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Improving the Efficiency of Information Flow Routing in Wireless Self-Organizing Networks Based on Natural Computing

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Abstract: With the constant growth of requirements to the quality of infocommunication services, special attention is paid to the management of information transfer in wireless self-organizing networks. The clustering algorithm based on the Motley signal propagation model has been improved, resulting in cluster formation based on the criterion of shortest distance and maximum signal power value. It is shown that the use of the improved clustering algorithm compared to its classical version is more efficient for the route search process. Ant and simulated annealing algorithms are presented to perform route search in a wireless sensor network based on the value of the quality of service parameter. A comprehensive routing method based on finding the global extremum of an ordered random search with node addition/removal is proposed by using the presented ant and simulated annealing algorithms. It is shown that the integration of the proposed clustering and routing solutions can reduce the route search duration up to two times.

Keywords: ant algorithm; simulated annealing; k-means; signal-to-noise ratio (SNR)

1. Introduction

In today's world, wireless self-organizing networks are powerful tools for collecting, transmitting, and processing large amounts of data, widely used in various fields, including environmental monitoring, "smart" home systems, fire systems, health monitoring systems, etc. The choice of how to organize information transmission between a sensor or network node and gateways or base stations is an important issue that directly affects the quality of services provided and, consequently, the level of end-user satisfaction [1–4].

During the last decade, a significant number of solutions have been proposed, in particular [5,6] to improve the routing process, but with the constant technological progress in microelectronics, the need to provide new services and new applications of wireless self-organizing networks requires more and more research to improve the information transfer process according to user requirements.

The simplest type of information flow routing in wireless self-organizing networks is greedy routing, but it can be unsuccessful in the presence of various topological heterogeneities.

In recent years, the scientific direction "Natural Computing" has been intensively developed, which is based on the principles of natural decision-making mechanisms. One of such natural mechanisms, which is actively used to solve various problems, including routing in the sensor network, is the ant algorithm [7]. Ant optimization results are particularly good for non-stationary systems whose parameters change over time, such as telecommunications and computer networks. For large-dimensional optimization problems, it is also appropriate to use the annealing simulation method, which avoids local maxima due to a probabilistic approach in choosing the best solution at each stage of operation [8].

Clustering requires separate attention, which in many works, in particular, [9], is considered as one of the steps to improve the routing process in wireless self-organizing networks.

Thus, given the increase in the number of devices in wireless self-organizing networks, improving the routing methods of information flows in self-organizing networks by improving the timing parameters of routing and information transfer to meet the needs of users is an urgent task.

To solve this problem, the paper proposes a method for routing information flows based on a combination of natural mechanisms: algorithms ant and simulated annealing, the use of which allows you to find the global extremum of some function based on an ordered random search and search for a route with the best value of the parameter quality of service (QoS) based on removing/adding a node from the route. Since the clustering characterizes the degree of interaction between the nearest neighbors of a particular wireless network node, the paper proposes to use an improved clustering algorithm k-means, which takes into account the model of signal propagation in the radio channel to account for signal power loss when passing through obstacles, which in turn reduces the chance of data loss and improves the transmission of information flows.

Considering the above, the following structure of the article was formed. Section 2 illustrates the state of research aimed at improving the efficiency of routing information flows in wireless networks based on natural computation mechanisms. Section 3 presents an improved k-means clustering algorithm for wireless sensor network nodes. Section 4 is devoted to the development of a routing method based on a combination of the ant algorithm and simulated annealing. Section 5 describes the operating principles of the developed software simulator. Section 6 presents the obtained simulation results. Section 7 contains conclusions based on the proposed solutions and the implemented research.

2. Related Works

Modern society is becoming increasingly dependent on the quality of modern information, and telecommunication services are a consequence of the rapid development of information technology. In the field of infocommunications, wireless self-organizing networks with dynamically changing topology, which has a direct influence on the choice of routing algorithms, are widespread.

Routing protocols are extremely diverse in their principle of operation (based on an ant colony, a swarm of bees, simulated annealing, etc.), but they have the same goals, which are to minimize (maximize) the values of selected service quality indicators (transmission speed, average delay, jitter, packet loss, etc.), as well as to provide a balanced network load, its channel resources. Thus, to provide quality information services, it is necessary to ensure control and collection of information about the state of the self-organizing network (topology, network resources load, etc.), the synthesis, and the selection of data transmission routes. In this regard, providing effective routing of information flows in networks with dynamically changing topology is relevant, as evidenced by a number of works of scientists from different countries.

In [10], the authors use clustering and routing to improve the data transmission process. A modified ant algorithm is given, for which a mechanism for updating pheromones and searching for ants was developed. To improve the heuristic information, it is proposed to use the distance and the amount of charge of the node, which minimizes energy consumption and maximizes the life of the network. The authors also developed a routing clustering algorithm, which has two main phases: the phase of selection of the main cluster node and the phase of data transmission. According to the proposed routing clustering algorithm, the choice of the main cluster node is based on the distance between nodes and the residual energy of nodes, after which a modified ant algorithm is used to determine the optimal routes. A number of studies related to the energy consumption of nodes have been carried out to evaluate the proposed solutions, but no study has been carried out to evaluate the duration of route search from the probability of packet error due to interference in the radio channel.

The paper [11] is devoted to the search of the optimal path between the departure point and the destination point in terms of its duration and safety (without collisions with obstacles). The authors proposed to improve the classical ant algorithm by using the age of ants, according to which the ant with the shortest path (junior) gets a higher value of pheromone. Route selection is based on the fitness function, which is based on the number of steps needed to reach the endpoint, and all other criteria for route selection are not considered.

In [12], a hybrid routing algorithm (FSACO) for wireless sensor networks based on a combination of artificial fish swarm and ant algorithms is presented. Additionally, an improved pheromone update strategy is used for FSACO, which takes into account the node energy level and the path length when updating the heuristic value and the trace pheromones. The above simulation results demonstrate the effectiveness of the hybrid routing algorithm in terms of reducing node energy consumption, increasing performance, and maximizing wireless network lifetime, but the performance evaluation did not consider the impact of various factors (e.g., interference).

The paper [13] demonstrates a comprehensive approach to reduce network latency and increase network lifetime by using three phases: clustering, duty cycle, and routing. Clustering is based on a combination of hybrid particle swarm optimization (PSO) and affinity propagation (AP) algorithms. PSO is applied to select the best path based on the value of the fitness function, which takes into account parameters such as node degree, residual energy, and distance. The AP algorithm then performs cluster formation. Routing consists of combining the work of the ant colony optimization (ACO) and firefly (FFA) algorithms. ACO creates many paths based on parameters such as residual energy of the node, number of hops, throughput, and distance, and the FFA algorithm selects the most optimal. The paper presents the results of the research carried out but does not study the formation time of data transmission routes in clusters.

In [14], a method for optimal information transmission in wireless sensor networks is presented, which has two steps: the use of the Low-Energy Adaptive Clustering Hierarchy(LEACH) algorithm to select the main nodes of clusters and the ant colony optimization algorithm to select the optimal route within the cluster based on heuristic information, which is constantly updated. The above results show the effectiveness of the proposed algorithm in terms of stability period, network lifetime, and total number of packets in a dense environment, but the effects of processes that are typical of a dense environment on information flows are not given.

A routing protocol based on simulated annealing for networks with mobile nodes is presented in [15]. For the developed algorithm, the data transmission path is based on the value of the cost function, which is calculated based on the number of hops and the average node interaction time. The presented research results demonstrate the effectiveness of the proposed solution in terms of delay in the information delivery process, but the simulation results on the total data transfer time between mobile nodes are not given.

The paper [16] is devoted to the development of a population-based annealing simulation algorithm to improve the route of vehicles. The author proposed to create routes by using exchange, insertion, and reversion operators, with the size of the population set in the initial data of the algorithm. The suitability of the routes formed is determined based on the value of the target function, which is the sum of all the distances between the nodes that form the route. Thus, in this paper, only one criterion—distance—is considered for route selection.

The paper [17] presents the use of an improved annealing simulation algorithm to optimize the cargo delivery process by finding the optimal route. The proposed improvement consists in moving the solution (route) obtained from the initial stage to the neighborhood:

exchange, inserts, and reverse moves. Neighborhood consists of exchanging positions between two nodes; insertion is the removal/addition of a node from the current solution. Reverse moves are performed by randomly selecting two nodes and setting them in reverse order, but the paper does not consider the probability of losing the current solution through external factors.

In [18], the use of k-means algorithm and fuzzy hierarchical comprehensive assessment method (FAHP) to improve the data routing process in wireless sensor networks is considered. The clustering process is performed based on the k-means algorithm, and then the main cluster node is selected based on the FAHP method, taking into account criteria such as node energy and distance to the base station.

The authors of [19] propose a hierarchical routing clustering algorithm based on k-means to reduce the latency of information flows in wireless sensor networks. To implement the clustering of network nodes, the distance between nodes and their energy is used, followed by hierarchical routing. To compare the effectiveness of the proposed algorithm (K-CHRA), the authors performed a comparison with the performance of partition greedy algorithm (P-greedy). The obtained results demonstrate the advantage of using K-CHRA in terms of reducing the data transmission delay and increasing the network lifetime, but the impact of radio channel parameters is not considered in this research.

