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Optimized Network Router Deployment and Routing in UAV Swarm Networks

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Abstract

The continuous growth of virtual reality (VR), augmented reality (AR), and telepresence applications within IMT-2030 networks has introduced new challenges in providing reliable communication and computational resources. These emerging services require flexible, scalable, and high-performance network infrastructures capable of supporting dynamic and bandwidth-intensive environments. In this regard, unmanned aerial vehicles (UAVs) offer a promising solution for extending wireless coverage, improving connectivity, and reducing network congestion in 5G and beyond communication systems. This paper presents a model and a set of methods for organizing a UAV-assisted wireless access network to support coverage extension and traffic offloading in next-generation mobile networks. The study focuses on the development of clustering and router distribution approaches within a swarm of UAVs to enable efficient and adaptive network deployment. The proposed methods support the intelligent placement of UAV-based routers while considering quality of service (QoS) requirements, maintaining stable mesh network connectivity, and ensuring seamless integration with existing mobile communication infrastructure. The obtained results demonstrate the effectiveness of the proposed approach in enhancing network coverage and connectivity in dynamic environments. The proposed model and methods can serve as a practical solution for service provisioning in 5G and future-generation wireless networks, particularly in scenarios where conventional communication infrastructure is limited or unavailable.

***Keywords**:* 5G and next-generation networks; clustering; UAVs; routing, access network; quality of service.

1. Introduction

The development of communication networks is aimed at improving the main quality indicators, such as the achievable data transmission rate, delivery delay, and network capacity [1–5]. 5G and next-generation networks are oriented toward providing services that are sensitive to delay and data transmission rate. The growing penetration of virtual and augmented reality services, and subsequently of telepresence services [6], gives rise to the need to ensure a high quality of traffic service in the network.

In particular, it becomes necessary to transmit traffic of holographic images [7], as well as traffic generated by telepresence suits that provide an interface for interaction with the metaverse [8]. The metaverse is aimed at creating a virtual world for all kinds of activities, including education, commerce, and gaming, and is considered the next generation of the Internet. With the support of AR/VR applications, online users are provided with services similar to in-person ones. To support metaverse applications, data synchronization and wide wireless network coverage are two practical problems that need to be solved, since telepresence services typically involve wearable wireless devices. Owing to the increase in the frequency range used in 5G networks and allocated for 6G, signal attenuation grows rapidly. As a result, deploying base stations in suburban areas with low population density becomes economically inefficient [9]. Unmanned aerial vehicles represent a cheaper solution for providing network coverage for metaverse data synchronization in suburban areas.

The use of telepresence suits or similar devices that provide information on the dynamics of the movement of people or other objects differs substantially from obtaining information through images and largely complements the "picture" of the state and changes of the world around us. The traffic generated by the aforementioned services must be handled with the level of quality required for their implementation. One of the methods for solving this problem is the use of traffic offloading or the allocation of additional resources for serving such traffic.

Improvement of the main quality indicators is achieved through the introduction of new technical solutions and new models and methods for organizing communication networks. One of the "bottlenecks" in solving the problem of improving quality indicators is the access network. In mobile communication networks, access networks are limited owing to the constraints of the available radio frequency resource. The most effective method is to increase the achievable data transmission rate. Throughout the evolution of mobile communication networks, one can observe a process of widening the frequency band occupied by the communication channel and increasing the operating frequencies. This is a natural process that occurs due to the need to increase throughput.

According to the well-known expression of C. Shannon [10], the achievable transmission rate is bit/s, where w is the channel bandwidth and SNR is the signal-to-noise ratio. Despite a certain decrease in SNR with an increase in bandwidth, this is the most "straightforward" method of increasing the transmission rate. The word "straightforward" is placed in quotation marks because increasing bandwidth is associated with raising the operating frequency and with the need to solve many problems associated with this.

However, each successive generation of communication networks presupposes an increase in the frequency band and an increase in operating frequencies. Thus, 6G networks are already expected to use the sub-millimeter range and operating frequencies of up to 1 THz.

