\tau_{ma} = \sum_{k=1}^{K}\left(\tau_{ama} + \frac{S_d}{\tau_p} + \frac{S_{ma,k} + S_{pc} + S_h}{d_{MAC}} + \tau_c\right), \tag{5}$$

In the expression (5) the following notations are adopted:

– K is a number of source nodes;
– τ_{ma} is a delay in access of the mobile agent, i.e., data delivery to the collection point;
– τ_p is a coefficient of time spent on processing;
– S_{pc} is a total amount of delivered data;
– $S_{ma,i}$ is a size of the mobile agent's data at the *i*-th node.

Using expressions (3)...(5), calculations of the average energy consumption for delivery (Fig. 2) and the average data delivery delay (Fig. 3) were performed for wireless sensor networks with mobile agents (MA). To obtain comparative characteristics Fig. 2 and 3 show the corresponding graphs for the client-server (CS) information delivery algorithm. Calculations were performed with different total amounts of information in wireless sensor networks.

In the works of various authors [4, 6, 9, 12] it is shown that to obtain acceptable results for practical use, calculations and modeling should be carried out for a network consisting of 50…200 sensors. In Fig. 2 and 3 for a wireless sensor network with 200 sensors the solid line shows the MA_1 graphs for the mobile agent algorithm and the CS_1 graphs for the client-server algorithm. The dashed line shows the corresponding MA_2 and CS_2 graphs for a network consisting of 100 sensors. As can be seen from the figures, with an increase in the observation time for both cases, the graphs practically coincide. It is shown that using 20 mobile agents, the volume of the program code is approximately 10…12 times less than the volume of transmitted data without losing the accuracy of measurements and observation results.

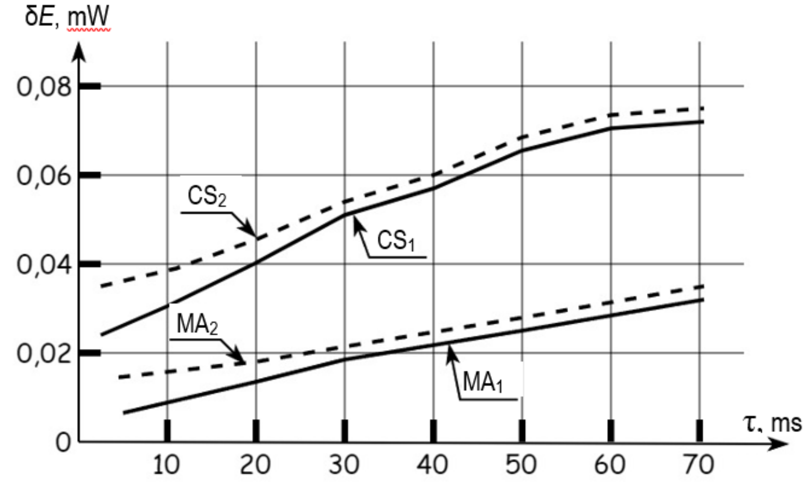

Fig. 2. Average energy consumption during data transmission in WSN

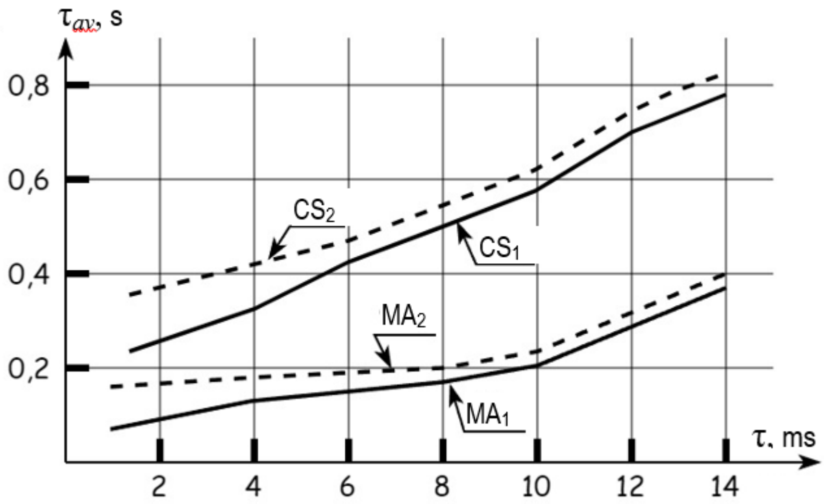

Fig. 3. Dependence of data delivery delay on mobile agent access delay

4. CONCLUSIONS

For wireless sensor networks with random sensor placement data delivery methods using mobile agents are found to be more efficient than traditional methods with client-server architecture.

However, a number of requirements and limitations arise:

- given the random nature of network formation, the algorithms and exchange protocols used must be capable of decentralized network self-organization;
- wireless sensor networks elements have low computing and communication resources;
- limited capacity of the energy source;
- data transmission at close frequencies causes mutual interference and data distortion;
- lack of individual identifiers, which makes the sources of the information received anonymous.

To overcome these limitations, we use the method of control with the help of mobile agents, i.e. program code, during the transmission of which the original amount of data can be reduced by eliminating redundancy using deterministic and stochastic optimization methods.

Regulation of the delivery speed with restrictions on the required energy consumption of the sensors is carried out by applying controlled Markov processes to form a bundle of routes. The control task is to optimally determine the vector of wear coefficients and the matrix of diffusion coefficients, which minimize the traffic volume for a simple search for the optimal number of routes with a constraint on energy consumption and taking into account the asymmetry of the quality of communication between successive nodes. This is especially relevant for specialized networks with limited physical access, which do not provide for maintenance, routine monitoring and replacement of failed sensors.

Calculations of average energy costs for delivery and average data delivery delay for wireless sensor networks with mobile agents are performed. Comparative characteristics of systems using the algorithm with mobile agents and the client-server information delivery algorithm are presented. Calculations were performed with different total amounts of information in wireless sensor network.

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