The paper [20] is devoted to improving the efficiency of routing in wireless sensor networks based on the use of swarm intelligence. The authors propose a swarm-intelligence-centric routing algorithm (SICROA) based on the ant algorithm, which allows you to quickly adapt to the dynamically variable network topology, avoiding various obstacles in the transmission of data. Routing is established by considering the residual energy of the node based on the ad hoc on-demand distance vector (AODV) protocol. For this purpose, a 1 byte Warning_Energy (W) field was added to the route reply (RREP) packet used in the AODV protocol. Based on the simulations performed in NS-2, the effectiveness of the SICROA routing protocol compared to AODV and dynamic source routing (DSR) was shown. The authors also noted that an increase in the number of connections and nodes leads to an increase in signal interference, but this issue was not investigated in more detail.

In paper [21], an improved ant colony algorithm is presented to reduce the energy consumption of wireless sensor nodes during data transmission. To select the optimal node in the process of route formation, it is proposed to take into account the distance and the current quality of communication between the nodes under consideration. Based on the results of the simulations performed, it is shown that the use of the improved ant colony algorithm (IACS) can accelerate its convergence and improve the global search capabilities, allowing one to reduce network congestion. The main focus of the research is on node energy and network lifetime, while route setup duration is not considered.

Thus, based on the analysis of the conducted inspection of works, it was determined that, in order to increase routing efficiency in wireless networks, the complex approach—a combination of clustering and routing algorithms—is a relevant solution. It is also worth noting that the reviewed works did not take into account the influence of the instability of the noise level in the radio channels of modern wireless networks for the provision of quality services.

In this regard, this paper proposes a method based on a combination of clustering and routing, taking into account the impact of noise levels on the efficiency of data transmission in wireless networks, which reduced the duration of route search.

3. Improved K-Means Clustering Algorithm for Wireless Sensor Networks

Clustering is one of the most important methods for creating wireless sensor networks (WSNs). The functioning of a clustered WSN depends to a large extent on the algorithm for selecting the main node, in which there is the requirement to maximize the life cycle of the network and the maximum coverage of the required territories.

Since the processes of signal propagation over the radio channel and the value of the signal-to-noise ratio (SNR) in the WSN perform a significant impact on the transmitted data, particularly leading to their loss, it is proposed to improve the well-known algorithm k-means by taking into account the model of signal propagation.

The k-means algorithm is a non-hierarchical iterative clustering method, which has received a great deal of popularity due to its simplicity and high enough performance quality. Its basic idea is that the data are randomly partitioned into clusters, then the center of mass for each cluster obtained in the previous step is iteratively recalculated, then the vectors are partitioned into clusters again according to which new centers are closer by the chosen metric [22].

The k-means algorithm is applied to an array of point values in d (dimensional vector space). Thus, these are clusters of a set of d, dimensional vectors, $D = \{x_i | i = 1, \ldots, N\}$, where $x_j \in S_i$ denotes the j-th object or data point. Thus, the algorithm combines all data points in D such that each point x_j is included in one of k clusters, and its action is based on the principle of minimizing the total quadratic deviation of cluster points from the centers of these clusters (centroids). The k-means algorithm uses a proximity measure such as distance Euclidean:

$$V = \sum_{i=1}^{k} \sum_{x_j \in S_i} (x_j - \mu_i)^2, \tag{1}$$

where:
k—the number of clusters;
x_j—each vector, which is represented by a point;
S_i—the clusters obtained;
μ_i—mass centers of vectors x_j (centroids).

The value of k is the main input of the algorithm.

To estimate the losses in the wireless self-organizing network, it is proposed to use the Motley model [23], which allows one to take into account the signal power loss when passing through obstacles and to monitor the bit error rate (BER) level when passing through each node of the network:

$$L = L_M + 10n\log(d) + k_w L_w \tag{2}$$

where:
L_M—loss of signal power at a distance of 1 m;
k_{w_i}—number of nodes passed;
L_{w_i}—signal power loss when passing through a node i.

Figure 1 presents the basic steps of the k-means clustering algorithm with the proposed enhancements.

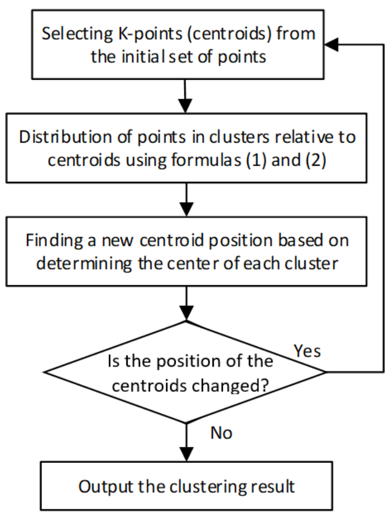


Figure 1. The basic steps of the improved k-means clustering algorithm.

Thus, the k-means clustering algorithm is proposed for improvement by using the Motley model, resulting in the formation of the cluster and, accordingly, finding its centroid until all nodes nearest measured by distance with a maximum value of signal power are found will lower the probability of loss of data transmitted in wireless sensor networks.

4. The Method for Routing Information Flows Based on Natural Decision-Making Mechanisms

The problem of data route optimization is an essential component of modern self-organizing networks. In recent years, the scientific direction "Natural Computing" has been intensively developed, which is based on the principles of natural decision-making mechanisms, in particular these algorithms of ants, simulated annealing, etc.

4.1. Ant Algorithm

The idea of the ant algorithm is based on modeling the behavior of a colony of ants, which search for a path (route) from the anthill to the food using chemical regulation. An important property of this kind of algorithm in terms of the routing problem is their adaptivity—if a certain route becomes unavailable, the system is able to quickly find a suitable replacement.

Thus, such an algorithm can be used to find the shortest route between the source node and the destination node in the presence of various network heterogeneities, e.g., node congestion. Let us consider this process in more detail.

An ant selects a route based on the path length l_i, $i = \overline{1, n}$, where n is the number of routes from the current source node, which depends on the number of pheromones left on the i-th route by other ants.

When reaching the destination node, an ant marks the route of its movement with pheromones, adding a certain increment on each section, $\Delta\tau = \frac{Q}{L}$, where Q is a parameter, the value of which is chosen of the same order as the length of the optimal path, and L is the length of the traversed path. At the same time, on other routes, pheromone evaporation is carried out, $\tau_i = \gamma_i(t-1) + \Delta\tau$, where t is the discrete time (iteration number). $\gamma \in [0, 1]$ is a parameter, the value of which affects the rate of pheromone evaporation (renewal factor). At $\gamma = 0$, its complete evaporation occurs, and at $\gamma = 1$, its value is saved. Obviously, the routes that are most often used, i.e., optimal by the value of the quality of service parameter, contain the largest number of pheromones.

Thus, for each ant, the transition probability between nodes connecting an edge i is defined as:

$$p_i = \frac{(\tau_i)^{\alpha}(\eta_i)^{\beta}}{\sum\limits_{j=1}^{n}(\tau_j)^{\alpha}(\eta_j)^{\beta}} \quad (3)$$

where:
η_i—edge attractiveness;
α—parameter that controls the effect of τ_i;
β—parameter that controls the effect of η.

Considering the above information to determine the effective route of data transmission in wireless self-organizing networks, an ant algorithm was developed, whose work consists of the following steps (Figure 2) [24,25].

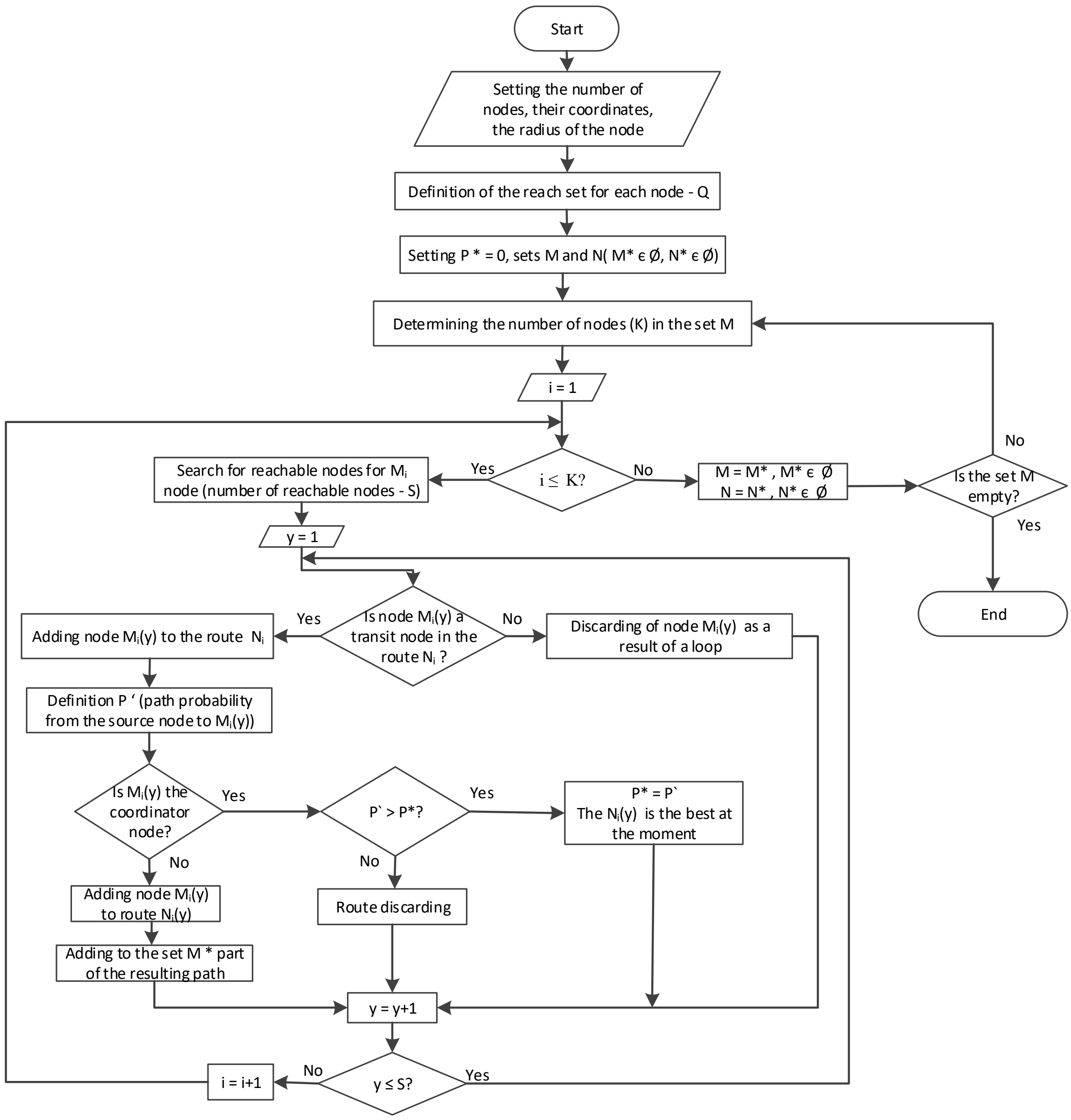


Figure 2. Block diagram of the developed ant Algorithm 1.

