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DESIGN WIRELESS SENSOR NETWORKS USING MOBILE AGENTS

The issues of building wireless sensor networks with the use of stochastic mobile agents for information exchange between nodes are considered. The basic requirements, features and limitations of algorithms for processing and transmitting measured data in a sensor network are analyzed. It is shown that the actual task of collecting data from sensor networks with dense coverage of the territory is to optimize traffic by decoupling, i.e., eliminating information redundancy. A comparative assessment of energy consumption and average delay of data delivery from the source to the collection point for a conventional client-server structure and a sensor network with mobile agents is given.
Keywords: wireless sensor network, mobile agent, sensor radio sensor, data transmission delay, energy consumption, Markov process, multi-agent control, directed diffusion.

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ПОБУДОВА БЕСПРОВІДНИХ СЕНСОРНИХ МЕРЕЖ З ВИКОРИСТАННЯМ МОБІЛЬНИХ АГЕНТІВ

Розглянуті питання побудови безпровідних сенсорних мереж з використанням для обміну інформацією між вузлами стохастичних мобільних агентів. Проаналізовані основні вимоги, особливості і обмеження щодо алгоритмів обробки і передачі виміряних даних в сенсорній мережі. Дано визначення поняття «мобільний агент», описані основні їх властивості. При дослідженні сенсорних мереж у якості мобільних агентів розуміють певний набір елементів програмного коду, розподілених між окремими мережними вузлами (сенсорами). Показано, що актуальним завданням збору даних сенсорних мереж із щільним покриттям території є оптимізація трафіку шляхом декореляції, тобто усунення інформаційної надлишковості. В основі архітектури мережі лежить багаторівнева ієрархія вузлів та пов'язана з нею система мобільних агентів. Мобільні інтелектуальні агенти в умовах безпровідних сенсорних мереж можуть адаптуватися до інформаційного середовища, що змінюється, у разі обриву зв'язку з координатором мережі працюють автономно, а при відновленні з'єднання передають йому накопичену інформацію.

Як модель механізму стохастичної оптимізації надмірності передачі даних у щільній мережі сенсорних радіодатчиків використано керований дифузійний марківський процес. Завдання управління полягає в оптимальному виборі параметрів сенсорної мережі, при якому мінімізується обсяг трафіку для пошуку оптимального числа маршрутів з обмеженням на енергоспоживання і з урахуванням якості зв'язку між послідовними вузлами. Дана порівняльна оцінка енергоспоживання та середньої затримки доставки даних від джерела до пункту збору для звичайної клієнт-серверної структури і сенсорної мережі з мобільними агентами.
Ключові слова: безпровідна сенсорна мережа, мобільний агент, сенсорний радіодатчик, затримка передачі даних, енергоспоживання, марковський процес, мультиагентне керування, направлена дифузія.

1. INTRODUCTION

A wireless sensor network (WSN) or a network of radio sensors consists of a large number of signal processing systems (elements), distributed (often randomly) in space in the vicinity of the observed object and exchanging data via wireless communication. Each element of the network consists of sensor, computing and communication components - inexpensive, miniature, energy-efficient and multifunctional elements. With proper organization and algorithmic support, FSUs have significant advantages over traditional sensors [1-4]. Unlike communication networks, which are based on TCP/IP protocols, sensor nodes, as a rule, do not have global addresses [5-7]. Also, since the maintenance of a specialized network after deployment is usually impossible, there are limitations on the time of operation (due to low battery charge) [8, 9].

A number of requirements and limitations arise during the development of WSN. They are caused, in particular, by the following features [1, 3-5].

1) Due to the random nature of the distribution of elements in space, the susceptibility of elements to failures, and the topology of the network to changes, the applied algorithms and exchange protocols must have the ability to decentralized self-organization of the network.

2) The individual element has low computational and communication resources. A typical reason is the limited capacity of the power source.

3) The elements transmit data at close frequencies, causing mutual interference and data distortion.

4) Often the elements do not have individual identifiers. As a result, the sources of the received information are anonymized.

To overcome these limitations, the method of control with the help of mobile agents (MA) – software code, during the transmission of which the original amount of data can be reduced by eliminating redundancy by deterministic methods and stochastic optimization methods [5, 9-11].