The features of signal propagation in this wave range are such that they can be effectively used only over relatively short distances between the receiver and the transmitter and within the line of sight between them. The properties of signals in this wave range approach those of the propagation of light.

At present, the tasks of creating electronic devices that would make it possible to implement equipment for generating, modulating, receiving, and processing such signals remain open. Questions concerning the creation of antenna devices in this frequency range also remain open. However, studies [11, 12] suggest that such components will be created and will make it possible to use the features of this range to increase the efficiency of communication networks.

Nevertheless, problems associated with the features of signal propagation in the sub-millimeter wave range require a solution at the level of access network organization. In particular, "shadowing" by surrounding objects, including the human body, can lead to a complete loss of communication. This requires the use of a larger number of base stations (antennas) and the corresponding management thereof.

One of the approaches to solving the problem of organizing coverage in 5G and 6G networks may be the use of mobile routers. Equipment manufacturers are already producing 5G routers with autonomous power supply [13], which make it possible to organize a local network conforming to the IEEE 802.11 standard. The main purpose of such a device is to ensure a sufficiently high transmission rate at the level of connection to the 5G network.

When operating in prospective networks at sub-millimeter frequencies, it is necessary to ensure a sufficiently short distance and direct line of sight between the router and the antenna of the base station. One way to achieve this is to use unmanned aerial vehicles (UAVs) [14–16]. This paper proposes a method for using a UAV or a group of UAVs to deploy routers and provide service to users located in challenging conditions for receiving network signals.

2. Model and Problem Statement

In the general case, when placing a router on a UAV, it is necessary to solve the problem of selecting the point of its placement. Two scenarios are possible: when the UAV is stationary, for example, a tethered UAV [17], and when the UAV can move both relative to the users and relative to other UAVs. These scenarios differ in the nature of UAV motion: whereas in the first scenario the network structure does not need to be changed due to changes in the positions of network nodes, in the second scenario such a need may arise. However, both scenarios require solving two main problems:

1. selecting UAV positions relative to users and base stations of the communication network;
2. selecting the logical structure of the network, i.e., the routes for passing traffic in the mesh network.

A conceptual model of the network is shown in Figure 1. The figure depicts a single UAV and a group (swarm) of UAVs. The router placed on the single UAV plays the role of an access point, serving users within its communication zone. The routers placed on the UAVs of the swarm are organized into a mesh network. One or several routers of this group may interact with the base stations of the mobile communication network. The routers within the "swarm," depending on conditions, may perform a number of functions: communication with the base station of the mobile communication network, communication with other routers of the group, and communication with users.

The use of a group of UAVs makes it possible to provide communication coverage for users distributed over a certain area or within a certain volume and to organize traffic exchange between them and the mobile communication network.

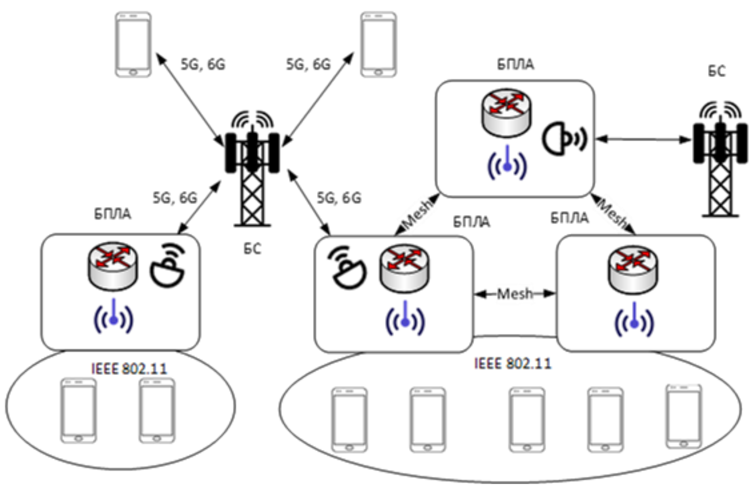

***Figure 1**: Network model using routers on UAVs*

3. Selection of Router Positions

Consider the case where there is a group of n routers. In the general case, $n \in \mathbb{N}$, and may be specified or constrained, $n \leq n_{\max}$.

