UDC 621.396.4

CAPACITY INCREASING OF SENSOR TELECOMMUNICATION NETWORKS

Oleksandr I. Lysenko, Stanislav V. Valuiskyi

National Technical University of Ukraine “KPI”, Kyiv, Ukraine

A method of capacity increasing of sensor telecommunication networks has been proposed and investigated. The method proposed is based on a placement control of unmanned aerial vehicles in view of the rapid and unpredictable movement of mobile subscribers. A distinctive feature of developed method is combining mathematical models of connectivity estimation taking into account a quality of service of mobile subscribers and an advanced search algorithm of quasi-optimal placement of unmanned aerial vehicles in a single computational procedure. An application of the method proposed allows increasing the throughput of telecommunication networks to 15—20 percent in comparison with existing methods. Deviations of obtained sub-optimal solutions from optimal ones received by exhaustive method do not exceed 5—7 percent.

Introduction

Natural and technological emergencies and military conflicts are resulting in complete or partial failure of the terrestrial infrastructure including telecommunication facilities such as base stations of cellular communication, microwave and satellite stations, cable lines etc. In these situations, an operative providing the communication can be arranged by employment of mobile sensor networks based on telecommunication aerial platforms. Especially actual issue is applying platforms based on small unmanned aerial vehicles (UAV) which are more available and economical in comparison with large high-altitude platforms [1]. Such networks are widely used for communication arrangement between mobile subscribers.

Mobile subscribers (MS) of such networks equipped with various sensors may easily move in a given region and connect with each other directly in line of sight zone or with packets relaying through neighboring routing nodes. In this way, the multi-element networks of arbitrary structure are formed as shown in Fig. 1. Topologies of such mobile radio networks are dynamic and constantly evolving. This requires an effective control system (CS) that could quickly respond to structural and functional changes of environment. These objectives can provide the structural connectivity, quality of data routes between subscribers, increase of network capacity and decrease energy consumption. In this case, the transmitted power, direction of ground and airborne antennas, load and position of nodes can be considered as controlled parameters.

The increase of packet radio network capacity was a subject of many scientific investigations. However, despite the significant achievements of scientists, the problem of the network capacity increase at the expense of UAV placement control is not solved. The functional model of UAV network control system which part is a subsystem of network topology control was proposed in [2]. It determines the optimal UAV placement regulations under the chosen criteria and directs flight control subsystem for the specified purpose, that is, network capacity increase. Most of currently developed methods that are laid in the network topology control subsystem are based on principles of cellular networks, according to which repeaters are placed around the largest cluster of nodes [3, 4]. If there is enough number of unmanned aerial vehicles to cover the whole territory of service, the problem of UAV placement will be resolved. But under conditions of unmanned aerial vehicles deficiency, such principle of UAV placement is not optimal because it does not take into account the structural and functional parameters of the mobile subscriber network, and therefore subject to improvement. Besides, the detailed methods of network topology synthesis [5] require a large time consuming and not allow solving the unmanned aerial vehicles placement problem in real time. The works [6, 7] have established a methodology of optimal real-time UAV network topology control to improve mobile sensor networks capacity. The results of these works will form the basis for this paper and remove further development.

Problem statement

The purpose of this work is sensor networks capacity increase with simultaneous provision of structural and functional connectivity of mobile subscribers in view of their rapid and unpredictable movements. According to the purpose delivered in this paper, the following independent problems are supplied and resolved: analysis of sensor networks operation principles; developing the method of sensor networks capacity increase based on UAV placement control, which allows organizing the proposed and existing mathematical models and algorithms; improvement of the algorithm for finding quasi-optimal unmanned aerial vehicles position which allows obtaining the solution in real time closed to optimal one and realizing the operational UAV placement control; estimation of proposed method effectiveness.

Operation analysis of sensor networks

This section describes main aspects of the operation and unmanned aerial vehicles placement control of mobile sensor networks. An example of such network architecture is shown in Fig. 1.

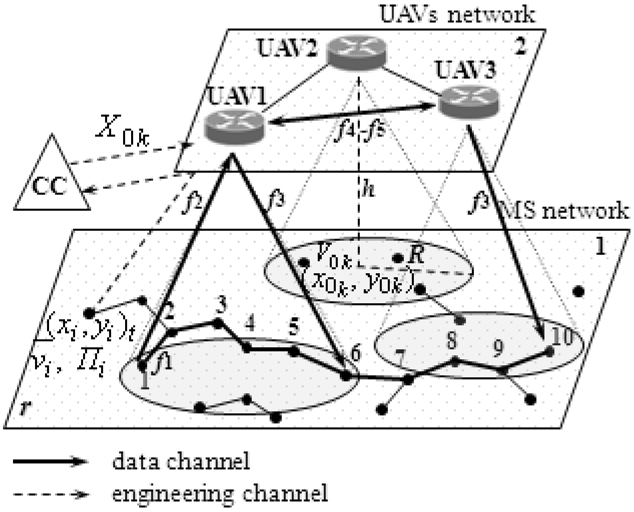

Fig. 1. Configuration of mobile sensor network.

The first level of considered architecture is the network of mobile subscribers which can arbitrarily move in a certain region of size r. In the line of sight, mobile subscribers communicate with each other through a common broadcast channel at the frequency f_1. If the line of sight is absent, they apply a principle of packet routing through intermediate nodes. Thus, mobile terminals are multifunctional devices, operating in one-half-duplex mode on the principle of "store-and-forward". To relay messages of unmanned aerial vehicles, each subscriber has also a second set of radio equipment and memory operating in two frequency duplex mode at frequencies f_2, f_3. In the case of sufficient spatial separation of cells generated by unmanned aerial vehicles, the frequencies can be repeated. To organize multiple access (MAC) to the common channel resource in MS—MS channels at the frequency f_1, we use a busy-tone multiple access (BTMA) protocol to solve the problem of "hidden subscribers". For MS—UAV—MS channel, we have chosen an adaptive protocol with reservation (APR), which allows sending blocks of n packets and controlling the size of the block by the intensity of traffic generated by subscribers during the stage of operational unmanned aerial vehicles network control. Analytical models of these mobile subscriber protocol parameters are reviewed in [3].