4.2. Simulated Annealing

With the development of computer technology, classical methods for solving routing problems began to give way to metaheuristic methods. One of the methods that allows finding optimal solutions is the simulated annealing. This method finds a global extremum of some function based on an ordered random search. The annealing simulation method is used to solve global optimization problems. With the help of simulation, a process, a point, or a set of points are searched, on which a minimum of a certain numerical function is achieved.

The annealing simulation method builds a sequence of routes, starting from the initial route x_0 at the t-th iteration (iterations are numbered from zero), moving from route x_t to $x_t + 1$. At each iteration, the method works as follows [26,27].

First, $N(x_t)$ is formed for the route x_t, giving the set of "neighbors" to x_{t_i} routes and, for each of them, the probability of its choice.

Algorithm 1. Ant algorithm (Figure 2)

1. Assume that the transition probability of the best route from source node (i) is $P^* = 0$. Given that the route at this stage of the algorithm is unknown, $P^* = 0$, it is obvious that, for any existing route, the transition probability is larger than 0.
2. We introduce set M i N, which at this stage contains only source node. Further set M consists of transit nodes, N consists of routes from source node to nodes of the set M. We also introduce auxiliary sets M^* and N^*, which at this stage are $\varnothing$.
3. Determine the number of nodes K in the set M.
4. Accept $i = 1$, where i is an element of the set M
5. Define the condition $i \leq K$.
  5.1. If this condition is satisfied, then determine the number of nodes in the range set for M_i node.
    5.1.1. Accept $y = 1$, where y is an element of the reachability set $Q_i(y)$.
    5.1.2. Determine whether node $M_i(y)$ is a transit node on route $N_i(y)$.
      (a) If this node is a transit node, then add it to the route. Move on to the next point.
      (b) Otherwise, a loop will appear due to the fact that node m has no reachable nodes to further establish the route. The next transit node cannot be a node that was used in the route before. Let us go to step 5.1.5.
    5.1.3. Determine the probability of choosing path P from the source node n to $M_i(y)$.
    5.1.4. Check whether $M_i(y)$ is a coordinate node.
      (a) If yes, then the comparison of P is assigned to P^* is performed. In the case of $P \succ P^*$, the value of P is assigned to P^*. Thus, route $N_i(y)$ is the best route at the moment. Otherwise, the route is rejected.
      (b) If $M_i(y)$ is not a coordinator node, then this node is added to the route $N_i(y)$.
    5.1.5. Increase the number of reachable nodes as follows: $y = y + 1$.
    5.1.6. Check condition $y \leq S$.
      (a) If it satisfied, go to step 5.1.1.
      (b) Otherwise, increase the number of source nodes as follows: $i = i + 1$, and then go to step 4.
  5.2. If the condition is not satisfied, then take $M = M^*,\ M^* \in \varnothing$.
    5.2.1. If the set M has elements, return to step 3.
    5.2.2. At $M^* \in \varnothing$ the work of the algorithm ends.

Based on the selection probabilities of $N(x_t)$, route x_{new} is chosen. Let us assume that $f(x)$ is the cost of the route x. If $f(x_{new}) \prec f(x_t)$, then route x_{new} is chosen as x_{t+1}. Otherwise, $x_t + 1$ is given according to the following formula:

$$x_{t+1} = \begin{cases} x_{new}, & p_t, \\ x_t, 1 - p_t, \end{cases} \tag{4}$$

where:
p_t—the probability of moving to the worst solution in the t-th iteration.

The construction of the route sequence ends after T iterations. The requirement for the probability function p_t is its positivity at $f(x_{new}) \geq f(x_t)$ (otherwise, the method will stop at the first local minimum).

An example of such a function is:

$$p_t = \frac{exp(f(x_t) - f(x_{new}))}{\theta_t} \tag{5}$$

where sequence θ_t decreases with increasing t. From all constructed routes, the route with the lowest cost is chosen, which is the result of the simulated annealing process.

Consider the developed simulated annealing algorithm to improve the routing of information flows in wireless networks (Figure 3) [28,29], which consists of the following steps.

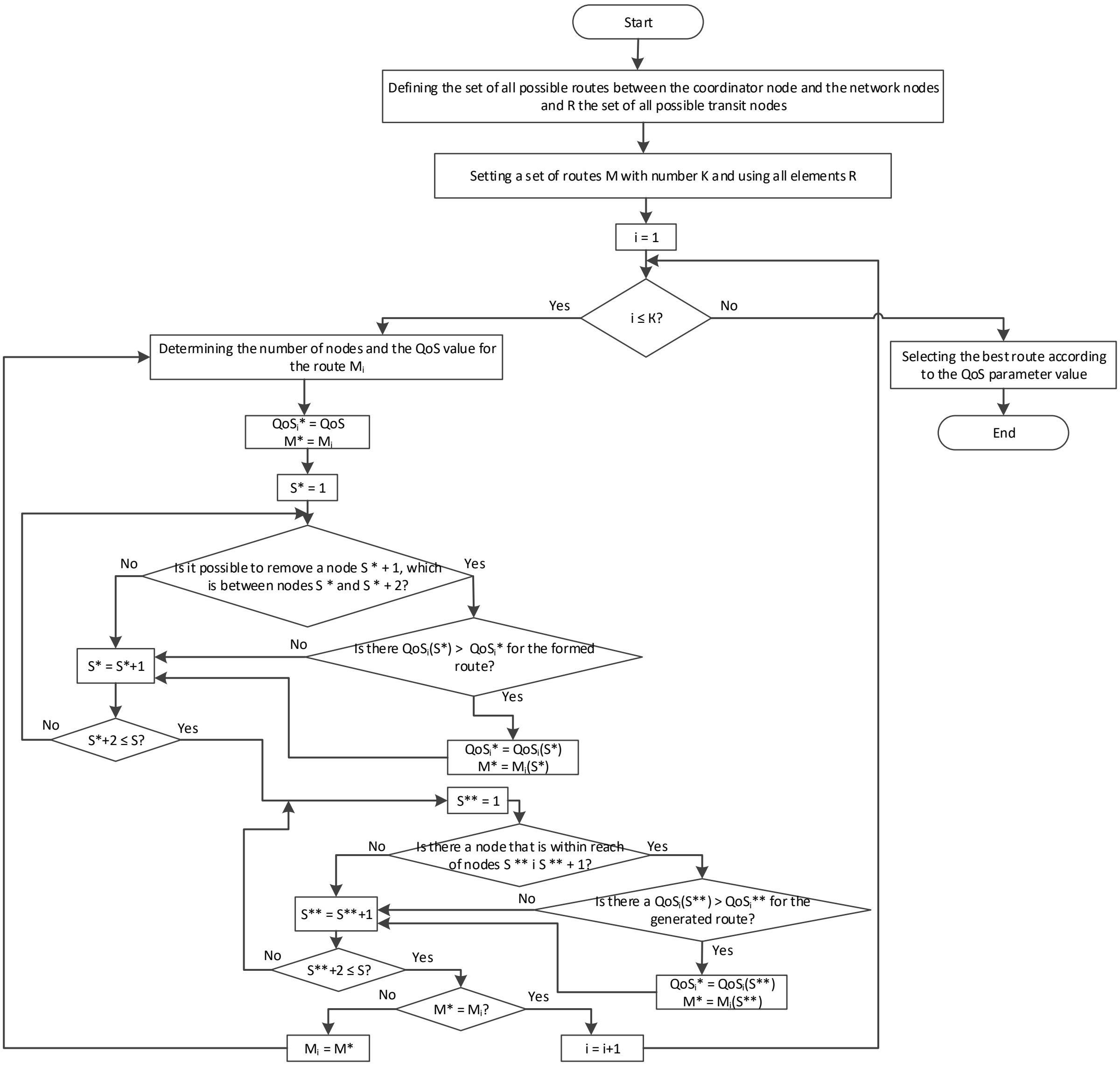


Figure 3. Block diagram of the developed simulated annealing Algorithm 2.

4.3. The Proposed Method for Routing Information Flows Based on a Combination of the Developed Ant and Simulated Annealing Algorithms

In order to select the best route of data transmission according to the time criterion, a method based on a combination of ant and simulated annealing algorithms described above is proposed, which makes it possible to find the global extremum of the function based on an ordered random search and search for a route with the best value of the QoS parameter based on the removal/addition of a node from the route as well as taking into account the inhomogeneities in the network (Figure 4).