The term "mobile agent" is very close to the term "system". The main properties of agents are:

– autonomy of work in a certain environment;

– the ability to receive a stream of input information coming from the environment;

– the ability to process the input information flow;

– the ability to influence the environment based on the results of this processing.

The agent is most often understood as a self-contained system that has the ability to accept influences from the outside world, to determine its reaction to these influences and to carry out this reaction. Without interaction with other agents for solving some general goal-oriented task, its existence has no sense. When researching sensor networks as an MA we understand a set of program code elements distributed between separate sensor nodes [12, 13]. The main difference of the approach, which is based on the principles of multi-agent control, is the relatively low computational complexity of the implementation of its algorithms, which allows to quickly make optimal or close to them decisions in the conditions of small situation.

2. PROBLEM STATEMENT

In most networks with energy saving traditional client-server technology is used, when each network node (radio sensor) sends the collected data to the collection and processing center. Obviously, the data streams of two closely located nodes can be correlated, and the degree of correlation decreases with increasing distance between the nodes. Therefore, the actual task of data collection of sensor networks with dense area coverage is to optimize the traffic by decorrelation, i.e., eliminating redundancy.

Let us consider a typical problem of information transmission under the mentioned constraints. An element has to transmit the results of observations at a remote distance to point A through a digital radio channel of capacity B bits/unit of time. Due to the limited capacity of the channel, the measurement y cannot be transmitted in its entirety (i.e., the values of all binary digits cannot be transmitted). Accordingly, a certain part of the measurements received by the moment t must be extracted from the measurements received by the moment t with the volume of B bits, which will be sent over the communication channel at the moment t. This activity is performed by the computational component of the element. Let us assume that its memory is large enough (so that we can consider it unlimited), but its performance is small and limited by the ability to perform a given number b of binary operations per unit time. The algorithm of the computational component of the element (let us call it the encoding algorithm) is not specified a priori.

In point A the data arrive in the encoded and truncated form. Accordingly, it is necessary to have a special device that decodes them and constructs an estimated value $bx(t)$ of $x(t)$ on the basis of the truncated data. The network architecture is based on a multilevel hierarchy of nodes and the associated MA system [1, 5, 8, 14]. Mobile intelligent agents in the conditions of wireless sensor networks can adapt to the changing information environment, in the case of communication breakdown with the network coordinator work autonomously, and when the connection is restored, they transmit the accumulated information to him.

The organization of multi-agent interaction in sensor groups is based on the following principles of collective management [5, 15, 16]:

– each member of the group collective independently forms its own management (determines its actions) in the current situation;

– formation of management (choice of actions) by each member of the collective is performed only on the basis of information about the collective goal facing the group, the situation in the environment in the previous segment and at the current moment of time, its current state and current actions of other members of the collective;

– optimal management (action) of each member of the collective in the current situation is understood as such management (action), which makes the maximum possible contribution to the achievement of the common (collective) goal or, in other words, gives the maximum possible increment of the target functional during the transition of the system "collective - environment" from the current state to the final one;

– optimal management is realized by the members of the collective during the nearest time interval in the future, and then a new management is determined;

– compromise decisions satisfying all members of the collective are allowed, i.e. each member of the collective can refuse from actions that bring him maximum benefit, if these actions bring small benefits or even damage to the collective as a whole.

3. MULTI-AGENT CONTROL OF DATA TRANSMISSION IN SENSOR NETWORK

The main feature of collective multi-agent control is the relatively low computational complexity of the algorithms [5, 15, 17]. This allows fast decision making close to optimal decisions under conditions of a priori uncertainty and randomly changing situation.

As a model of the mechanism of stochastic optimization of data transmission redundancy in a dense network of radio sensors, a controlled diffusion Markovian is used process $\xi = \xi(t)$, transient probability density $p(t, x, y)$ which in ε -neighborhood of each interior point *x* satisfies the inverse Kolmogorov equation [18, 19]:

$$\frac{\partial}{\partial t} = Lp, \quad L = \mathbf{A}(x)\frac{\partial}{\partial x} + \mathbf{B}(x)\frac{\partial^2}{\partial x^2}, \quad \mathbf{B}(x) = \frac{1}{2}\mathbf{R}(x), \tag{1}$$

where $\mathbf{A}(x)$ – vector of drift coefficients with dimension N ;

$\mathbf{B}(x)$ – matrix of diffusion coefficients with dimensionality $N \times N$;

$\mathbf{R}(x)$ – correlation matrix of dimension $N \times N$;

coefficients $a_i(x)$ and $b_{ij}(x)$, $i, j = \overline{1, N}$, are continuous, and $b_{ij}(x) > 0$.

