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ENERGY-EFFICIENT ROUTING IN DELAY/DISRUPTION-TOLERANT NETWORKS

Віноградов М. А., Лукашенко В. В. Енергоефективна маршрутизація в мережах з толерантністю до затримок доставки й розривам з'єднань. Показано, що зниження енергоспоживання в сучасних інформаційних і комунікаційних системах, особливо в мережах, толерантних до затримок і розривів з'єднань (мережі DTN) – один з основних чинників впливу на підвищення їх ефективності і надійності. Розроблена формальна модель енергозберігаючої системи доставки пакетів як проблема розподілу ресурсів, і встановлено, що проблема є NP-складною (з неполіноміальною складністю). Розроблені різні види цільових функцій для проблеми багатокритеріальної оптимізації з енергоефективною DTN-маршрутизацією. Для досягнення цілей організації мережі запропонований метаеврістичний алгоритм оптимальної маршрутизації на основі табу-пошуку.

Ключові слова**:** інфокомунікаційна мережа, толерантність до затримок/розривів з'єднань, DTN-маршрутизація, багатокритеріальна оптимізація, енергозберігаюча система, метаеврістичний алгоритм, неполіноміальна складність, проблема розміщення ресурсів

Виноградов Н. А., Лукашенко В. В. Энергоэффективная маршрутизация в сетях с толерантностью к задержкам доставки и разрывам соединений. Показано, что снижение энергопотребления в современных информационных и коммуникационных системах, особенно в сетях, толерантных к задержкам и разрывам соединений (сети DTN) – один из основных факторов влияния на повышение их эффективности и надежности. Разработана формальная модель энергосберегающей системы доставки пакетов как проблема распределения ресурсов, и установлено, что проблема является NP-сложной (с неполиномиальной сложностью). Разработаны различные виды целевых функций для проблемы многокритериальной оптимизации с энергоэффективной DTN маршрутизацией. Для достижения целей организации сети предложен метаэвристический алгоритм оптимальной маршрутизации на основе табу-поиска.

Ключевые слова**:** инфокоммуникационная сеть, толерантность к задержкам/разрывам соединений, DTN-маршрутизация, многокритериальная оптимизация, энергосберегающая система, метаэвристический алгоритм, неполиномиальная сложность, проблема размещения ресурсов

I. INTRODUCTION

This work focuses on the joint power consumption and optimal routing in delay/disruption tolerant networks, with the target of minimizing packet segments length or equivalently maximizing network throughput. This is an urgent long-standing problem. Due to the inherent complexity of joint power consumption and optimal routing finding optimal solutions or large-scale delay/disruption tolerant networks consumes extraordinary large time of calculations. Since joint power consumption and optimal routing problem is NP-hard, it is of great importance to design algorithms with both polynomial runtime and performance guarantees. Here an approximation meta heuristic algorithm is proposed, which can find near optimal solutions within a short runtime, bringing the theory closer to practice. In particular, the proposed polynomial-time taboo search algorithm has a bounded approximation ratio relative to the optimal solution. The algorithm and its bounded approximation ratio are general, and can be applied to any network topology, including networks with time-various parameters and structure, when some network nodes appear while another nodes disappear from network structure.

The model of energy-aware routing problem it's NP-hardness formally established. Then a heuristic routing algorithm of taboo search is proposed to achieve our design goal. The algorithm works in the following way. First of all, the network throughput, which is the most important performance metric for data-intensive computations, according to the routing on all switch nodes, is computed. The corresponding route is called basic energy-aware route. Then, switch nodes are gradually remove from the basic routing, until when the network throughput/energy consumption ratio decreases to a predefined performance threshold. At last, switch nodes not involved in the final routing are powered off or put into sleep mode.

The lowering of energy consumption in the modern information and communication systems is one of basic impact factors of the improvement of their efficiency and reliability. The large number of works is devoted to the problem of "green" information technologies: monographs, papers, and materials of conferences. In works [1...3] theoretical aspects and practical approaches to energy saving in mobile communication networks are considered, in the wireless networks of the IEEE 802.16 (Wireless MAN) and IEEE802.11 (Wireless LAN) standards, in the specialized sensory networks IEEE 802.15.4 (Wireless PAN). In addition, the problem of energy saving matters very much for networks with a low sensibility to the delays in delivery of messages – so-called Delay-Tolerant Networks (DTN) [1, 4].