At the first stage of the developed method, we set the coordinates of known nodes (source node and destination node) and the range of the node. For each node, we define a set of its reachability, assuming that there is at least one path between the given nodes of the "each to each" type.

Algorithm 2. Simulated annealing algorithm (Figure 3)

1. Define a set of all possible routes between the coordinator node and other nodes in the network, based on which we create a set of transit nodes R between the coordinator node and other nodes.
2. Define M, the set of routes, which contains K routes using all elements of R.
3. Assign $i = 1$, where i is a particular route from the set M.
4. Check the condition $i \leq K$.

4.1. If this condition is satisfied, the number of all nodes S for M_i and the parameter QoS_i for the route M_i are determined.

4.1.1. Assume that $QoS_i^* = QoS_i$, where QoS_i^* is the best value of the parameter of a particular route after the number of iterations by this algorithm, QoS_i is the QoS value for i-th route, and $M^* = M_i$, where M^* is the route with parameter QoS_i^*.

4.1.2. Accept $S^* = 1$, where S^* is the number of nodes from the route M_i to find the possibility of optimizing the route by removing a node.

4.1.3. Check if it is possible to remove a node $S^* + 1$ that is between nodes S^* and $S^* + 2$.

(a) If yes, then check the condition $QoS_i(S^*) \succ QoS_i^*$ for the formed route, where $QoS_i(S^*)$ is the QoS parameter for route $M_i(S^*)$, and $M_i(S^*)$ is the route M_i without node $S^* + 1$.

(a1) If yes, accept that $QoS_i^* = QoS_i(S^*),\ M^* = M_i(S^*)$ and proceed to step 4.1.4.

(a2) If no, go to step 4.1.4.

(b) If no, go to step 4.1.4.

4.1.4. Accept $S^* = S^* + 1$.

4.1.5. Check the condition $S^* + 2 \leq S$.

(a) If not, go to step 4.1.3.

(b) If the equality is fulfilled, then take that $S^{**} = 1$, where S^{**} is the number of nodes from route M_i to find the possibility of optimizing the route by adding a node.

4.1.6. Check whether there exists a node that is in the shared zone of availability for nodes S^{**} and $S^{**} + 1$.

(a) If such a node exists, then check for the formed route condition $QoS_i(S^{**}) \succ QoS_i^{**}$, where $QoS_i(S^{**})$ is the QoS parameter for the route $M_i(S^*)$, and $M_i(S^*)$ is the route M_i with the added node between nodes S^{**} and $S^{**} + 1$:

(a1) If yes, assume that $QoS_i^* = QoS_i(S^{**})$, $M^* = M_i(S^{**})$ and proceed to step 4.1.7.

(a2) If no, proceed to step 4.1.7.

(b) If such a node does not exist, go to step 4.1.7.

4.1.7. Assume $S^{**} = S^{**} + 1$.

4.1.8. Check the condition $S^{**} + 2 \leq S$.

(a) If no, go to step 4.1.6.

(b) If yes, then check the condition $M^* = M_i$.

(b1) If not, accept $M^* = M_i$ and go to step 4.1.

(b2) If yes, accept $i = i + 1$ and go to step 4.

4.2 If this condition is not satisfied, the route with the updated set M is selected (due to the addition/removal of route nodes) with a better QoS parameter value.

Next, we proceed as described in Figure 5 based on modeling the behavior of a colony of ants, which search for a route from the anthill (in our case, the source node) to the food (the destination node) by using pheromones. The best routes in terms of their path length are indicated by the highest number of pheromones. Due to the ants' ability to adapt quickly to new conditions, if a certain route is inaccessible (through network heterogeneity, node failure, etc.), its replacement is quickly found.

After performing the actions according to the proposed ant algorithm, the set n contains sequences of pairs of nodes that form the best routes in terms of data path length. To optimize the routes from the set, the principle of simulated annealing is further used by adding/removing from the routes formed by using the behavior of ants the nodes that are in the common zone of reach of the two nodes that are considered.

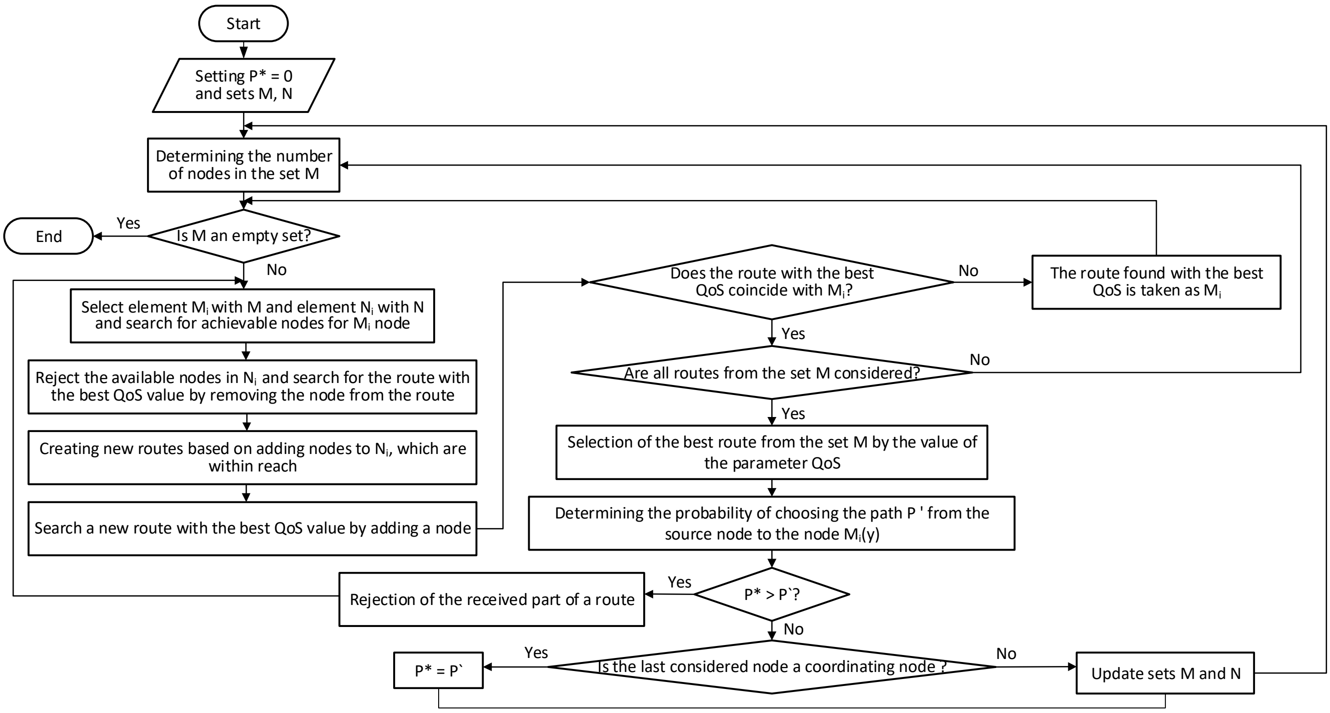


Figure 4. A generalized block diagram of the proposed routing method based on a combination of the developed ant algorithms and simulated annealing.

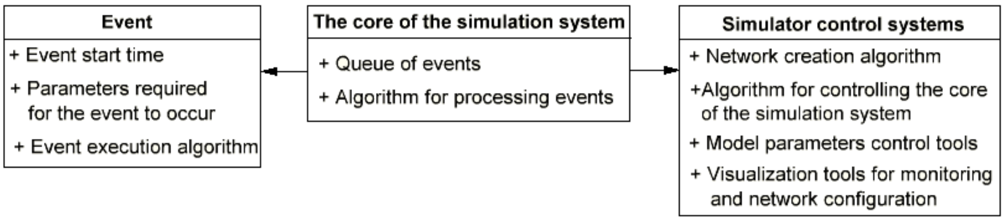


Figure 5. Unified Modeling Language (UML) diagram of the developed simulator.

Thus, consider each node of the route M_i. If a node can be removed, we check whether the value of the QoS parameter for the newly formed route (considered newly formed, since the number of nodes decreases) exceeds the value for the preliminary route (the one in which the node is not removed). If the newly created route shows a better QoS value, we replace the old route with the new one in set N.

A similar principle is used to add nodes to existing routes. Each existing route must be tested for the feasibility of adding/removing nodes in it twice each. The described procedure is carried out until there is only one data route with the best QoS value in the set N or until the given time of the algorithm operation is over.

As the QoS parameter in this paper, we consider the route search time between the nodes of the wireless sensor network but under this concept can also be considered the probability of packet loss, the residual energy of the node, etc. The structure of the algorithm presented in Figure 4 allows the use of any QoS parameter that needs to be used to investigate the quality of service of users in wireless sensor networks. In the future, it will be possible to use multi-criteria metrics, which will be based on several QoS parameters.

5. The Basis for the Operation of the Developed Software Simulator

To research the processes of data transmission in wireless self-organizing networks, we developed a software simulator, the basis of which is the principle of simulation with discrete events. The simulator allows you to study the behavior of self-organizing networks under conditions of high noise levels and to determine the conditions under which the duration of route search and data transfer in the network will be the best.

Logically, the simulator consists of three functional parts, namely the simulation system, the network, and the node (Figure 5).

The simulation system includes abstract events, simulation and event processing kernel, network configuration creation and initialization tools, experimentation scenarios, simulation control tools, and simulation results visualization tools. The network consists of a transmission plane, a control plane, and a monitoring system (Figure 6).