The second level of architecture shown in Fig. 1 is the network of routers based on unmanned aerial vehicles moving at a height h in a minimum radius circle around the projection point of their optimal position $(x_{0k}, y_{0k}), k=\overline{1,K}$, where K is the number of UAV using in the network and forming cells of radius R on the earth's surface. Subscribers that are in unmanned aerial vehicles radio coverage area can transmit packets through UAV to other subscribers of the same cell or through cross-platform lines to other cell subscribers, reducing the number of relays in long routes. Thus, the unmanned aerial vehicles borne equipment is also multifunctional device with separate radio interface that allows routing packets relaying by their address information in the middle of the cell or beyond its boundary. Cross-platform connections (UAV—UAV) operate in duplex mode with frequency division multiplexing (FDMA) using a set of carrier frequencies ($f_4, f_5, \ldots, f_k$) distributed by the cellular principle with separate demodulator for each frequency [8]. By a single transmitter, packets are sent to neighboring unmanned aerial vehicles according to existing query using separation in time. It is assumed that there is information on a board of each unmanned aerial vehicle about its position and frequency distribution in cells that allows determining the frequency which should be used at given moment in the case of changing of UAV position.

Thus, there are following possible variants of data routes between mobile subscribers (for example, between MS1 and MS10), marked by thickened solid arrows in Fig. 1: through mobile subscribers network (MA1—MA2—...—MA10); through unmanned aerial vehicles network (MS1—UAV1—UAV3—MS10); by mixed way (MS1—MS6—UAV1—...—MS10).

Such routes must satisfy:

1. Requirements for connectivity (Ω_1):

a) There must be the connectivity of given distance on all hops of route m_{ab} between given pair of sender a — destination b. It can be described as $d_{ij} \le d^0$; $D_{ik} \le \underline{D^0(R_{ik} \le R^0)}$; $D_{kl} \le D' \quad \forall\, ij, ik, kl \in m_{ab}$; $i,j=\overline{1,N}$; $k,l=\overline{1,K}$, where d_{ij}, d^0 are the distance between i th and j th mobile subscribers and corresponding upper bound; D_{ik}, D^0 are the slant distance between i th mobile subscriber and k th UAV and corresponding upper bound; R_{ik}, R^0 are the distance between i th mobile subscriber and nadir point of k th UAV and corresponding maximum radius of stable coverage zone of k th UAV; D_{kl}, D' are the distance between k th and l th UAV and corresponding upper bound. Values of d^0, D^0, R^0, D' are determined by radio link energy and by the effectiveness of multiple access protocols, that is studied in detail in [9].

b) There must be the continuance of the connectivity of each hop ij of route m_{ab} between the given pair of sender a — destination b at $T_{con\ ij} \ge T^0_{con}$, where T^0_{con} is the minimum time, during of which the UAV can work out a given position, set the route and transfer the minimum amount of information. The study of mobile subscriber connectivity continuance is discussed in [10].

2. Requirements for network operation parameters (Ω_2):

a) There should be taken into account requirements for the capacity of route m_{ab} between the given pair of sender a — destination b defined by $s(m_{ab}) \ge s^0$; $a,b=\overline{1,N}$; $m=\overline{1,M}$, where N is a number of mobile subscribers in the network; M indicates the number of routes in the network; s^0 is a minimum acceptable level of route capacity, defined by requirements for a given type of traffic (voice, data, transactions, etc.).

b) There should be taken into account requirements for the transmission delay (or the number of relays) in the route m_{ab} between a given pair of sender a — destination b according to denotation $t_d\,(m_{ab}) \le t^0_d$ as a function of limitation $l(m_{ab}) \le l^0$, where t^0_d (l^0) is the maximum delay in a route, defined by requirements for a given type of traffic. Analytical models of these parameters are determined by selected multiple access protocols and reviewed in [3].

Route selection is performed in accordance with known methods of routing [11]. For the convenience of unmanned aerial vehicles placement control, it is expedient to use tabularly oriented methods (eg, OLSR). Then, each mobile subscriber has its own routing table of shortest paths Π_i to all other network nodes.

A network control center rendered outside of district r is applied to carry out the unmanned aerial vehicles placement. Using a separate official channel shown in Fig. 1 by dotted line, the control center via the unmanned aerial vehicle network can easily gather input data about primary network topology at some moment t. These data are coordinates and movement speeds of each mobile subscriber $(x_i, y_i)_t, \overrightarrow{v_i}$ and previously placed unmanned aerial vehicles $X_{0k} = [x_{0k}, y_{0k}, z_{0k}], \overrightarrow{V_{0k}}$, as well as the situation about the network operation Π_i such as present routes and their quality. This allows making the appropriate control solution based on proposed method described below, for example, launching of new unmanned aerial vehicle or moving one launched UAV in some new position of space X_{0k} to achieve the desired increase of network capacity. It is assumed that at the time of UAV network planning on control center the information about the distribution of traffic between each pair of sender — recipient ab, defined by a matrix of gravity $\Gamma = \gamma_{ab}(t)$ is known. In this case, the total subscriber load can be denoted as

$$\gamma = \sum_{a=1}^{N}\sum_{b=1}^{N}\gamma_{ab}(t).$$

Then, we can formulate the generalized statement of problem to be solved. It is necessary to define such placement of unmanned aerial vehicles group which ensures the maximum of network capacity

$$S = f(X) \to \max_{X\in\Omega},$$

where $X = (X_{01}, X_{02}, \dots, X_{0k})$; $X_{0k} = (x_{0k}, y_{0k}, z_{0k})$; $k=\overline{1,K}$; Ω is admitted region defined by requirements for connectivity and operation of sensor telecommunication network.

Having the considered physical model, we can go to its mathematical formalization.