DTN have the following key features, which is necessary to take into account at introduction of energy saving technologies:

- route (routes) of messages delivery, as a rule, is unknown, and sometimes does not exist in general;
- during the message (special Bundle-packets [4]) transfer possible considerable worsening of quality of service, appearance of external noises or even intermittences of connection. On the last reason such networks sometimes name Delay/Disruption-Tolerant Networks, i.e. by networks tolerant to the delays in delivery and intermittences of connections;
- time of delivery of messages can change in wide limits – from hundred milliseconds in the specialized ground networks of to minutes, hours or even dozens of hours in space networks.

Actually, modern networks are based on a fairly limited list of ideas:

- packet principle of users', control, and service data;
- dynamic routing;
- adaptation of packet size to conditions for data transfer via the network (fragmentation/defragmentation);
- data transfer in special "containers" (encapsulation of packets one in another with ensuing decapsulation).

In fact, all these ideas are implemented in DTN with some modifications. The approach "Store-and-Forward" is fundamental in DTN as well, but the time of delivery may be undetermined and on the average it is much more than in common networks because of channel inaccessibility and/or unreliability. So the DTN routing protocols provide the node transmits packet to the network even if the recipient of the package does not exist. Any device in zone of access receives data and transmits it further or stores it while there are no neighbour recipients at all. Hence the routing in DTN is non-trivial problem, especially under energy consumption constraints.

The Fig. 1 demonstrates the differences between protocol stacks of OSI, TCP/IP and DTN models.

We should note the condensed composition of layers in TCP/IP model with so called vertical approach unlike OSI model with horizontal approach. First of all, the implementation of stack of TCP/IP protocols is characterized by relative small signal propagation latencies (on the order of milliseconds) and a continuous end-to-end connection. The point is that because of imperfection of both the OSI model and its stack of protocols the mentioned layers are almost empty whilst data layer and network layer are overloaded [4]. That's what the session and presentation layers are excluded in TCP/IP model at all. From the other side, the replacement of session and presentation layers with the bundle layer in DTN multilayer model with mixed (vertical and horizontal) approach is conditioned by the need of store of transferred data during undetermined, sometimes rather long time.

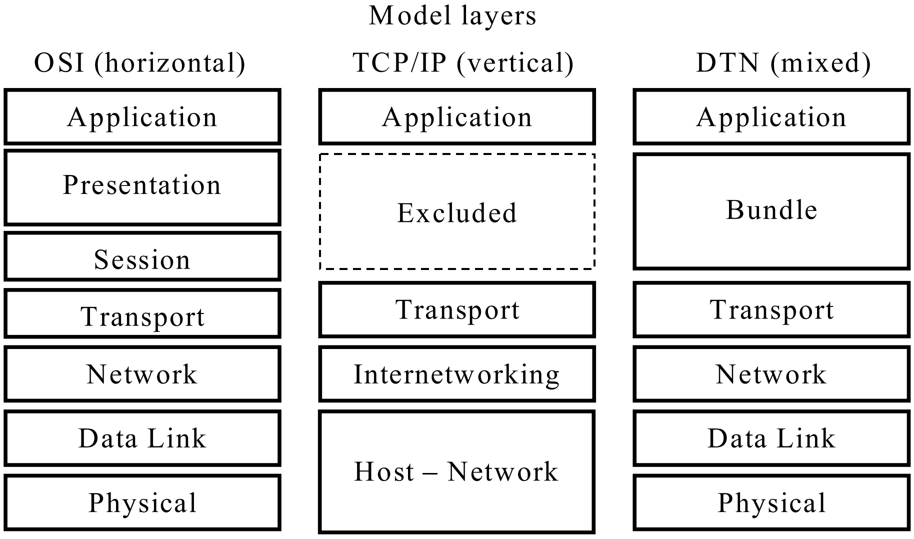

Fig. 1. The differences between protocol stacks of OSI, TCP/IP and DTN models

The tasks of choice of the best route of delivery in these terms in general are difficult and ambiguous, and taking into account criticality of application of DTN-networks and hard resources constraints, above all on energetic resources, possibility of functioning of DTN-network depends on quality of decision of these tasks. In work [5] the comparative analysis of energy consumption at the use of different methods of choice of routes and organization of delivery of messages in DTN-networks is executed. In [6] the algorithm of choice of the best route of delivery of messages in DTN-networks on the criterion of minimum time of intermittence of connections on a route is offered.