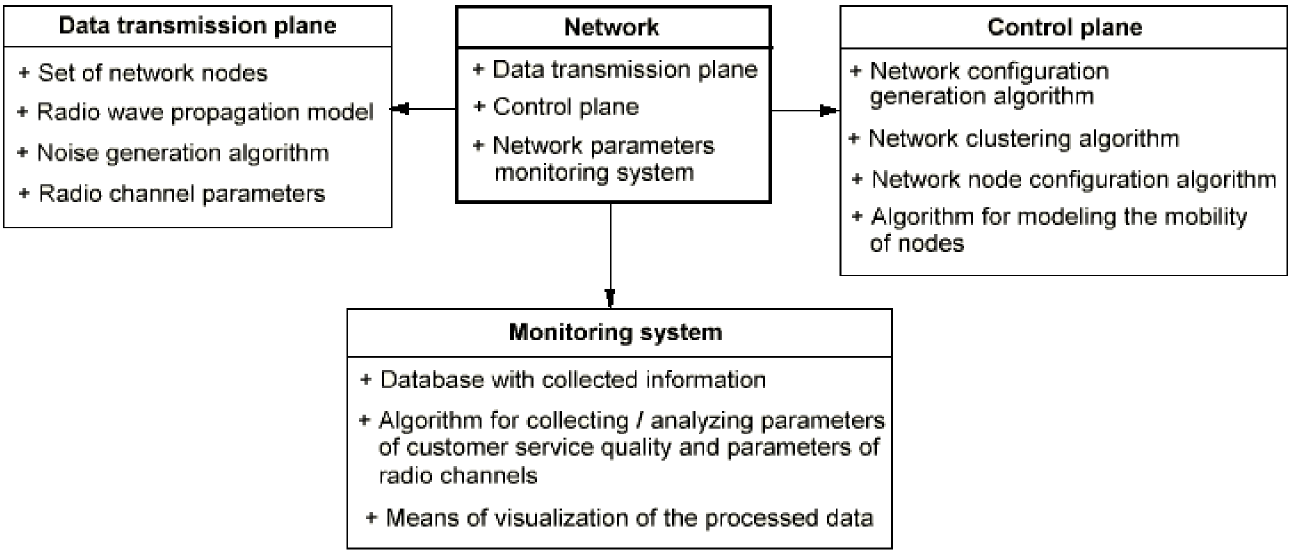


Figure 6. Diagram of network management system operation.

The network data plane aggregates network nodes and contains information about radio channel parameters. The control plane contains algorithms for mobility, configuration, and clustering of network nodes.

A separate part of the network is the monitoring system, which in essence, although it belongs to the control plane, is an independent, dedicated component. The monitoring system uses the network control plane to communicate with all network nodes and to collect the necessary parameters for network operation and data transmission. The main element of the network data plane is a node, which is characterized by its position in space and consists of two main parts—control and data transmission planes (Figure 7).

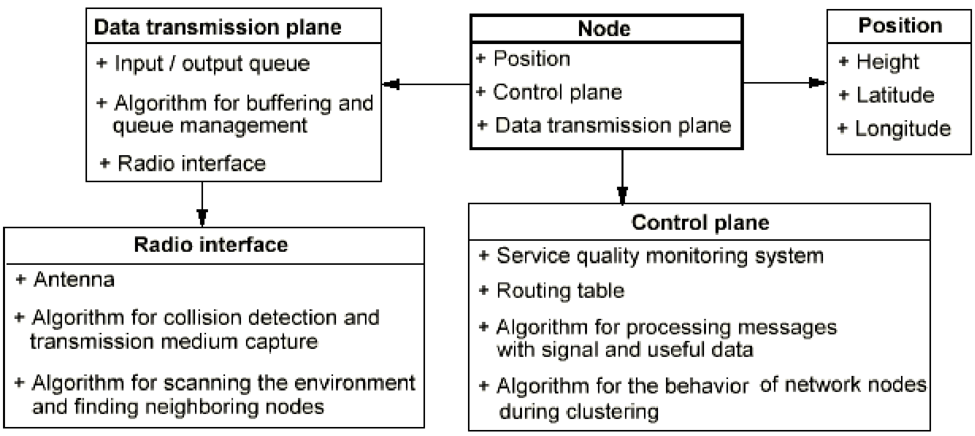


Figure 7. Network node functioning scheme.

It is the control plane that is responsible for the behavior of the node and performs message processing according to data transmission protocols. Any message is transmitted over the radio channel, taking into account its parameters, and can be transmitted with errors in the case of low signal-to-noise ratio. Each node generates messages with useful data.

To send a message to another node in the network, the control system generates a request, transmitted to the data plane, which in turn uses the radio interface to scan the radio channels and identify nodes within range for transmission.

The procedure to find neighboring nodes also takes place at a specified interval, and all found nodes are stored in a special list. For further transmission of a message, the control system makes a call to the transmission plane in which the message is the parameter.

For the data plane, the message type does not matter, and the message processing algorithm is the same. The data plane uses the radio interface to listen to the radio channels. If one of the neighboring nodes detects a transmission on the desired radio channel, the transmission plane waits for a certain time, after which it listens to the radio channel again. If the radio channel is free, the transmission plane starts transmitting a message to the next node.

The transmission plane contains input and output message queues. The output message queue allows the control plane to make a request to send a message and continue performing its own functions. After sending data to another node, the transmission plane selects the next message from the input queue and begins the transmission procedure. This is done until the original queue is empty. Obviously, as the number of neighboring nodes increases, the probability of a message being sent by one of its neighbors increases.

Thus, the probability of collisions and the average waiting time for the node at the moment when the radio channel is free and it is possible to transmit their own message increases. This, first of all, negatively affects the functioning of the network as a whole, since the duration of transmission of signaling messages increases. Thus, the time of convergence of routing protocols and adaptation of the network to the new conditions of the radio channel increases accordingly.

The network monitoring system, mediated by the control system, communicates with all nodes and receives from them the necessary information about the duration of route search, the frequency of collisions, and the state of the radio channels. The control system reads from the nodes every second to collect information in order to obtain timely data to improve the quality of monitoring results.

The simulator’s control system allows the user to configure a large number of simulation parameters, namely: location parameters, number of nodes, radio channel parameters, route search and data transmission protocols, and clustering algorithms. This system also provides visualization of monitoring results and helps to evaluate how this or that network configuration is effective.

The developed model makes it possible to check the adequacy of the proposed solutions, because all the processes that are generated are as close as possible to the operating conditions of the real network. The developed software simulator can be used to improve user service quality parameters at the stages of design and operation of modern wireless networks.

6. The Results of the Research Conducted

6.1. Study of the Effectiveness of the Improved Clustering Algorithm

In order to determine how appropriate the use of the advanced k-means clustering algorithm is for improving the efficiency of the routing process, network modeling was carried out for 20 nodes placed randomly on the plane (Figure 8) for two cases: using the classical k-means clustering algorithm and using its advanced version.

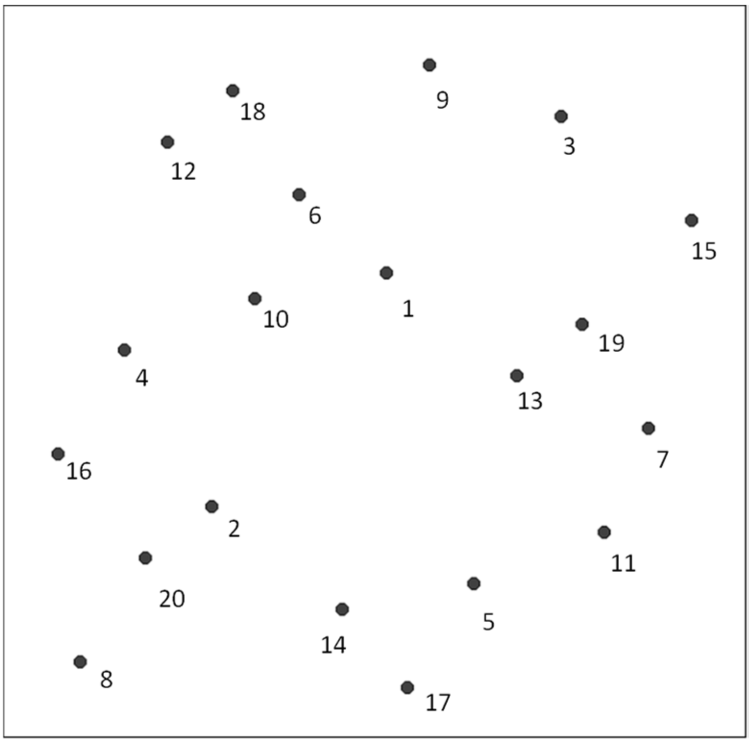


Figure 8. Network topology for research.

The emission power was 20 dBm, and the minimum receiver sensitivity was 65 dBm. Messages were generated for 1000 s, and the size of each message was 500 bytes. Average duration of message processing by one node was 1 s.

Figures 9 and 10 show the network load ingress rate and the volume of messages transmitted for a network of 20 nodes, respectively.