The control task is to optimally select the values of the $\mathbf{A}(x)$ and $\mathbf{B}(x)$, which minimizes the amount of traffic to simply find the optimal number of routes with energy constraint and considering the asymmetry of link quality between consecutive nodes.

In the case of dense distribution of sensors on the surface or in space, we can consider a random process $\xi(t)$ as a process controlled by a vector stochastic differential equation of the form

$$d\xi(t) = \mathbf{A}\left[\xi(t)\right]dt + \mathbf{R}\left[\xi(t)\right]d\eta(t) \tag{2}$$

Here $\eta(t) = \dfrac{\xi(t) - \xi(t) - \left[\mathbf{A}(t) - \mathbf{A}(t_0)\right]}{\sqrt{\left|D(t) - D(t_0)\right|}}$ – network utilization efficiency function;

$\left|D(t) - D(t_0)\right| = \int\limits_{t_0}^{t} \left\|\mathbf{B}(\tau)\right\| d\tau$ – function describing the Brownian motion process;

$\|\cdot\|$ – matrix norm.

Thus, the transmission process under consideration is essentially a directed diffusion process driven by mobile agents.

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

The drift coefficient in this problem plays the role of the average deviation of the process from the desired trajectory of data propagation from the source to the collection and processing point. The simplest such trajectory is a straight line Trs (see Fig. 1).

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

Consider the following optimization criteria:

• network utilization efficiency η_T – the ratio of the amount of useful traffic to the total amount of traffic in the network;

• sensor utilization efficiency η_E – the total number of data packets received by a collection point before any node fails due to power supply discharge.

Network utilization efficiency is calculated by the formula [5]:

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

where V_d and V_s – integral volumes of user and service information, respectively;

N_{res} – total number of normalized data packets at the collection point;

N_d^{Σ} and N_s^{Σ} – total number of normalized data packets and signal packets, respectively.

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

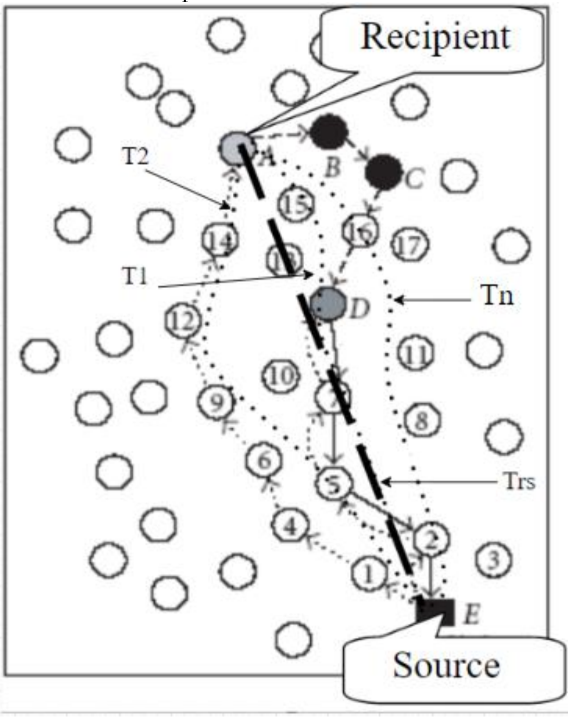

Fig. 1. WSN configuration
Trs – the best data delivery trajectory; T1, T2, …, Tn – possible trajectories

Therefore, the larger the value of η_T is, the more efficiently the routing protocol utilizes the link bandwidth. For simplicity, we assume that all data packets and signaling packets have fixed sizes, which are specified in the network model parameters. For an ideal communication channel, the values N_d^{Σ} and N_s^{Σ} include only "useful" data packets and retransmission packets. With a real communication channel in N_d^{Σ} and N_s^{Σ} include packets retransmitted due to delivery losses.

We determine the average delivery delay from source to 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 dissemination to the collection point

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

where τ_e – average time of delivery trajectory generation;

n_p – number of packets to be delivered;

s_d and s_h – packet data size and packet header size, respectively;

d_{MAC} – data latency at the medium access layer;

τ_c and τ_a – average control and access delays, respectively;

N_h – number of transitions along the optimal trajectory with the minimum number of nodes;

$N_h + n_h$ –is the average number of transitions along all admissible trajectories.