However taken into account influence of intermittences of connections, methods of delivery of messages on the resulting expense of energy of network and terminal nodes of DTN-network is not in these works. An attempt to fill in this omission is done in this work.

II. MATHEMATICAL MODEL

DTN has been developed to combine the long delivery delay (on the order of minutes, hours or even days) and sporadic communication intermittences (disruptions) as it happen in space communications, special networks, in particular in mesh sensor networks. As in mentioned earlier, DTN adopts a store-and forward custody transmission mechanism to deal with challenging environments and incidental number of network nodes. So each DTN node has to keep a copy of every data packet sent until receiving an ACK confirming the packet has been received successfully from the next node in the end-to-end path. This ensures that no data packets are lost even if a router is temporarily out of sight due to out of the coverage area, occultation or rotation in space. Because of the DTN routing problem actually has to be considered as nodes assignment problem it has NP-hardness property.

We will submit the mathematical model of DTN-network as the oriented graph [7] with the set the V vertexes (terminal and network nodes) and set R of the routes of delivery of messages, thus a j-th route r_j from the set R can include s_{ni} intermediate network nodes. Let the common number of routes for a couple a "source s_{ti} – destination d_{ti}" is equal M_i. For every area $s_{nij} \rightarrow s_{n,i+1,j}$ of j-th route a certain coefficient k_i, which represents the weighted sum of throughput c_i, distance d_i and delay τ_i: $k_i = w_1 c_i + w_2 d_i + w_3 \tau_i$. Here w_1, w_2, w_3 are weighting coefficients selecting on considering of economy and reliability of delivery on the real DTN-network. A stream f_i on an area $s_{nij} \to s_{n,i+1,j}$ must meet main condition $0 \le f_i < c_i$.

When practical implementing it is necessary to take into account both the number of data sent from a node to node and average number of distances of intermediate network nodes on distances, where the loss of communication will take place, mean conditional time of intermittences of connection. Thus common time of delivery must not exceed maximally possible time-to-live of message.

As a result we will get the task of minimization

$$\min_K \left(\sum_{n=1}^{M} k_n y_n + \mu \sum_{n=1}^{M} \sum_{j=1}^{N} u_n q_n x_{nj} \right), \qquad (1)$$

which is the classic allocation problem [7] with constraints of kind $\sum_{i=1}^{n} x_{ij} = 1,\ i \in N$; $x_{ij} \le y_i,\ i \in N,\ j \in M$; $0 \le q_i \le Q_{\max},\ i \in N$, where x_{ij}, y_j are binary variables: $x_{ij},\ y_j \in \{0,1\},\ \ i \in N,\ j \in M$, are real variables which describe the relative improvement of model in the process of clarification of its parameters; $0 < \mu \le 1$ is coefficient of compromise, selecting from data of experiments on the real network.

Not going into details of comparative analysis of methods of combinatory optimisation (there is the detailed bibliography on this subject in given references), let consider the task of construction of the combined algorithm of search of optimum routes in sites with the delays in delivery and intermittences of connection.

For the tasks of combinatory optimisation, having non-polynomial (NP) complication, the regular methods of search of optimum parameters for the real-time systems are inapplicable sites unacceptable calculable complication [7]. Therefore we use one of methods of meta-heuristic optimisation is taboo-search [8].

The main idea of taboo search methods is to design the heuristic decision-making type of prohibition "unsuccessful" directions and encouragements of "successful". High efficiency of taboo search brought it the deserved attention of researchers [9]. Practically on all tasks the offered algorithm is extraordinarily effective and showed the best results as compared to the algorithms of robust taboo search, ant colony and method of imitation of annealing. So for the decision of task about the optimum choice of network nodes on the routes of transfer we use a method and algorithm of taboo search, modified for the most complete account of a priori and posterior information.

The main elements of algorithm are the next.

1. Set of the optimised parameters. In our case there is this number of routes, number of intermediate nodes, signal power on the entrance of receivers of recipients of information, throughput on the intermediate areas of route.