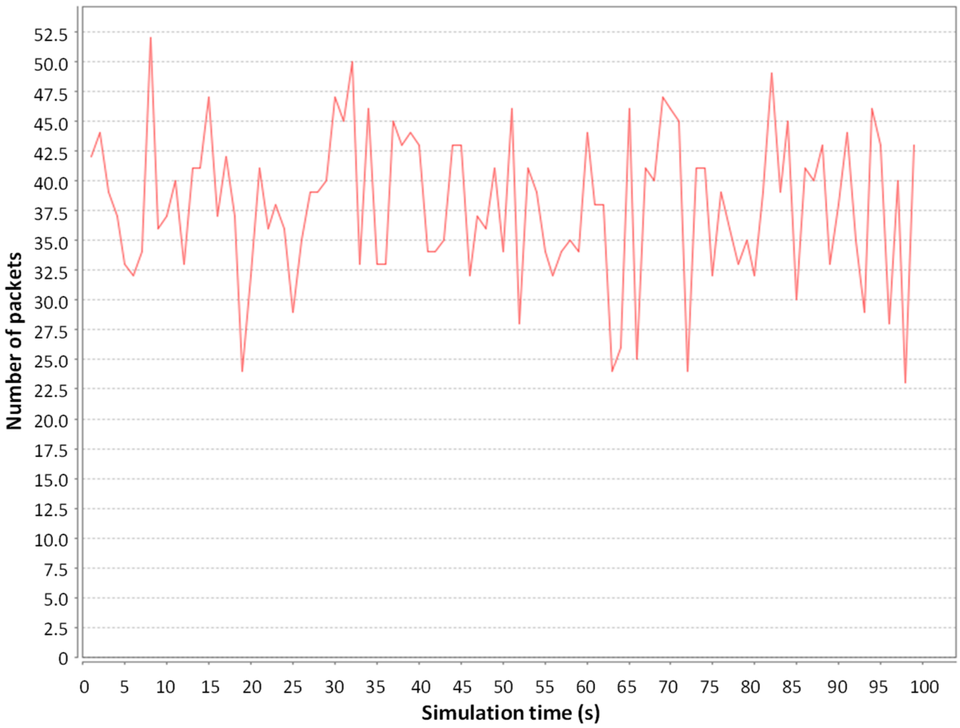


Figure 9. Intensity of the incoming load.

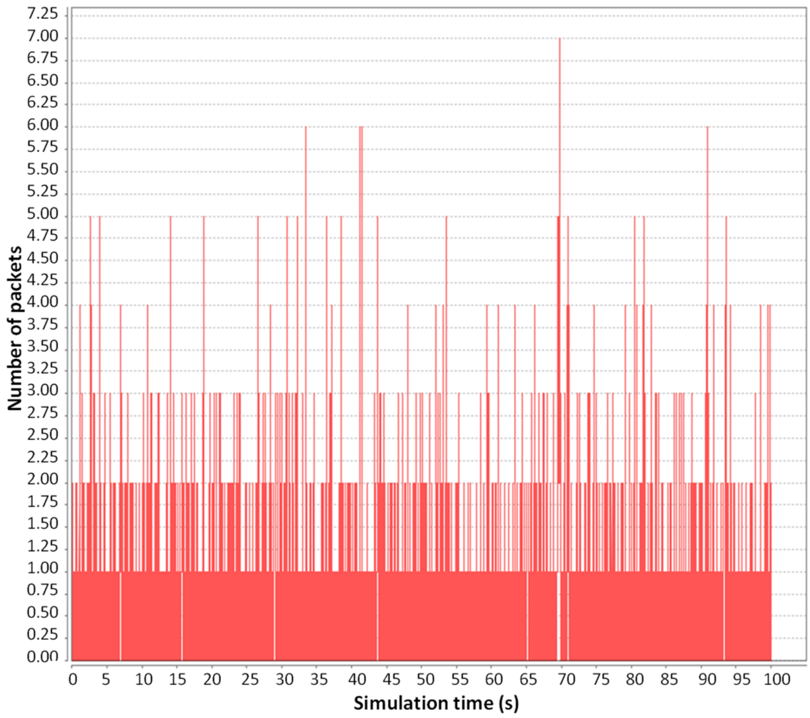


Figure 10. Volume of transmitted messages.

The advantage of the developed model is the ability to evaluate the signal-to-noise ratio between each pair of nodes and to average its value across the network (Figure 11). Figure 11 shows that the average SNR at the first node was 17 dBm and at the 19th node was 16 dBm.

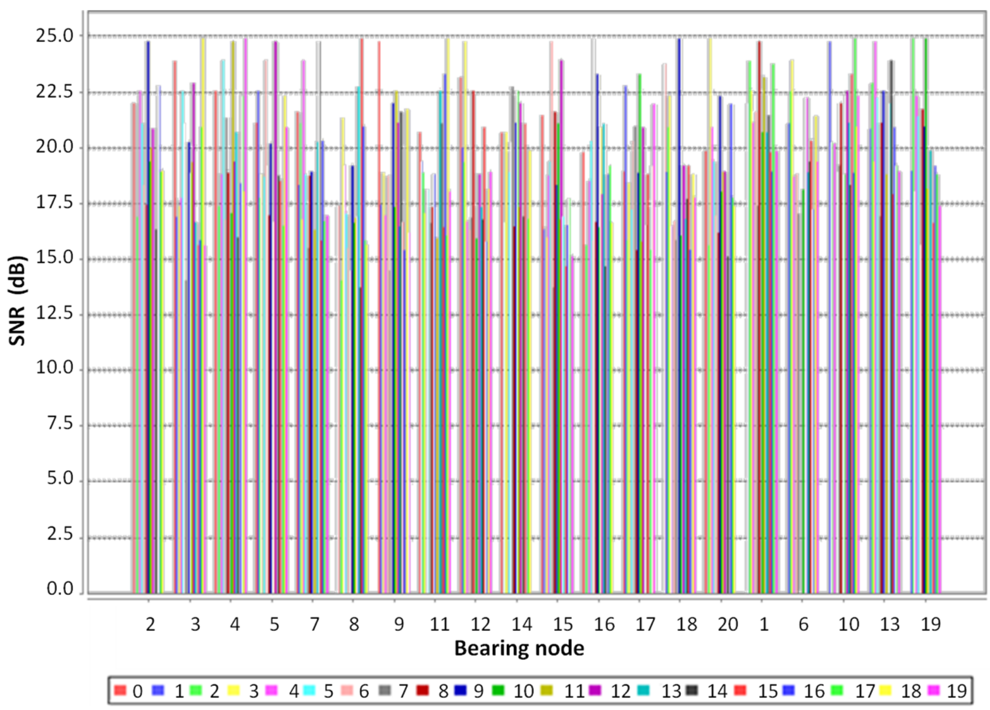


Figure 11. Average signal-to-noise ratio (SNR) estimation for the network of 20 nodes.

Figure 12 gives an estimate of the average SNR for some of the network nodes considered.

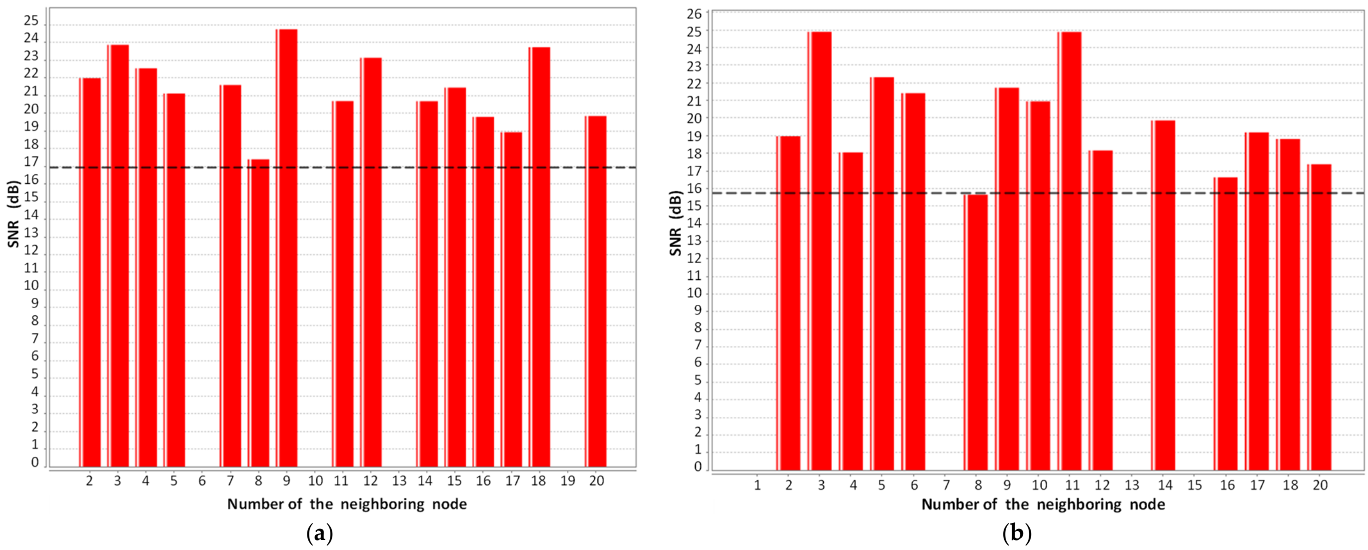
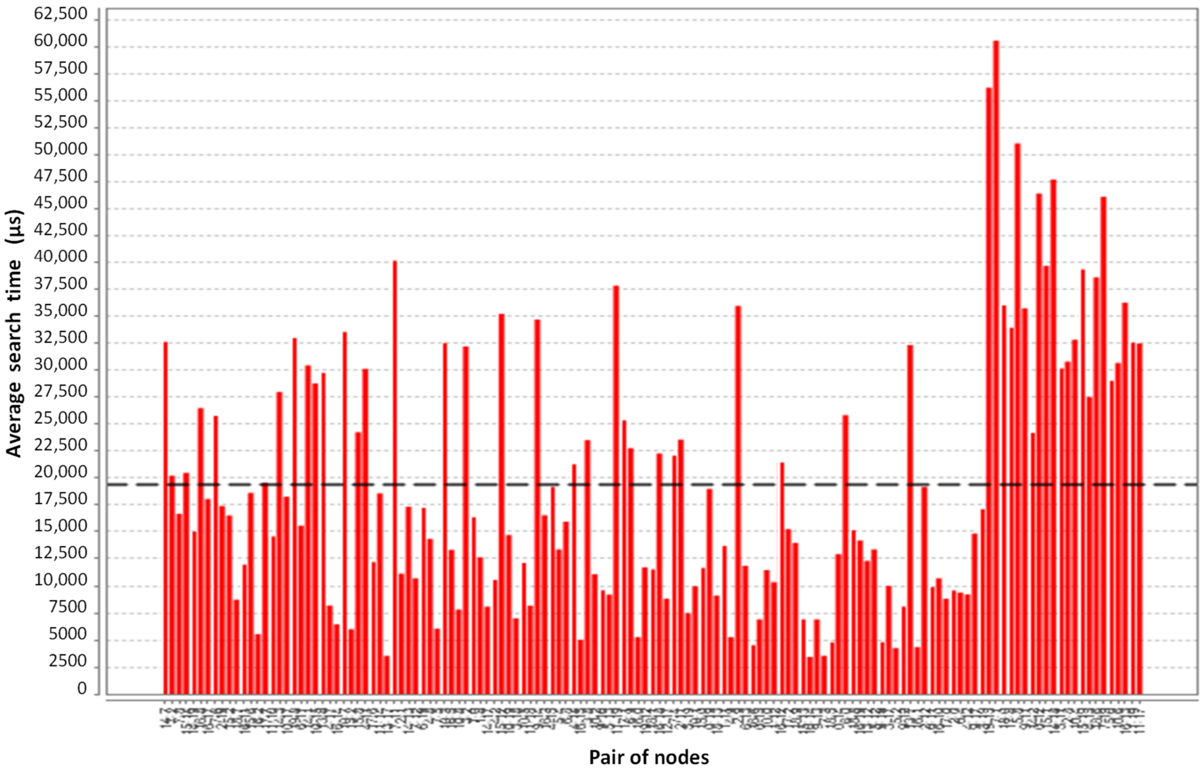