To select the positions for placing access points, various clustering methods are most commonly applied [18]. In this case, the objects of clustering are the users, and the centers of the identified clusters are taken as the positions for placing the access points.

The clustering problem is typically solved using algorithms such as *k*-means, DBSCAN, and FOREL [19]; in [20], an algorithm using the fractal properties of the network was developed. Each of these algorithms has its advantages and disadvantages. For example, the *k*-means algorithm is suitable when users are uniformly distributed and the number of clusters is known in advance (as the number of objects grows, the cluster shape tends toward that of a polyhedron); DBSCAN is suitable for pronounced clusters of users, where the user density in the cluster zones must be approximately the same (a cluster may have an arbitrary shape); FOREL makes it possible to find solutions both with pronounced clusters of users and with their uniform distribution (the cluster shape tends toward that of a circle), and its working principle is applicable to pronounced clusters of users.

In the present problem, the clustering algorithm must, alongside identifying groups of users (clusters), take into account their mutual positioning, since the routers at the centers of the clusters must form a connected network, and this network itself must be connected to the mobile communication network.

In what follows, an algorithm is proposed that is based on the FOREL clustering algorithm [21]. The idea of this algorithm is preferable for several reasons. First, this method specifies the cluster size R, which is essentially the maximum possible size of the cluster being formed. In the network construction problem, this makes it possible to determine the cluster size through the achievable data transmission rate b in the user-to-access-point segment. If the dependence $b = f(R)$ is defined, then

$$R = \arg\{b_{\min} = f(R)\} \tag{1}$$

where b_{min} is the minimum allowable data transmission rate, specified as a parameter when constructing the network.

The functional dependence $f(R)$ is specific to the standard or group of standards applied and may be determined on their basis, for example [22].

For greater generality, this function can be approximated using the well-known expression of C. Shannon, taking into account a correction coefficient α:

$$b(R) = \alpha w \log_2 (1 + \gamma(R)) \tag{2}$$

where α is a correction coefficient accounting for the difference between the technology used and the analytical model (theoretically achievable rate);

γ is the signal-to-noise ratio;

w is the bandwidth (Hz).

In the general case, $0 < \alpha$. When space-time multiplexing methods (MIMO) are not applied, $0 < \alpha < 1$. When such methods are applied, the coefficient may exceed unity.

The signal-to-noise ratio as a function of distance can be defined as:

$$\gamma(R) = \frac{s_{RX}}{p_n} = \frac{1}{p_n} a(R) s_{TX} \tag{3}$$

where $a(R)$ is the dependence of signal attenuation on distance; one of the well-known models [23] may be adopted for it.

The dependence of the data transmission rate on distance, according to the IEEE 802.11ac standard, at w = 20 MHz, is shown in Figure 2 (blue line). The red curve was obtained according to expression (2) with w = 20 MHz, α = 0.5.