2. Trial and current decisions. There are the elements of search and comparison of current results of dissolving.

3. Steps of search, which describe the process of generation of trial decisions related to current status of search.

4. The set of probable directions of step of search is the set of trial decisions closed to the current decision. In the task (1) the part of arguments are continuous values; hence, the set of trial decisions can aspire to infinity. For practical realisation of algorithm we will operate on subset with the limited number of trial decisions.

5. Prohibitions on some steps of search, which are unsuccessful. The forbidden steps are remembered and not used in future. Efficiency of decision (speed of convergence, absence of loops on local extremes) directly depends on the number of found out unsuccessful steps. The number of the forbidden steps is related to the dimension of task. Usually it does not exceed 25% – 35% from the dimension of task [10].

6. The criterion of overcoming is the rule of ignoring of prohibition. If the forbidden step results in the decision with the best having a criterion function, than that one what was got on that step, this step is adopted. Flexibility of procedure of search stays some more.

7. The criterion of stop is a condition, with which the process of search is finished. It can be exceeding of possible number of iterations after the last update of the best decision or exceeding of maximally possible number of iterations.

An algorithm with local a posterior optimisation is developed, in which conception of balance is realised between the detailed search in area of perspective decisions and movement in neighbour areas for search decisions of the yet best quality (by the smaller value of criterion function). Such search can require more time of calculations. However, conducting the search only in some perspective area of decision space, it is possible to miss out other, it is possible even more perspective areas. On the other side, without deep research of environs of good decisions we will find the decisions of low quality only. Balance between the deep search in the surrounding of good decisions and by research of all decision space for finding other perspective areas moves in one or another side on results the previous analysis, i.e. by the account of a posterior information about parameters and state of network on the previous stages of its work.

At the design the programs of classic and iterated taboo-search [10, 11] were used, modified for the account of functions of delay in delivery and connection intermittence.

Due to application of local a posterior optimisations local (LAO) extremes are fully excluding from consideration in practice. In addition, due to excluding of areas of routes with the large distances between intermediate network nodes the energy consumption on the message stays smaller.

On the Fig. 2 the algorithm of taboo-search with local a posterior optimisation (LAO taboo search) is resulted.

```
function LAO TabuSearch(s°);
// input: s° - the initial solution; output: s* - the best solution found //
TL ← 0; // initialize the tabu list T
s· ← TabuSearch(s°); // improve the initial solution s° by TS, get the resulting solution s· //
s ← s·; s* ← s·;
repeat // continue the cycle of the LAO TabuSearch //
s ← CandidateAcceptance(s·,s, ...); // select a solution for reconstruction //
s~ ← Reconstruction(s); // ruin the selected solution, obtain a new solution s~ //
s· ← TabuSearch(s~); // improve the solution s~ by TabuSearch, get the resulting solution s· //
if f(s·) < f(s*) then s* ← s· // save the best so far solution (as a possible result of LAO TabuSearch) //
or s· ← T_cur // add resulting solution s· to tabu list T
TL ← T_cur; // modify the tabu list T
until termination criterion is satisfied;
return s*
end.
```

Fig. 2. Algorithm of taboo search with local a posterior optimisation (pseudo code)

We can see rather successful overcoming the local extremes with various parameters of initial point of search. Nevertheless the necessary number of search steps depends from the success of choice of initial step.

Fig. 3 illustrates the bad choice of initial step, e.g., start of search from the farthest node (respectively, the nearest node to destination). Vice versa, Fig. 4 illustrates the good choice of initial step, e.g., centre of attraction of intermediate nodes on the space of DTN. The problem of definition of the best initial step is not trivial but it is not insoluble.

As a rule, it dissolved trough taking in consideration the goal of delay/disruption tolerant networking (space, terrestrial, over/underwater etc.), total number of network nodes, analysing parameters of appearance and out of the coverage area of network nodes, conditional mean of connection intermittent time and so on.

We can see that the difference in calculation time in the cases of bad and good initial point choice has the same order of value. So the problem of the success choice of initial point is not critical. Note that the problem of data delivery affects more impact on energy efficiency of DTN.