Figure 12. Estimation of the average SNR: (**a**) from node 1; (**b**) from node 19 to the other nodes of the considered network.

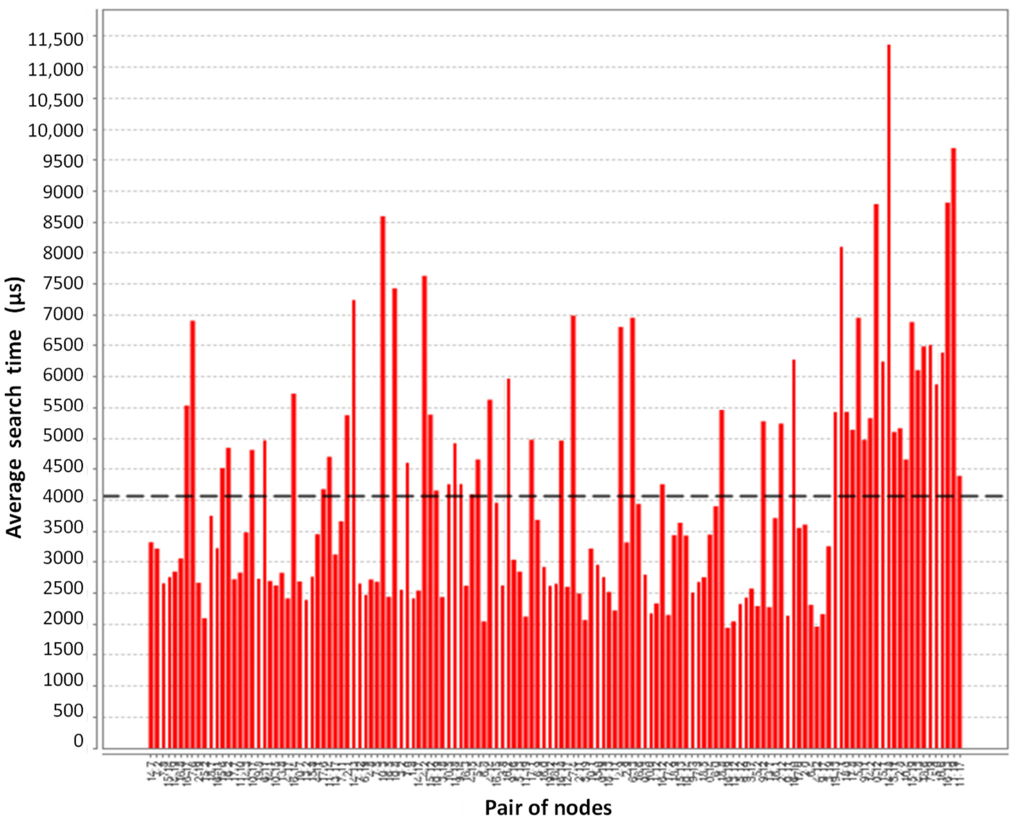
According to the results presented, the nearest node in terms of power to node 1 was node 9, whereas for node 19, it was nodes 3 and 11.

Next, we evaluated the duration of the route search in the network using the k-means clustering algorithm and its improved version (Figure 13). To accurately assess the feasibility of using the improved clustering algorithm, Figure 13 shows all possible pairs of nodes on the x-axis according to the network topology shown in Figure 8, which determined the density of these pairs on the graph and therefore their size.



(**a**)

Figure 13. *Cont.*



(**b**)

Figure 13. Estimation of the route search duration in the network using the k-means clustering algorithm (**a**) and its improved version (**b**).

Evaluation of the route search duration in the network with the k-means clustering algorithm between an arbitrary pair of nodes showed that the average route search time took about 18.5 ms (Figure 13a).

After using the improved clustering algorithm in the simulator, four clusters were formed in the network according to the minimum values of the Euclidean metric and the maximum value of the average SNR criterion. Evaluation of the route search duration in the network (between an randomly taken pair of nodes) using the improved clustering algorithm showed that the average route search time decreased to four times and was 4100 µs (Figure 13b).

Considering the case when the network operated from 4 to 18 nodes within four clusters, Figure 14 shows an estimate of the duration of route search depending on the number of nodes with the standard k-means clustering algorithm.

Figure 14 shows that the larger the number of nodes in the network was, the longer it took to find the shortest route between a randomly taken pair of nodes. In particular, when there were four nodes in the network, the duration of the search for the shortest route between an arbitrarily taken pair of nodes could last up to 7.5 s, while for 17 nodes, the search could take up to 45 s.

This was due to the irregularity of the requests to the network nodes, the low ecfficiency of the use of communication channels resources, and the high level of bit errors.

Figure 15 demonstrates the estimation of the route search duration in the functioning of 18 network nodes when implementing the improved k-means clustering algorithm.