Mathematical problem statement

Represent the network as a stochastic non-directional weighting graph $G(V,E)$ shown in Fig. 2. The graph consists of a plurality of vertices which display mobile subscribers and unmanned aerial vehicles $V = \{v_i\} \cup \{b_k\}$ and a set of edges $E = \{(i,j)\,|\,d_{ij} \le d^0\} \cup \{(i,k)\,|\,R_{ik} \le R^0\} \cup \{(k,l)\,|\,D_{kl} \le D'\}$; $i,j=\overline{1,N}$; $k,l=\overline{1,K}$ which determine the connectivity matrix $C = (c_{ij})$, where $c_{ij} = \{0,1\}$ is Boolean variable. As the weight of edges, a length of corresponding radio link can be used.

Usually, the network capacity is defined as the maximum value of traffic load γ, which can be served by network per unit of time at a constant traffic matrix Γ [12]. Since the packet is considered as served when it sent from one end of route to its another end the network capacity can be presented as an amount of capacities of single routes between all pairs of sender — recipient:

$$S(C) = \sum_{a=1}^{N}\sum_{b=1}^{N} s(m_{ab}),\ a \ne b. \tag{1}$$

Usually, the capacity of the route is defined as the least capacity of channel which is included in this route

$$s(m_{ab}) = \min_{(i,j)\in m} \{s(c_{ij})\}.$$

In this case, the channel capacity is the average packet transfer rate defined as the average number of packets transmitted without conflict over time unit. In this paper, we take per time unit the transfer time of one packet *T*. This value is determined by the selected multiple access protocol in channel as it has been discussed above.

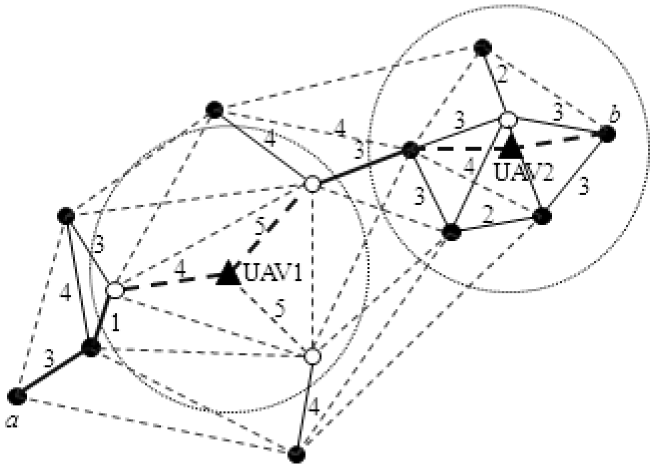

Fig. 2. Example of sensor network graph *G*(*V*,*E*) consisting of 14 mobile subscribers and 2 unmanned aerial vehicles.

Let the set of initial data are expressed as follows: *N*; *K*; *r*; $(x_i, y_i)_t$, $i=\overline{1,N}$; d^0; D^0; R^0; D'; s^0; $t^0_{con}(l^0)$; $\Pi_i = l(m_{ab})$, $a,b=\overline{1,N}$; $\Gamma = \gamma_{ab}(t)$. Then, we can formulate the following problem of unmanned aerial vehicles placement control. It is necessary to find real time coordinates of unmanned aerial vehicles position in space X_{0k}, $k=\overline{1,K}$ defined by the connectivity matrix *C** which provides the maximum of network capacity $S(C)$

$$C^* = \arg \max_{X_0\in\Omega_{1,2,3}} S(C) =$$

$$= \arg \max_{X_0\in\Omega_{1,2,3}} \sum_{a=1}^{N}\sum_{b=1}^{N} s(m_{ab}), a \neq b \qquad (2)$$

at fulfilment of limitations on the plurality of control actions and on network resources

$$\Omega_1\text{:}\{\, d_{ij} \le d^0; R_{ik} \le R^0; D_{kl} \le D'; \; T_{con\; ij} \ge T^0_{con}$$

$$\forall\; ij,ik,kl \in m_{ab};\; i,j=\overline{1,N};\; k,l=\overline{1,K}\; \};$$

$$\Omega_2\text{:}\{\, s(m_{ab}) \ge s^0;\; t_з(m_{ab}) \le t^0_з;\; a,b=\overline{1,N}\; \};$$

$$\Omega_3\text{:}\{N \le 200, K \le 10\}.$$

To solve this problem defind by (2) a method based on unmanned aerial vehicles placement control has been developed, which will be considered below.

Method for increasing of mobile sensor network capacity

The method proposed is based on the idea of unmanned aerial vehicles placement control application to increase mobile sensor network capacity. The main point of this idea is that the optimal placement of unmanned aerial vehicles in space allows creating such network structure that ensures larger number of independent data transfer routes between subscribers. According to Ford — Falkerson theorem, it allows increasing the minimal intersection and maximal traffic flow which can be transferred by the network in time unit. As a result, significant increase of the network capacity is achieved.

The essence of methodology which realizes the proposed idea is to combine mathematical models of structural-functional connectivity estimation [13] and an advanced search algorithm of quasi-optimal placement of unmanned aerial vehicles in space into a single computational procedure. This procedure considered in detail below allows achieving near-extreme values of network capacity under the rapid and unpredictable movement of mobile subscribers.

The scheme of the algorithm realizing the developed method is shown in Fig. 3. The algorithm proposed includes the following steps.

Step 1. Gathering information about the initial network topology and initial data input (in planning stage) as displayed by the block 1: parameters of mobile subscribers *N*, $(x_i, y_i)_t, \vec{v}_i$, $i=\overline{1,N}$ and previously launched unmanned aerial vehicles X_{0k}, V_{0k}, $k=\overline{1,K}$ obtained by the data gathering system using separated engineering channel; allowable values of parameters d^0, D^0, R^0, D', T^0_{con}, s^0, $t^0_{con}(l^0)$, *r*; number of UAV in operation *K*; multiple access protocol and routing protocol parameters.

Parameters denoted above and their limitations determine the initial network topology without using the unmanned aerial vehicles $C_k, k=\overline{1,K}$, where *k* is sequential number of UAV. The value $k=0$ indicates the iteration number of finding solution.