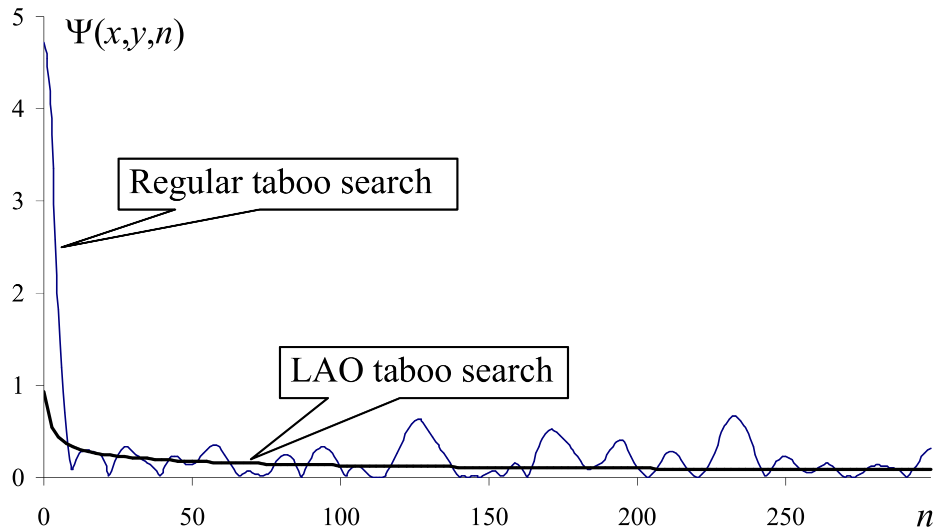

Fig. 3. Bad choice of initial point.
Criterion function is near optimum after about 300 steps of search.

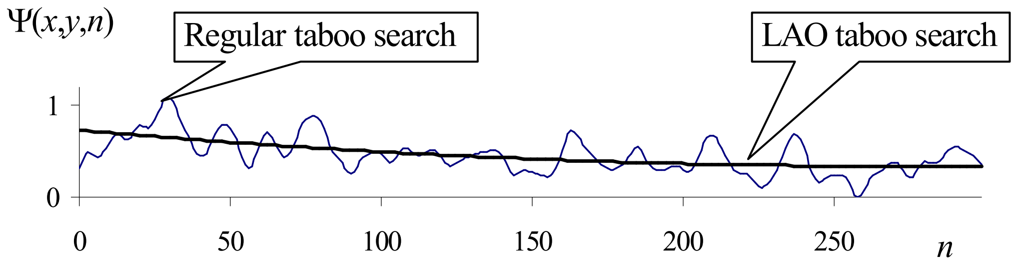

Fig. 4. Good choice of initial point.
Criterion function is near optimum after about 150 steps of search.

III. OPTIMISATION OF DATA DELIVERY PROBLEM

For the increase of reliability of data delivery the replication or reproduction of messages is used in DTN. It is thus necessary to dissolve the problem of optimum choice of number of the transferred copies as of minimisation problem of redundancy and energy consumption at the assured probability of delivery.

DTN data storage system has to retain data during random, rather long period. So the special layer – bundle layer is included in DTN protocol layers.

Bundle layer (BL) is responsible for data transfer through all DTN regions. Service information transmitted in discrete moments of time, then routing tables renew in accordance with network segment state. For the calculation of mean intensity of service traffic we use such simple formula:

$$\overline{\lambda} = \sum_{k=1}^{K}\left\{ r_{ck}\sum_{n=1}^{N}\left(\xi_j / r_{n\max}\right)\left[\left(L_{hf} + r_{n\max}L_{rn} + L_{df}\right)/T_n\right]\right\}, \qquad (2)$$

where K is current number of network nodes;

r_{ck} is the number of deliveries from n^{th} node;

N is number of various cervices;

ξ_i is random number of current routes; $r_{n\max}$ is maximal number of routes described in n^{th} service sending;

L_{hf} is the length of header of fragmented bundle;

L_{rn} is the length of message described route;

L_{df} is time for fragments assembly.

We will consider statistical descriptions of delays in a DTN with circulating of messages. Lets there are two mobile network nodes n_i and n_j. During rapprochement of nodes the successful contact can take place, i.e. transmission of data. We will designate mean time between the successful contacts through $\Delta\tau\left(n_i, n_j\right)$, $i, j = \overline{1, N}$, $i \neq j$. If the total number N of nodes in a network is great enough ($N >> 1$), in accordance with the queuing theory [3] probabilities of that on the interval of supervision T_{i}, $T_{\text{i}} >> \Delta\tau\left(n_i, n_j\right)$ will take place exactly k successful contacts, submits to the Poisson law:

$$P_k\left[\Delta\tau\left(n_i, n_j\right)\right] = \frac{\lambda^k \exp(-\lambda)}{k!}, \qquad (3)$$

where $\lambda = q / \Delta\tau\left(n_i, n_j\right)$ is intensity of contacts on the interval of searching.