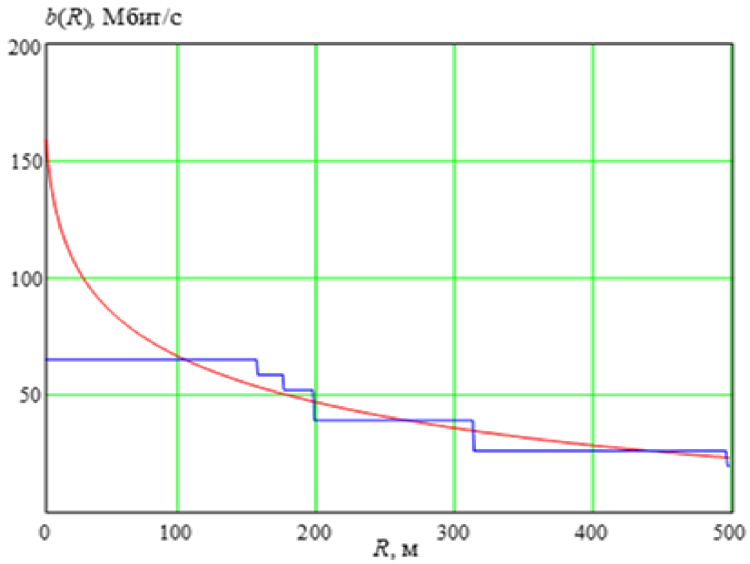

***Figure 2:** Dependence of the data transmission rate on the distance between the user equipment and the access point.*

The presented graph shows a sufficiently close agreement between model (2) and the dependence obtained from the standard's data. The largest error occurs at small distances, i.e., at high values of the signal-to-noise ratio. This can be explained by the technological capabilities that are accounted for in this standard.

The application of the selected clustering approach solves the problem of minimizing the sum of distances between elements and the centers of the clusters. When the system is described by the expressions given above, the clustering objective function will be expressed as:

$$O = \max_{c_j, j=1\ldots n} \sum_{j=1}^{n} \sum_{i=1}^{m_j} b\left(c_j, u_{ji}\right) \tag{4}$$

where $b(c_j, u_{ji}) = b(d(c_j, u_{ji}))$ is the achievable transmission rate between the center of the j-th cluster and the i-th element of the j-th cluster, and $d(c_j, u_{ji})$ is the distance between the center of the j-th cluster and the i-th element of the j-th cluster.

Thus, the application of this method makes it possible to select the positions of the cluster centers (positions of access points) such that the total transmission rate in the network is maximized, while condition (1) ensures the minimum allowable value of the data transmission rate.

The solution to (4) yields near-optimal positions for the cluster centers relative to the elements, which are the users. However, in this case it is also necessary to take into account the position of the cluster centers relative to the base stations of the mobile communication network and relative to one another.

Let us assume that R_C is the radius of the cluster's communication zone, and R_M is the router's communication zone radius with the base station of the mobile communication network. These parameters must be introduced as constraints in the clustering algorithm used.

A distinctive feature of this algorithm is that the selection of the cluster center position is performed taking the aforementioned constraints into account, namely:

$$\begin{aligned} &\exists j \in \{1\ldots n\}, \quad d(c_{\mathrm{j}}, B) \le R_{\mathrm{M}} \\ &\exists (j,i) \in \{1\ldots n\},\ j \ne i, \quad d(c_{\mathrm{j}}, c_{\mathrm{i}}) \le R_{\mathrm{C}} \end{aligned} \tag{5}$$

These constraints, in essence, determine that at least one of the routers must be within the communication zone of the base station of the mobile communication network, and each of the routers must be within the communication zone of at least one of the neighboring routers. These constraints ensure connectivity between the routers placed on the UAVs and connectivity with the mobile communication network.

These constraints can be strengthened by specifying a minimum number of links between routers $r_{\min}$ and with the base stations of the mobile communication network $M_{\min}$:

$$\begin{aligned} &\exists J \in \{1\ldots n\}, \quad |J| \ge M_{\min}, \quad d(c_{\mathrm{j}} \in J, B) \le R_{\mathrm{M}} \\ &\exists L \in \{1\ldots n\}, \quad |L| \ge r_{\min}, \qquad d(c_{\mathrm{j}} \in L, c_{\mathrm{i}} \in L) \le R_{\mathrm{C}}, \quad j \ne i \end{aligned} \tag{6}$$

The pseudocode of the proposed algorithm is given below.