Step 2. Prediction of the continuance of sensor network nodes connectivity based on developed in [10] models of mobile subscribers movement (block 2) and testing the conditions $T_{con\; ij} \ge T^0_{con}$ (block 3) which determines the possibility of the unmanned aerial vehicle to fulfill solutions until significant changes in topology.

Step 3. Analysis of structural connectivity existence (blocks 3, 4) which includes:

1. Calculation of parameters d_{ij}, R_{ik}, D_{kl} using developed in [9] analytical models.

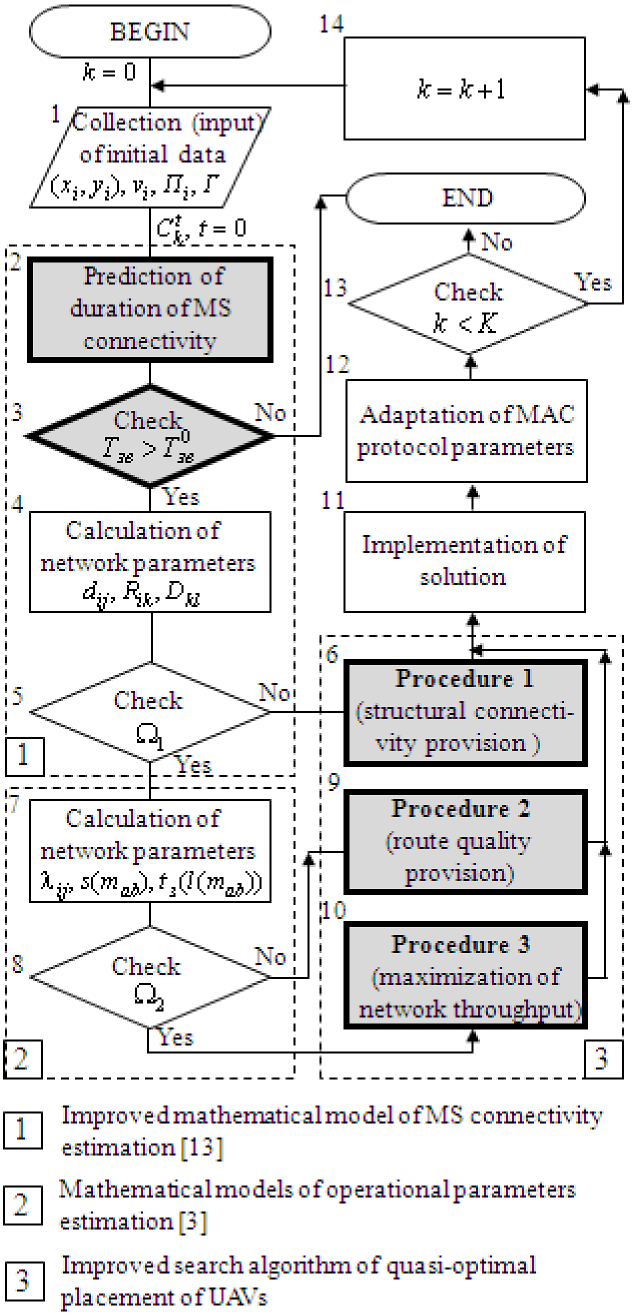

Fig. 3. Scheme of the algorithm realizing the proposed method for increasing capacity of sensor networks using unmanned aerial vehicles (to be continued in Fig. 4).

2. Checking the fulfillment of limitations Ω_1 (block 5). If these limitations are fulfilled, then the additional condition of the network integrity $k = 1$ is checked, otherwise there is a transition to step 4. The network integrity signifies the presence of only one connectivity component of network graph. Checking the network integrity can be performed by constructing a minimum spanning tree (MST) of the graph (for example, by Prima algorithm [14]) and testing each edge of this tree on the fulfillment of conditions Ω_1.

Step 4. Implementation of the procedure 1 to provide the structural connectivity (block 6) which is a part of an improved search algorithm of finding the quasi-optimal placement of unmanned aerial vehicles in space that will be considered below.

In the case of new solutions existence that ensure the fulfillment of conditions Ω_1, there are the deployment of unmanned aerial vehicles in a given position (block 11) and fulfillment of the adaptation of multiple access protocol parameters to actual conditions of operation (block 12) according to operating control procedures specified in [3]. Then, the test of hardware resource existence is performed (block 13). If unmanned aerial vehicles exist in given space region for $k < K$, then there is a transition to step 1, otherwise to END.

Step 5. Gathering information about network operation (block 1) including calculations of the shortest routes matrix Π_i and gravity matrix Γ. In the case of existence of launched unmanned aerial vehicles, collection of this information can be done at the planning stage via communication channel from control center as shown in Fig. 1 or at the deployment stage by data reading from any ground node of sensor network using one of the routing protocols [11].

Step 6. Analysis of quality requirements for transfer routes (blocks 7, 8) which includes the following operations:

1. Calculation of network operation parameters λ, $s(m_{ab})$, $t_{con}(l(m_{ab}))$ according to relations given in [3].

2. Checking the fulfillment of limitations Ω_2. If these limitations are fulfilled, then there is a transition to step 8, otherwise to step 7.

Step 7. Implementation of procedure 2 to provide the route quality by using block 9 and blocks 11—14 which are parts of an improved search algorithm of finding the quasi-optimal placement of unmanned aerial vehicles in space that will be considered below.

In the case of new solutions existence that ensure the fulfillment of conditions Ω_2, there are the deployment of unmanned aerial vehicles in a given position (block 11) and fulfillment of the adaptation of multiple access protocol parameters to actual conditions of operation (block 12) according to operating control procedures specified in [3]. Then, the test of hardware resource existence is performed (block 13). If unmanned aerial vehicles are existed in given space region for $k < K$, then there is a transition to step 1, otherwise to END.

Step 8. Implementation of procedure 3 to increase the network capacity by using block 10 which is a part of an improved search algorithm of finding the quasi-optimal placement of unmanned aerial vehicles that will be considered below. Further, the same calculations will be provided by blocks 11—14.