It is possible to show that at the choice of optimum algorithm of routing for mobile networks without an infrastructure [2], mean expected time deliveries is described by a formula

$$t_d = \frac{\sum_{k=1}^{N-1}(1/k)}{N-1}\Delta\tau\left(n_i, n_j\right). \qquad (4)$$

For the algorithm of routing with circulating of report on M network nodes, $M < N$, mean expected time deliveries t_{dm} is described by a formula

$$t_{dm} = \sum_{k=1}^{M-1}\left[\frac{\Delta\tau\left(n_i, n_j\right)}{M-k}\right] + \left[\frac{(M-N)\Delta\tau\left(n_i, n_j\right)}{(M-1)N}\right]. \qquad (5)$$

For the receipt of comparative estimations of mean time of delivery of messages the design of process of delivery with optimum routing and routing with replication on M network nodes was conducted. Results are represented in a next section.

Now we can show the results of simulate process of data delivery in DTN for calculation parameters of network characteristics.

IV. Simulation results

On the first stage of design estimation of distributing of delay in delivery of packets was executed. A network consisted of 100 mobile nodes, moving in space on casual trajectories which were described by stochastic differential equation of the second order, – diffusive Markov process. The values of delays were calculated on expressions (4) and (5) and then averaged: the value for every point averaged for to a 1200 counting out. On the Fig. 5 the histograms of distributing of time of delivery are shown for the variants of circulating on $M = 2$ and $M = 12$ network nodes.

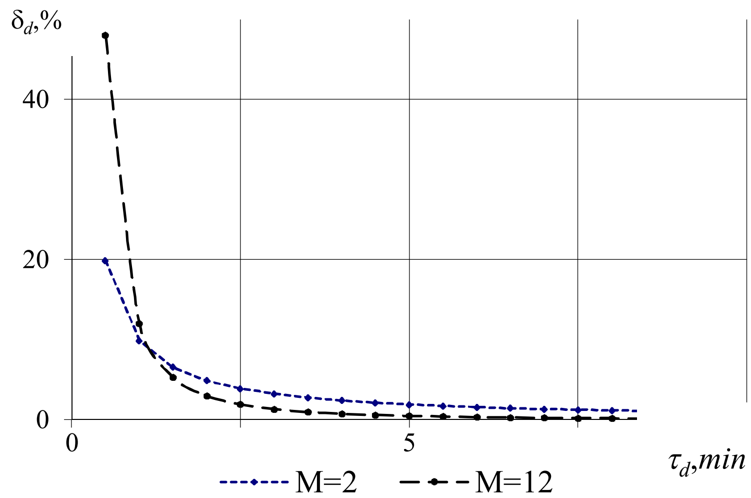

Fig. 5. Distribution of the part of delivered data δ_d on time of delivery τ_d

Comparison was executed on the relative number of the delivered reports, time of delivery of which did not exceed time of life of report $T_{tl} = 10$ min.

As is obvious from picture, the histogram of distributing of number of the delivered reports at times of delivery is enough smooth curve, and she can be approximated by simple mathematical functions – exponential or rational, with the proper selection of coefficients of scaling. In future it is possible to use such approximations for analytical description of processes of delivery of data in networks with tolerance to the delays and breaks of connections in communication channels.

Next stage of modelling is research of influence of trustworthiness and actuality of routing information oh reliability of data delivery and percent of lost data while delivery.

Routing table is the list of routes' parameters including metrics of route R_m and administrative distances A_D [2]. Let calculate weighted sum of last parameters:

$$R_\Sigma = c_1 R_m + c_2 A_D, \; c_1 + c_2 = 1 .$$

The reliable estimate of state of the routing table P_r is the function of period of renewing of routing information.

Fig. 6 shows dependence of reliability of routing information from the period of routing data delivery.