Input data:

— a set of clustering objects (users) $U = \{u_i\}, \quad i = 1 \ldots m$. Each of the objects corresponds to a point with specified coordinates

$$u_i = p(u_i) = \left(x_i^{(u)}, y_i^{(u)}, z_i^{(u)}\right), \quad i = 1 \ldots m$$

— a set of base stations of the mobile communication network $V = \{v_i\}$, $i = 1\ldots k$. Each of the objects corresponds to a point with specified coordinates

$$c_i = p(c_i) = \left(x_i^{(c)}, y_i^{(c)}, z_i^{(c)}\right), \quad i = 1 \ldots n$$

— a set of cluster centers $C = \{c_i\}$, $i = 1\ldots n$. Each of the cluster centers c_j, $j = 1\ldots n$, corresponds to a point with specified coordinates

$$c_i = p(c_i) = \left(x_i^{(c)}, y_i^{(c)}, z_i^{(c)}\right), \quad i = 1 \ldots n$$

Algorithm
$U_0 = \{u_i\},\ i = 1 \ldots m_;$ *// Set of unclustered objects*
$C = \emptyset$ // Set of clusters
$i = 1;$
// Random point in the service area

$$p(c_i) = \left\{\text{randomPos}\ (x, y, z) \in S,\ d(c_i, v_q) \le R_M,\ d(c_i, c_j) \le R_C,\ v_q \in V\right\}$$

$$C_0 = \left\{u_j \in U_0;\ d(c_i, u_j) \le R\right\}_{;//Form\ cluster\ C_0}$$

While $U_0 \ne \emptyset$
{
// Compute the cluster center

$$cm = S(U, V, R)$$

// If the center of mass does not coincide with the cluster center, and it is located at a distance not exceeding R_C from the center of another cluster
if $cm \ne p(c_i)$

if $\exists c_j \in C,\ d(cm, c_j) \le R_C$
$p(c_i) = cm$ // *Move to the center of mass*
else

$$\omega = \omega + \Delta\omega;$$

else
{
$U_0 = U_0 \setminus C_0$ / *Remove cluster elements from set of unclustered elements*

$$C = C \cup cm$$

} //End while
ReDistributeNones(cend) //optional

The cluster center (center of mass) is computed according to the following expression:

$$S_m(C_0, V, R) = \left\{ \begin{array}{l} x_0 = \frac{1}{K}\left(\sum_{i=1}^{K} x_i \eta_i + x_{Cn}\omega\right), y_0 = \frac{1}{K}\left(\sum_{i=1}^{K} y_i \eta_i + y_{Cn}\omega\right), \\ z_0 = \frac{1}{K}\left(\sum_{i=1}^{K} z_i \eta_i + z_{Cn}\omega\right) \end{array} \right\},$$

$$K = |C_0|, \quad (x_i, y_i, z_i) = p(u_i), \quad u_i \in C_0, \quad (x_{Cn}, y_{Cn}, z_{Cn}) = p(c_n), \quad c_n \in C, \quad \eta_i, \omega \ge 0 \qquad (7)$$

where K is the number of elements in the cluster; x_0, y_0, z_0 are the coordinates of the cluster center; η_i is the weighting coefficient of the element (user); x_{Cn}, y_{Cn}, z_{Cn} are the coordinates of the center of the nearest neighboring cluster; ω is the weighting coefficient.

A particular feature of computing the cluster center is that the distance to the center of the nearest cluster is taken into account. By varying the value of ω, one can control the "gravitation" of the center of the cluster being sought toward the nearest neighboring cluster.

The algorithm presented above describes the general three-dimensional case, in which a cluster is a sphere. Owing to the insufficient clarity of representing the clustering results in space, Figure 3 shows an example of clustering on a plane. In this example, the clustering of 1000 users distributed on a plane is simulated. A Gibbs point process [24] is used for the simulation.