If at the operating control stage all unmanned aerial vehicles are optimally placed in space, each of them periodically tests the scheme discussed above to verify the necessity to change their position. In this case, all components of the network are fixed at a given time. The period of testing this method should be large enough to build routs and pass through them with the minimum amount of data and also it should be small enough so that the network topology would not change significantly. The frequency of testing this method is determined by the duration of connectivity between mobile subscribers, expected on the basis of MS movement models, which have been considered in [10]. It is assumed also that during the time of source data collecting, performing calculations and launching unmanned aerial vehicles in a given position, the network topology does not change significantly.

Improved search algorithm of finding the quasi-optimal placement of unmanned aerial vehicles

In general case, the algorithm for finding a new position of unmanned aerial vehicles is reduced to search of all the possible variants of UAV placement. However, this problem belongs to the class of NP-complete, so the exhaustive search of variants of unmanned aerial vehicles placement can be reduced by using the previously designed set of rules proposed for variants selection of such changes of network connectivity, which increase its capacity and reduce the computation time. This enables to obtain solutions close to optimal in real time and to use an algorithm for operative control of unmanned aerial vehicles position. The scheme of improved search algorithm of the unmanned aerial vehicles quasi-optimal placement using a set of proposed rules which allows increasing network capacity is shown in Fig. 4.

To improve the network software, a set of rules can be used, as shown in Fig. 4, in accordance with the following steps:

Step 1. Search of new solution C_k^{t+1} for topology of the current placement of unmanned aerial vehicle by using some heuristic rules and procedures of their implementation providing the maximum of network capacity S.

Step 2. Construction of route tables $\Pi_i(C_k^{t+1})$ defined by the matrix of gravity and accepted method of routing. Redistribution of data flows λ_{ij} according to these tables. Calculating the parameters $s(m_{ab})$ and $t_{con}(l(m_{ab}))$ for existing sender — recipient pairs by analytical models [3].

Step 3. Check the fulfillment of conditions Ω_2 for C_k^{t+1}. If conditions Ω_2 are not fulfilled or $S(C_k^{t+1}) < S(C_k^t)$, then C_k^{t+1} should be rejected, otherwise $C_k^t = C_k^{t+1}$.

A set of these rules corresponds to the production type ones consisting of two components such as the condition and the action [15]. The condition determines the possibility of applying the rules in quantitative terms, whereas the action is used to fulfill the condition and describes the change of network connectivity, which leads to the achievement of one control purposes:

$$Rule_i:\ \alpha_i \rightarrow \beta_i,$$

where $Rule_i$ denotes the i th rule; α_i indicates the condition; β_i represents the control action. In this case, the control action provides the placement (displacement) of unmanned aerial vehicle in some point of space.

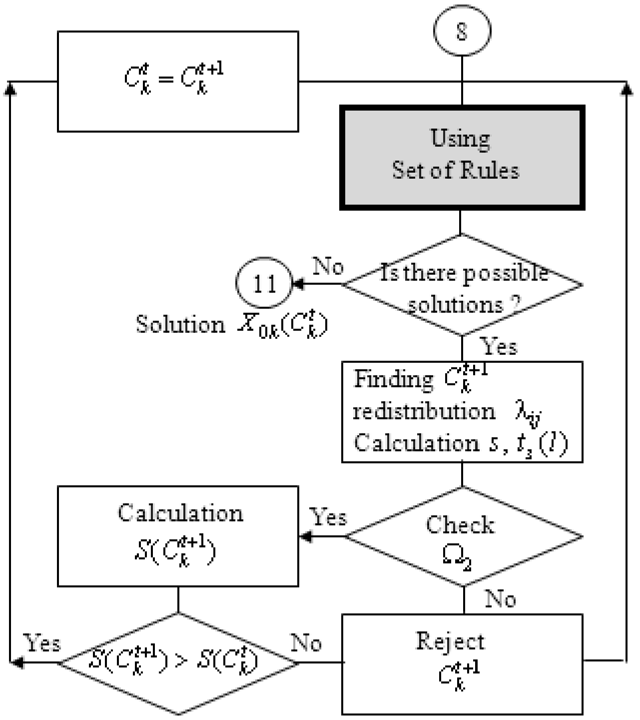

Fig. 4. Scheme of improved search algorithm of quasi-optimal placement of unmanned aerial vehicles using the set of rules (beginning in Fig. 2).

If several rules are successfully matched with the facts, it is possible to use meta-rules which allow choosing one of the rules. Meta-rules define the advantage of rules depending on the p th network control purpose ($MRule_i:\ Rule_i \rightarrow w_j^p$). The rule which increasingly improves given parameters will have more weight w_j^p.

As a result of experimental investigations of network structures and the application of graph theory [16], a lot of structural rules have been obtained [17]. Careful researches of these rules allowed developing a new modified rules and appropriate control actions for purposes of quasi-optimal placement of unmanned aerial vehicles in the space.

All rules are classified into three groups: 1) to provide requirements for network connectivity (Ω_1); 2) to provide requirements for the functional parameters (Ω_2); 3) to increase the network capacity. Examples of several rules or meta-rules and procedures of their implementation are listed below.

Rule No. 1. If the number of connectivity components of network graph $k > 1$, then the unmanned aerial vehicles should be placed in the space so as to connect a larger number of connectivity components.

Meta-rule No.1. If there are several variants of the unmanned aerial vehicles placement with combining the same number of connectivity components, it is advisable to choose the one which allows covering more nodes of these components.

To implement this rule, the procedure using lattice initialization can be applied as shown in Fig. 5. This procedure provides the search of unmanned aerial vehicles placement variants in each lattice site and a choice one that satisfies the rule or meta-rule.

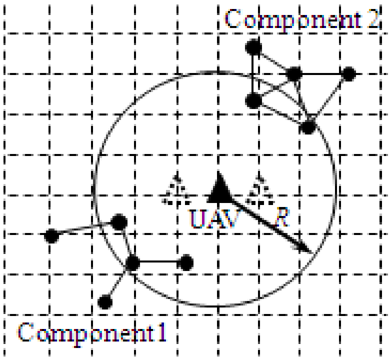

Fig. 5. Illustration of procedure for realization of rule *No. 1* using the lattice initialization.