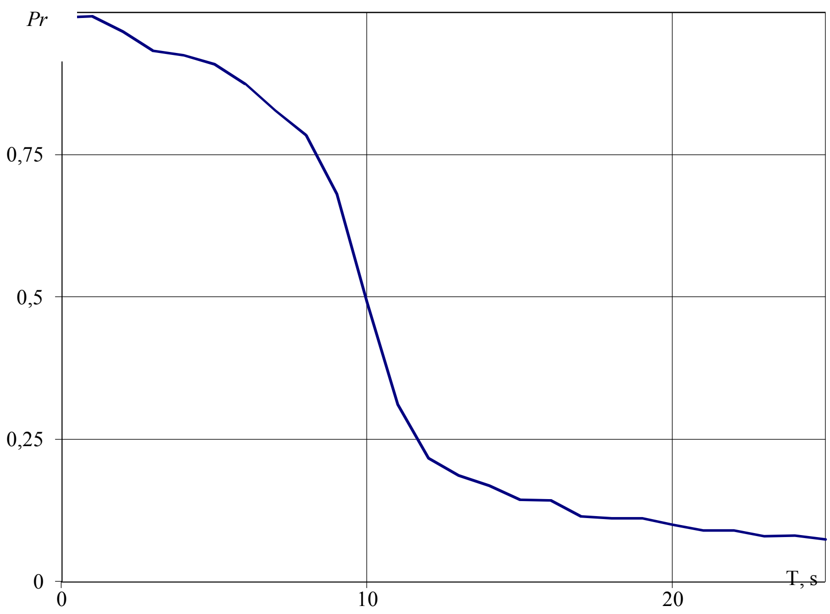

Fig. 6. Dependence of reliability of routing information from the period of routing data delivery

The more period of renewing of routing information the more precise is routing information, the less intensity of service traffic, but the more packet losses (see fig. 7).

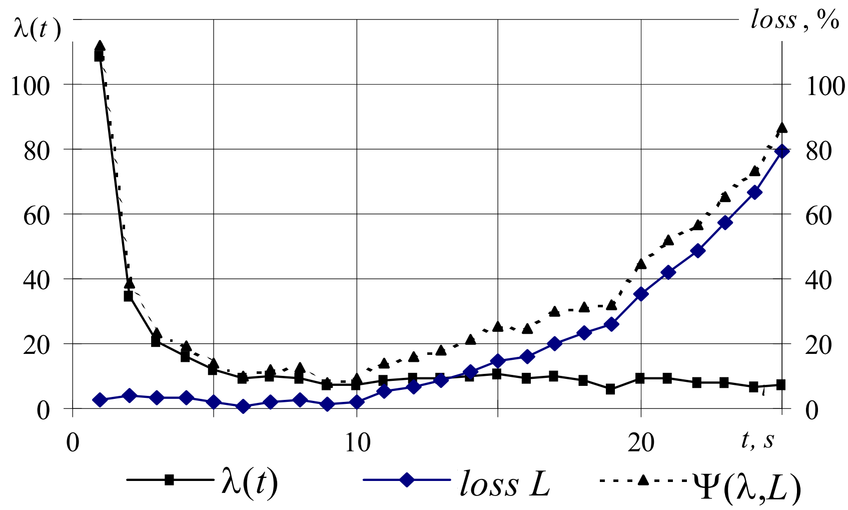

Fig. 7. Intensity of service traffic $\lambda(t)$ and packet losses L. Criterion function $\Psi(\lambda, L)$ as non-weighted sum of factors $\lambda(t)$ and L

Using these results we can choose optimal period of delivery of routing information in DTN. After obtaining additional information about relative importance of various impact factors we can use weighted convolution of factors for improving stability of search algorithm and decreasing influence of local extremes.

V. Conclusions

The problem of organisation of processes of delivery of messages in networks with insensibility to the delays in delivery and breaks of communication between network nodes (DTN-networks) is considered. We consider the energy-saving problem in delay-tolerant networks from an optimal routing perspective. Computer simulation of the process of delivery of messages in a mobile DTN-network shown that meta heuristic taboo search algorithm is sufficiently robust for implementation to resource allocation problems, in particular, to problem of optimal choice network nodes and sent copies under energy consumptions constraints. Comparative quantitative estimates are given for parameters of algorithm complexity, reliability of delivery depending on the number of the circulated messages.

Represented results are preliminary but they show that the problem of optimal energy-aware routing in DTN is promising. In further works we plan to research the influence of kind of criterion function on parameters of optimisation of delay/disruption tolerant networks of various scale and appointment.

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