If the number of packets delivered to the collection point is many more than one, expression (3) is simplified:

$$\tau_{dd} \approx \left(\frac{s_d + s_h}{d_{MAC}} + \tau_c + \tau_a \right) (N_h + n_h) . \qquad (4)$$

When delivering data using mobile agents, the corresponding expression for the delivery delay has the form

$$\tau_{ma} = \sum_{k=1}^{K} \left(\tau_{ama} + \frac{s_d}{\tau_p} + \frac{s_{ma,k} + s_{pc} + s_h}{d_{MAC}} + \tau_c \right), \qquad (5)$$

where K – number of source nodes;

τ_{ama} – delayed access by the mobile agent, i.e., delivery of data to the collection point;

τ_p – coefficient of time consumption for processing;

s_{pc} – total amount of data delivered;

$s_{ma,i}$ – size of the mobile agent's data on *k*-th node.

Using expressions (3-5) for the system with mobile agents (MA) average delivery energy consumption (δE) and delivery delay of data (τ) with different total volumes were calculated (Figs. 2, 3). Graphs of the corresponding dependencies are shown (Figures 2 and 3). For comparison the graph of delay for client-server (CS) delivery is shown.

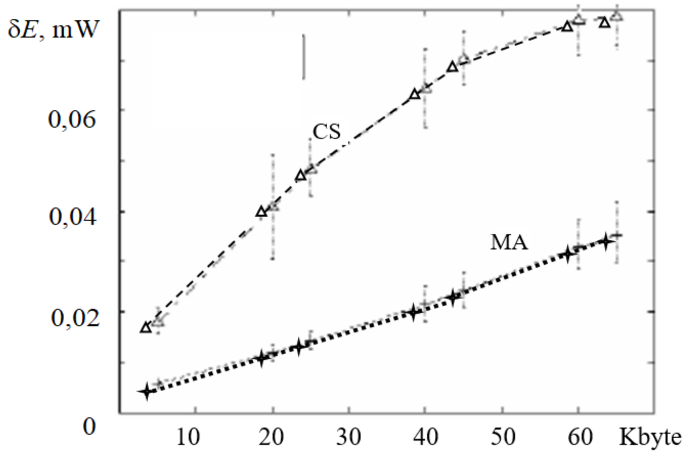

Fig. 2. Average energy consumption during data transmission

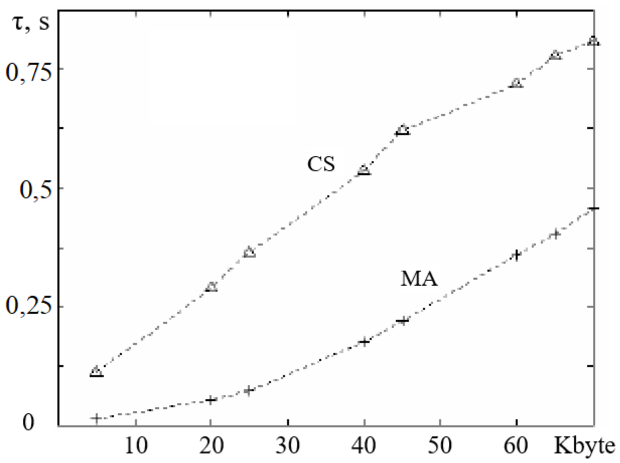

Fig. 3. Dependence of delivery delay on mobile agent access

The WSN, consisting of 200 sensors, used 18 mobile agents with the amount of program code, about 10...12 times less than the amount of transmitted data.

4. CONCLUSIONS

For wireless sensor networks with randomly placed nodes, data delivery methods with mobile agents are more efficient than traditional methods with client-server architecture.

The calculations show that for systems with mobile agents compared to client-server architecture, energy consumption and data delivery delay by 2...4 times are reduced.

The proposed methodology allows you to increase the life cycle of sensor network functionality, reduce the load and prevent overvoltage of the network as a whole, and its individual lines.

Regulation of the delivery rate under restrictions on the required energy consumption of sensors is realized by applying controlled Markov processes to form a bundle of routes. This is especially relevant for specialized networks with limited physical access, where maintenance, routine monitoring and replacement of failed sensors are not provided.

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