Rule No. 2. If average transmission delay defined by number of relays in some routes is more than necessary, then unmanned aerial vehicles should be placed so as to reduce the number of relays in the route.

Meta-rule No. 2. If there are several variants of the unmanned aerial vehicles placement which equally reduce the delay in the routes, it should be chosen the one that allows maximization of the route capacity.

To reduce the average transmission delay defined by the number of relays in route, it is necessary to place unmanned aerial vehicles so as to cover given sender-recipient pair nodes in the best way or to cover the most remote pair of nodes in the route.

For this purpose, the following simple procedure based on centroidal initialization can be used as illustrated by Fig. 6:

1. Define the route m_{ab} of network, for which the condition $\overline{t_{con}} \le t^0_{con}$ $(l(m_{ab}) \le l^0)$ is not fulfilled, and the number of relays belonging to it $l^0 = N' - 1$, where N' is the number of nodes in the route.

2. Build straight line segments which connect a given node i of the route (for example, $i = 1$, as shown in Fig. 6) with all other nodes j of the route, where $i, j = \overline{1, N'}$.

3. Check the coverage availability of each segment *ij* by unmanned aerial vehicles service area of radius *R* for placement of UAV in the center of each segment $d_{ij} \le 2R$.

4. For all segments in which the previous condition does not fulfilled, it is necessary to calculate the new number of relays in the route through the unmanned aerial vehicle using the following formula:

$$l_{ij}(m_{ab}) = \begin{cases} |N-j| + |1-i| + 2, & i < j \\ |N-i| + |1-j| + 2, & i > j \end{cases}, \quad a, b, i, j = \overline{1, N}.$$

5. Among all possible segments, it is necessary to select that one which minimizes the number of relays in the route at the unmanned aerial vehicle positioning in segment center.

Computational expenses of this procedure have the order $O(N^2)$.

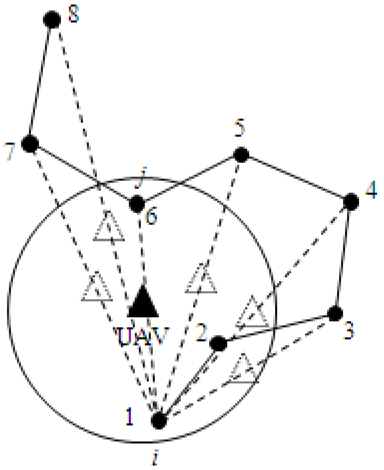

Fig. 6. Illustration of procedure for realization of rule *No. 2* using the centroidal initialization.

To illustrate applying the procedure discussed above, let us consider the case when the unmanned aerial vehicle is placed in the center of the segment 1—6. This allows creation of a new route 1—UAV—6—7—8 which has 4 relays instead of 7 in the absence of UAV (route 1—2— ... —7—8).

In the case, when there are several solutions regarding to the placement of the unmanned aerial vehicle which gives the same number of relays in the route, it is advisable to apply certain meta-rules directed, for example, on achieving greater capacity of the route.

Rule No. 3. If it is necessary to increase the network capacity, the unmanned aerial vehicle should be placed so as to cover the maximum number of overloaded nodes.

Nodes can be overloaded when the queue of buffer continuously grows due to ultra-high intensity of packets arrival for service or when the number of collisions in the organization of multiple access increases due to great clusters of nodes. In any case, one can assume that nodes are overloaded, if the capacity of incidental to their channels does not satisfy the requirement $s(m_{ab}) \geq 0.5$. The placement of unmanned aerial vehicle above such cluster of overloaded nodes allows organizing new data routes between nodes as illustrated in Fig. 7. At the functioning of one well-known routing protocol, this allows aligning the load balance in the network and increasing its capacity.

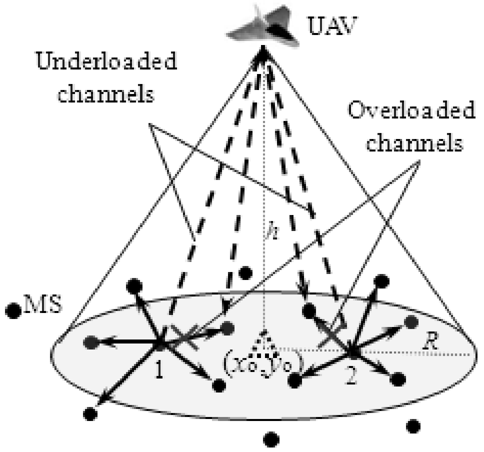

Fig. 7. Illustration of procedure for realization of rule *No. 3* using the centroidal initialization.

To implement this rule, the combination of lattice and centroidal initializations can be used as follows. Searching the maximum number of overloaded nodes is carried out according to lattice initialization. Then, searching the quasi-optimal position of unmanned aerial vehicle in the mass center of overloaded nodes is performed according to centroidal initialization. Center of mass of overloaded nodes group can be defined as:

$$x_{0k} = \sum_{i=1}^{N^o} \alpha_i x_i \ ; \ y_{0k} = \sum_{i=1}^{N^o} \alpha_i y_i \ ; \ \sum_{i=1}^{N^o} \alpha_i = 1 ,$$

where $\alpha_i = 1/N^o$; N^o is the number of overloaded nodes in the group.

Effectiveness estimation of proposed method

Modeling of sensor telecommunication networks was performed by applying the computer environment Maple. The following initial data were used: $N = 140$; $K = 5$; $r = 10,000 \times 10,000$ m^2; all mobile subscribers have the same transfer radius $d^0 = 600$ m; all unmanned aerial vehicles form on earth the same coverage area of radius $R = 1500$ m; the Dijkstra algorithm was chosen to find shortest paths; all mobile subscribers move at the same speed $v_i = 2$ m/s, $i = \overline{1, N}$; the random walk in a field was chosen as the mobile subscribers movement model [10]; transfer rate per channel is $V = 11$ Mbps; packet lengthes are the same $L = 1024$ bit; all subscribers have no priority of service; the traffic distribution matrix Γ is homogeneous; the traffic type is homogeneous Poisson (no priority of service); the type of packet service in network nodes is one with expectation without limitation of queue length.