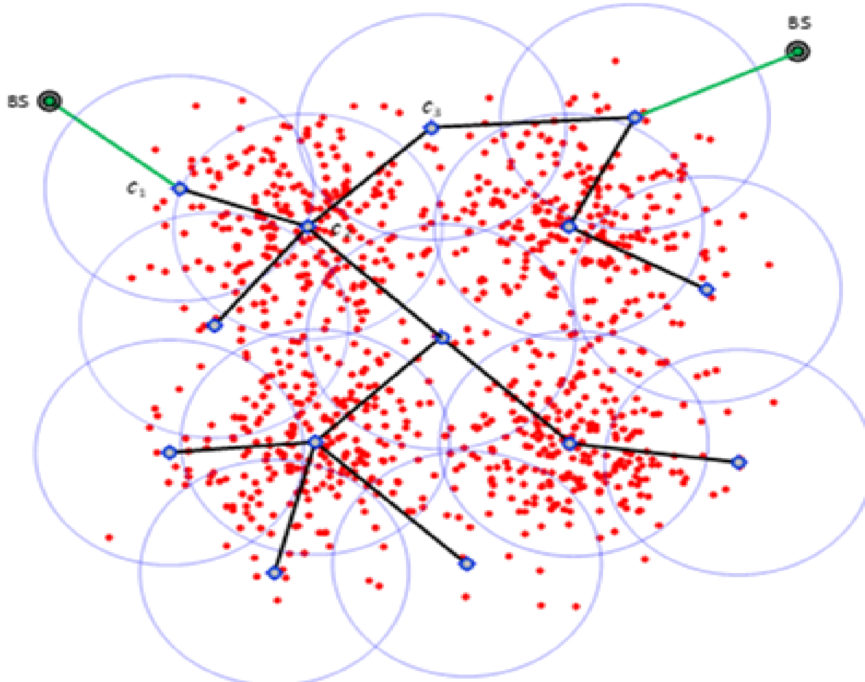

***Figure 3**: Result of clustering and selection of network structure.*

After the algorithm presented above is executed, the cluster centers will be found. The algorithm can be terminated at this point, and the elements can be assigned to clusters in the order in which the clusters were identified during the algorithm's execution. However, this approach yields good solutions in the case where there are clusters of elements (users) and the size of these clusters does not exceed the cluster size R. Otherwise, the cluster sizes may differ considerably.

In such a case, it is advisable, upon completion of the algorithm, to perform a redistribution of elements by assigning them to the nearest cluster centers. In the algorithm above, this operation is performed by the procedure ReDistributeNones(y/n), where the argument indicates whether to perform the redistribution operation or not.

After the operation of redistributing elements, the clusters will have the shape of polyhedra whose sides are determined by the Voronoi diagram [25] constructed with respect to the identified cluster centers; an example is shown in Figure 4.

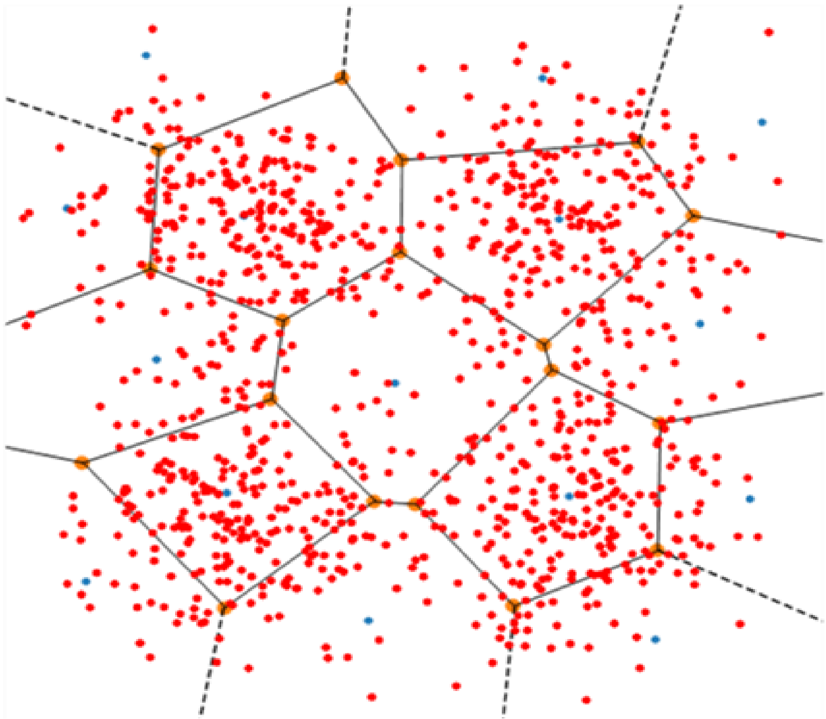

***Figure 4**: Result of modifying the cluster shapes*

As a criterion for the necessity of redistribution, it is proposed to use the variance of the number of elements in the clusters, defined as:

$$cond = \begin{cases} true & D_{II}(K) < D_I(K) \\ false & D_{II}(K) \geq D_I(K) \end{cases} \tag{8}$$

where D_{I}, D_{II} are the variances of the number of cluster elements for the algorithm without element redistribution and with their redistribution, respectively.

The variances for both cases can be found from the expression:

$$D(K) = \frac{1}{n}\sum_{i=1}^{n}\left(K_i - E(K)\right)^2, \quad E(K) = \frac{1}{n}\sum_{i=1}^{n} K_i \tag{9}$$

where n is the number of clusters, and K_i is the number of elements in the i-th cluster.

The proposed method and algorithm make it possible to perform the clustering of users in a specified service area while taking into account the allowable distances between cluster centers and the allowable distances to the base stations of the mobile communication network. Thanks to these properties, this method makes it possible to construct a connected mesh network based on routers placed at the cluster centers, with connectivity to the base stations of the mobile communication network. The clustering algorithm ensures the identification of clusters according to the maximum quality of service.

4. Traffic Routing

The identified router positions (cluster centers) are joined into a mesh network whose structure can be determined by the shortest routes between sender and receiver. By the shortest route, we mean the route that provides the highest quality of traffic service. We assume that the quality of service is characterized by such indicators as the achievable data transmission rate, the data delivery delay, and the probability of data loss.

The structure of the mesh network is defined by the matrix:

$$ST = \begin{bmatrix} l_{11} & \cdots & l_{1n} \\ \vdots & & \vdots \\ l_{n1} & \cdots & l_{nn} \end{bmatrix}, \quad l_{ij} = \begin{cases} q_{ij} & l_{ij} \leq R_C \\ \infty & l_{ij} > R_C \end{cases}, \quad i, j = 1 \dots n \tag{10}$$

where q_{ij} is the quality indicator of the communication link between network nodes, and l_{ij} is the characteristic of the communication link between network nodes.

As a quality indicator, an integral indicator is proposed that takes into account the data transmission rate, the load, and the loss probability:

$$q_{ij} = -\omega_1 b_{ij} + \omega_2 \rho_{ij} + \omega_3 p_{ij} \tag{11}$$

where ω_1, ω_2, ω_3 are the coefficients of the conditional cost per unit of the corresponding indicator.

The integral indicator has the meaning of a conditional gain or expense, depending on the sign. The sign of the term in expression (11) is positive for indicators whose growth leads to an increase in conditional expenses—in this case, to a decrease in the quality of service.

In this case, the use of any shortest-path search method for the network described by matrix (10) makes it possible to select the route that has the minimum value of the sum of coefficients for each of the edges entering it, which can be formally written as:

$$\Omega_{st} = arg\left(\Omega_{st} = \Omega_{st} \cup q_{ij} \quad | \quad \min_{q_{ij} \in ST} \sum_{r=1}^{L_{st}} q_{ij}, \quad i, j = 1 \dots n, \quad i \neq j\right) \tag{12}$$

where Ω_{st} is the set of vertices (nodes) entering the shortest path between vertices *s* and *t*.

To find all the shortest paths, the Dantzig algorithm [25], for example, can be used.

5. Efficiency

To evaluate the efficiency of the proposed methods, we choose the unmodified FOREL algorithm as an alternative. When this algorithm is applied, the distribution of routers in the service area does not guarantee the connectivity of the mesh network nor the availability of the mobile communication network. In such a case, the positions of the routers are random and depend on the distribution of users, but they are in no way constrained with respect to their mutual arrangement. Consequently, the connectivity of the network they form is also a random variable.