Taking into account these initial data, three variants of unmanned aerial vehicle placement control system have been studied:

(CS1) the control system based on principles of cellular radio networks which implies the UAV placement in the region of largest cluster of nodes;

(CS2) the control system based on exhaustive search method which implies the full enumeration of all possible variants of the UAV placement using lattice initialization with grid step $\Delta = 50$ m;

(CS3) the control system based on proposed method and set of rules.

The effectiveness estimation of proposed method was performed in the following sequence.

1. Determination of initial mobile subscriber network topology at some time moment t and placement of unmanned aerial vehicles according to CS1, CS2 and CS3 as shown in Fig. 8.
2. Calculation of network capacity $S(C)$ according to the unmanned aerial vehicle placement by each control system. Determination of operation gain of CS2 and CS3 relative to CS1 one. Accuracy estimation of CS1 and CS3 operation results relative to exhaustive search ones (CS2). These situations are illustrated by Fig. 9 — Fig. 11.
3. Calculation of solution finding time for proposed method (CS3) and for method of exhaustive search (CS2), as well as comparison of these values with duration time of the mobile subscriber connectivity.

Analyzing charts of network capacity $S(C)$ dependence from total load γ under different control systems, one can see that in the range of traffic intensity 500—2000 packets per packet transmission time T the proposed system of unmanned aerial vehicle placement control (CS3) considerably prevails the base system (CS1) and all control systems are almost equally ineffective in other ranges.

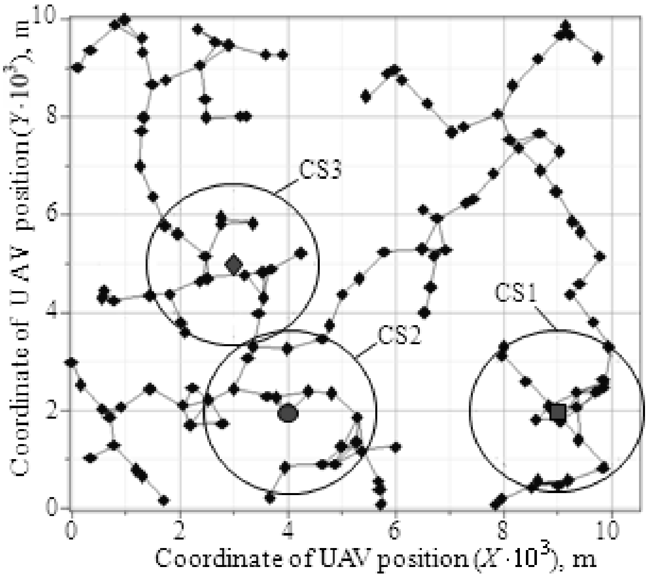

Fig. 8. The initial network topology with unmanned aerial vehicle placement according to CS1, CS2 and CS3.

Therefore, the results of evaluated effectiveness estimation of proposed method allow making the following conclusions.

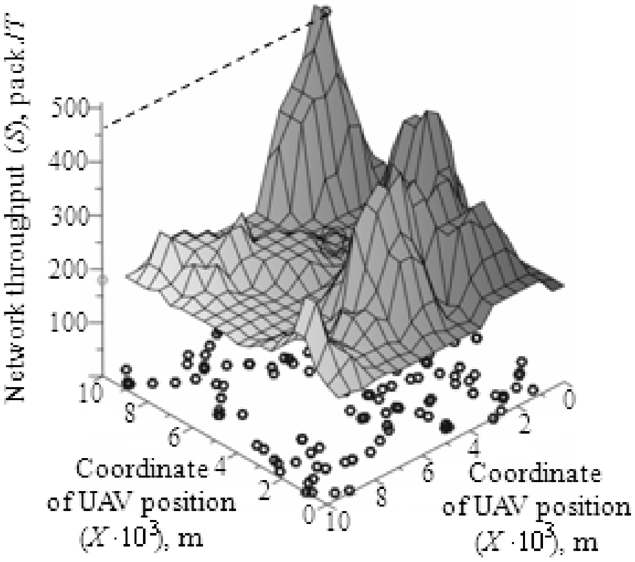

Fig. 9. Dependence of network throughput as a function of placement coordinates of one unmanned aerial vehicle (according to CS3).

1. Average gain of the proposed method (CS3) relatively CS1 under the random generation of 100 variants of initial topology is 15—20 percents.

2. Average deviation of network capacity value under CS3 with respect to method of exhaustive search (CS2) is 5—7 percents.

3. The solution finding time for CS3 is units of seconds as opposed to units of minutes for CS2 that allows implementing the unmanned aerial vehicles placement control in real time under average duration of connectivity 348 s according to [10].

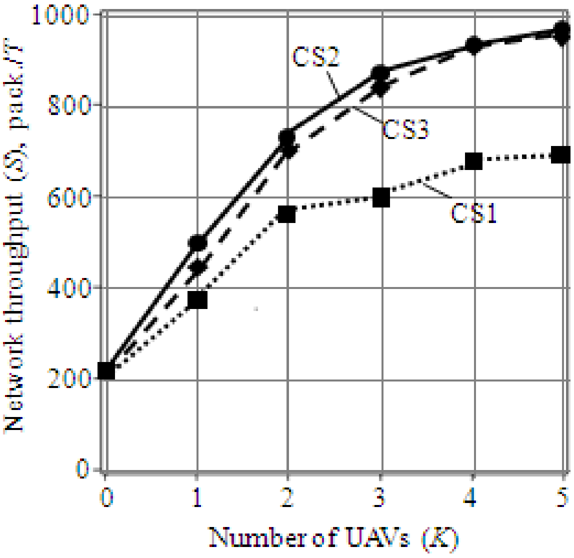

Fig. 10. Dependence of network throughput from number of placed unmanned aerial vehicles according to different CS.

Conclusion

In the paper, the important scientific and technical problem to improve the effectiveness of telecommunication networks has been solved. The method for increasing the sensor network capacity using unmanned aerial vehicles placement control in a view of the rapid and unpredictable movement of mobile subscribers is developed.