If the routers placed at the selected positions (cluster centers) do not form a connected network, then the users connected to these routers do not have access to the other part of the network and to the external network. Thus, for comparing the methods, the most representative characteristic is the connectivity of the network formed by the placement of routers.

The connectivity of the network can be described by the probability of connectivity, which can be estimated by the fraction of possible routes in the network:

$$con = \frac{n_e}{(n+1)^2} \tag{13}$$

where n is the number of clusters (routers), and n_e is the number of available routes.

The quantity $(n + 1)^2$ is the maximum possible number of routes between all n nodes of the network and one node describing the base station of the mobile communication network, which is attained at full network connectivity.

The connectivity probability (13) in the case of the unmodified algorithm does not exceed unity, whereas in the case of the modified algorithm it is always equal to unity. We will consider the quantity $1 - con$ as the gain obtained by using the proposed methods:

$$e = 1 - con \tag{14}$$

This quantity depends on the radius of the routers' communication zone R_C and R_M; assuming that these quantities are equal, $R_C = R_M$, it is possible to evaluate the dependence $e(R_C/W)$, where W is the size of the service area.

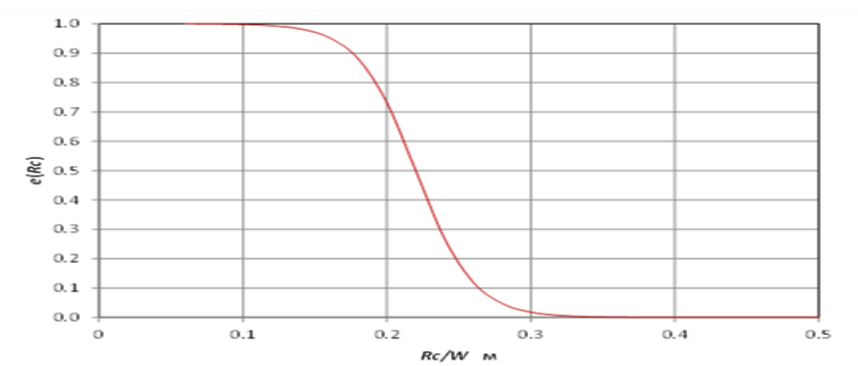

Figure 5: *Dependence of the method's efficiency on the radius of the inter-cluster communication zone R_C.*

We can observe in Figure 5 that the application of the method is appropriate when the radius of the routers' communication zone in the mesh network is smaller than the size of the service area. This is natural, since otherwise any placement of a router is equivalent from the standpoint of ensuring connectivity.

In the example given above, with a service area size of 500×500 m and the specified distribution of users, when the radius of the router's communication zone is approximately 0.23 of the service area size, the efficiency of the proposed method is about 50%.

The efficiency of the method is higher the smaller the ratio of the router's communication zone radius to the service area size. Thus, its application is advisable when relatively large areas or volumes need to be served.

6. Conclusion

1. Modeling the communication link between the router and the user using the C. Shannon model, taking into account the technological differences of its implementation in the current wireless access network standard, makes it possible to solve the user clustering problem as a problem of maximizing the total achievable data transmission rate.
2. The proposed clustering algorithm, which is a modification of the FOREL algorithm, ensures the selection of router positions for serving users and for organizing a connected mesh network and the connection of this network with the base station of the mobile communication network.
3. The modification of the clustering algorithm, which provides for the redistribution of cluster elements, makes it possible to improve the quality of clustering by equalizing the number of elements in the identified clusters.
4. The traffic routing method in the mesh network provides for the selection of routes based on the minimization of an integral route quality indicator that takes into account the achievable data transmission rate, the load magnitude, and the probability of losses.
5. The proposed methods for distributing routers in a swarm of UAVs or on single or tethered UAVs are effective in the case where the size of the router's communication zone is smaller than the size of the service area.

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