The developed method is based on the idea proposed to combine mathematical models of connectivity and quality of service of mobile subscriber estimation and advanced search algorithm of quasi-optimal placement of unmanned aerial vehicles into a single computational procedure. The implementation of the proposed idea allowed creating the effective method of analysis and optimization of sensor networks. Application of the developed method allows increasing the network capacity to 15—20 percents in comparison with existing methods. Deviations of suboptimal solutions from optimal ones received by exhaustive method do not exceed 5—7 percents.

The finding algorithm of quasi-optimal placement of telecommunication air platforms is improved. The essence of the algorithm improvement is that it allows avoiding the exhaustive search of unmanned aerial vehicles placement variants due to using the previously designed set of rules for selection of such changes of network connectivity which increase its capacity and reduce the computation time.

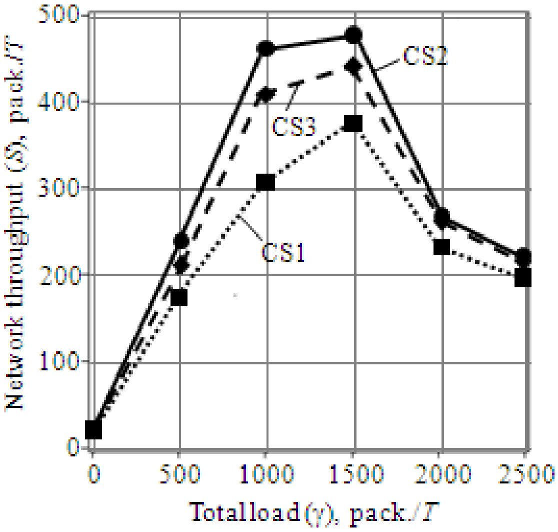

Fig. 11. Dependence of network throughput from total load according to different CS.

Modeling results show that solution finding time using set of rules is units of seconds as opposed to units of minutes for exhaustive search. This allows creating the effective systems of unmanned aerial vehicles placement control in real time.

The results obtained can be applied in the systems of operative providing the communication in regions of natural and technological emergencies.

The high effectiveness of obtained solutions can be arranged by employment of mobile sensor networks based on small unmanned aerial vehicles optimally placed in the space.

References

1. Han Z., Swindlehurst A. L., Liu K. J. R. Smart deployment/movement of unmanned air vehicle to improve connectivity in MANET // Proceedings of IEEE Wireless Communications and Networking Conference, April 3—6, 2006. — Las Vegas, 2006. — P. 252—257.

2. Minochkin A. I., Romanyuk V. A. Control system of mobile ad-hoc networks // Proceedings of International Conference on Telecommunications and Computer Science, February 19—23, 2008. — Lviv, 2008. — P. 414—415.

3. Ilchenko M. Yu., Bunin S. G., Voiter A. P. Cellular radio networks with packet switching — Kyiv: Naukova Dumka, 2003. — 266 p. [in Russian].

4. Basu P., Redi J., Shurbanov V. Coordinated flocking of UAVs for improved connectivity of mobile ground nodes // Proceedings of IEEE Military Communications Conference, October 31 — November 3, 2004. — Monterey, 2004. — Vol. 3. — P. 1628—1634.

5. Mizin I. A., Bogatyrev V. A., Kuleshov A. P. Packet switching networks / Edited by V. S. Semenikhin. — Moskow: Radio and Communications, 1986. — 408 p. [in Russian].

6. Lysenko O. I., Valuiskyi S. V. Structural and functional reliability of wireless ad-hoc networks // Telecommunication Sciences. — 2011. — Vol. 2, N. 1. — P. 17—25 [in Ukrainian].

7. A method of controlling the topology of aerial repeaters network to improve structural information connectivity of wireless ad hoc networks / O. I. Lysenko, I. V. Uryadnikova, S. V. Valuiskyi, I. O. Nechyporenko // Science & Military. — 2012. — N. 1. — P. 1—11 [in Ukrainian].

8. Cross-link architectures for a multiple satellite system / R. Binder, S. D. Huffman, I. Gurantz, P. A. Vena // Proceedings of the IEEE. — 1987. — Vol. 75, N. 1. — P. 74–82.

9. Lysenko O. I., Valuiskyi S. V. Determination of parameters of the vector criterion to assess the connectivity of wireless ad hoc networks using unmanned aerial vehicles // Scientific Papers of the Institute of Modeling Problems in Energy of NAS of Ukraine. — 2010. — Issue 57. — P. 134—141 [in Ukrainian].

10. Valuiskyi S. V. Evaluation of the duration of mobile subscribers connectivity of wireless ad hoc networks // Scientific Papers of Military Institute of Telecommunication and Informatization of NTUU “KPI”. — 2011. — N. 3. — P. 6—11 [in Ukrainian].

11. Minochkin A. I., Romanyuk V. A. Routing protocols in mobile radio networks // Zvyazok. — 2001. — N. 1. — P. 31—36 [in Russian].

12. Tobagi F. A. Modeling and performance analysis of multihop packet radio networks // Proceedings of the IEEE. — 1987. — Vol. 75, N. 1. — P. 135—155.

13. Valuiskyi S. V. Improved model for evaluating of nodes connectivity of wireless ad hoc networks // Proceedings of 6th International Conference “Problems of Telecommunications”, April 24—27, 2012. — Kyiv, 2012. — P. 125—127.

14. Popovsky V. V. Mathematical foundations of telecommunication systems theory / Edited by V. V. Popovsky. — Kharkiv: Smith, 2006. — 564 p. [in Ukrainian].

15. Gavrilova T. A., Khoroshevsky V. F. Knowledge base of intellectual systems. — St. Petersburg: Piter, 2000. — 384 p. [in Russian].

16. Harare F. Graph theory. — Boston: Addison Wesley, 1969. — 296 p.

17. Minochkin A. I., Romanyuk V. A. Topology control of mobile ad hoc networks // Zvyazok. — 2003. — N. 2. — P. 28—33 [in Ukrainian].

Received in final form April 24, 2012