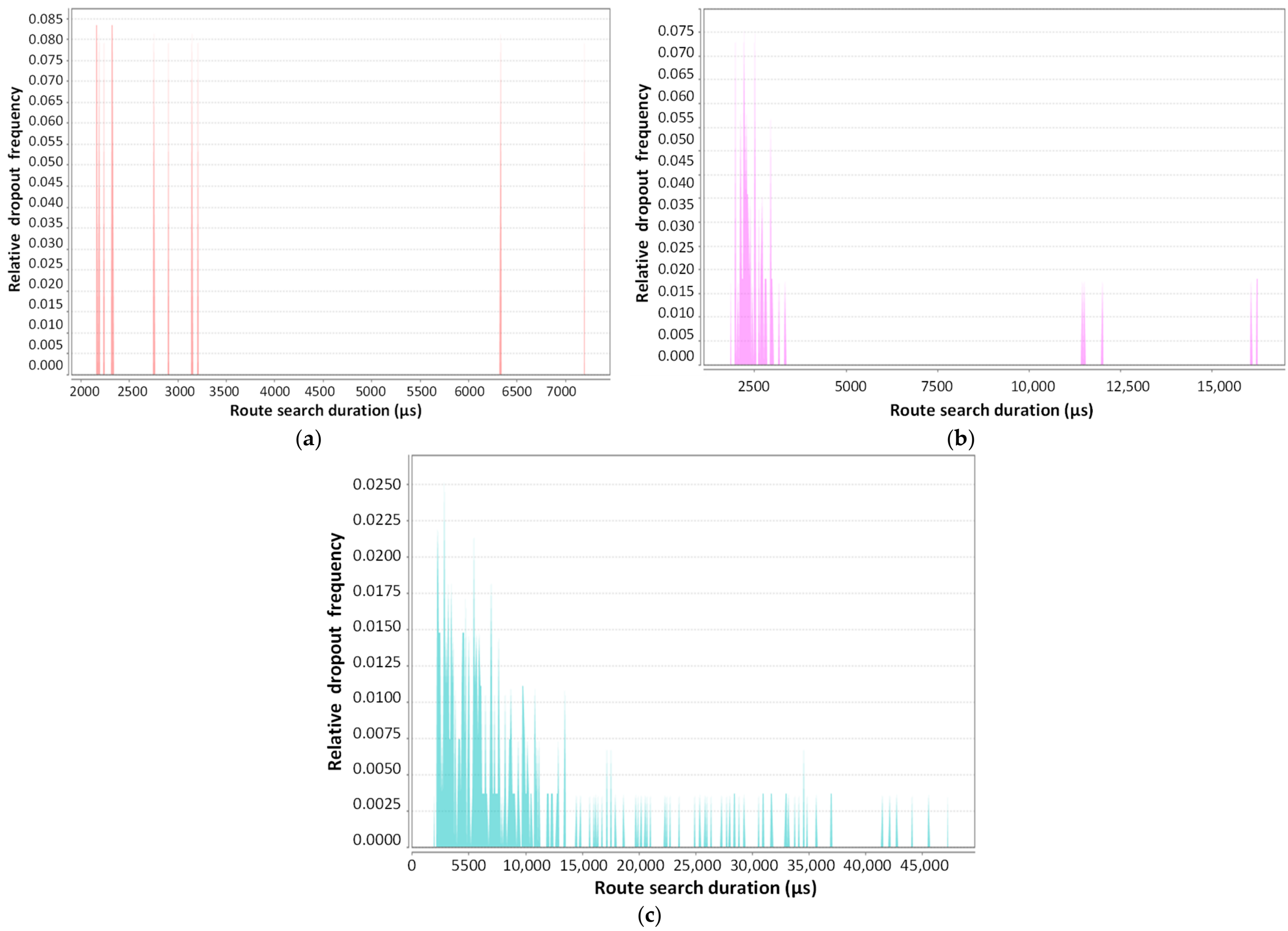


Figure 14. Estimation of the route search duration for (**a**) 4 nodes (**b**) 8 nodes (**c**) 18 nodes of the network using the standard k-means clustering algorithm.

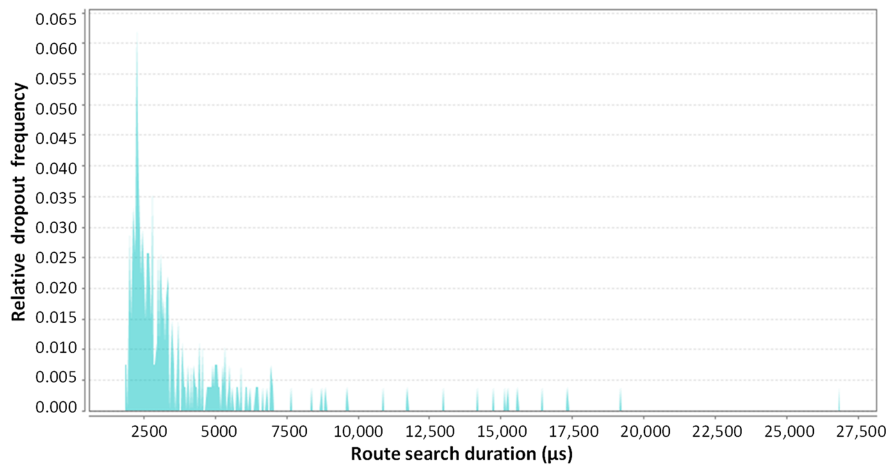


Figure 15. Estimation of the route search duration in the functioning of 18 nodes in the implementation of an improved clustering algorithm.

Based on the results of Figures 14 and 15, we see that the implementation of an improved clustering algorithm could reduce the duration of the search route; in particular, with 18 nodes in operation, the delay for data transmission was reduced to 27.5 s, that is, 1.6 times.

6.2. Research on the Effect of Interference on the Efficiency of Routing Information Flows

Modern wireless routing protocols must provide not only high-speed data transfer but also quality delivery of voice and video information in the presence of electromagnetic interference. By quality is meant the achievement of certain performance indicators and reliability when transmitting information over a wireless network. The latest versions of wireless standards introduced a number of mechanisms to support quality of service. Given the high utilization of radio frequency resource, currently, SNR is one of the main criteria for the quality of wireless network operation [30,31]. Bit error ratio (BER) has an important role in the process of information transfer, which allows you to assess the quality and the efficiency of transmission and the processing of requests. Evaluation of the duration of data transmission from the source node to the destination node and finding the shortest route in the wireless self-organizing network depend on the probability of packet error due to interference in the radio channel (Figure 16).

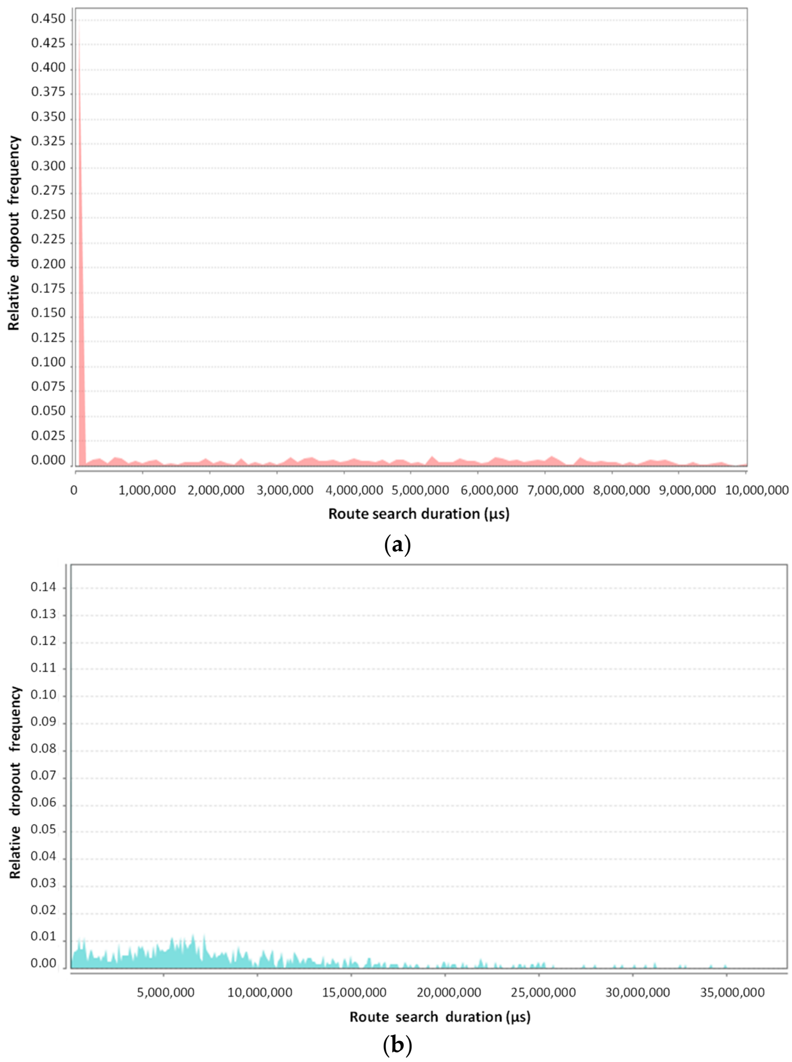


Figure 16. The duration of route search with different values of SNR: (**a**) 90 dBm; (**b**) 77 dBm.

According to the presented results in Figure 16, the route search duration increased as the noise level increased.

Next, we investigated the efficiency of the routing process when using the classical greedy routing algorithm and the improved k-means clustering algorithm at SNR values from −90 to −75 dBm. The studies were conducted on the developed software simulator.

With 30 nodes functioning, the network after using the improved k-means clustering algorithm was divided into six clusters, which are shown in Figure 17.

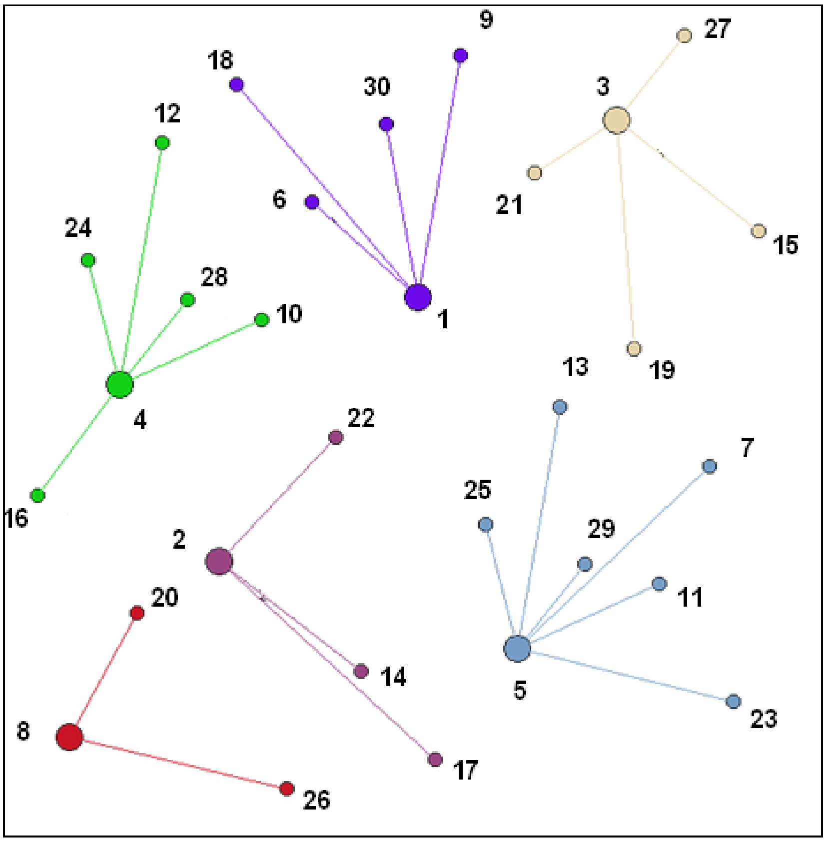
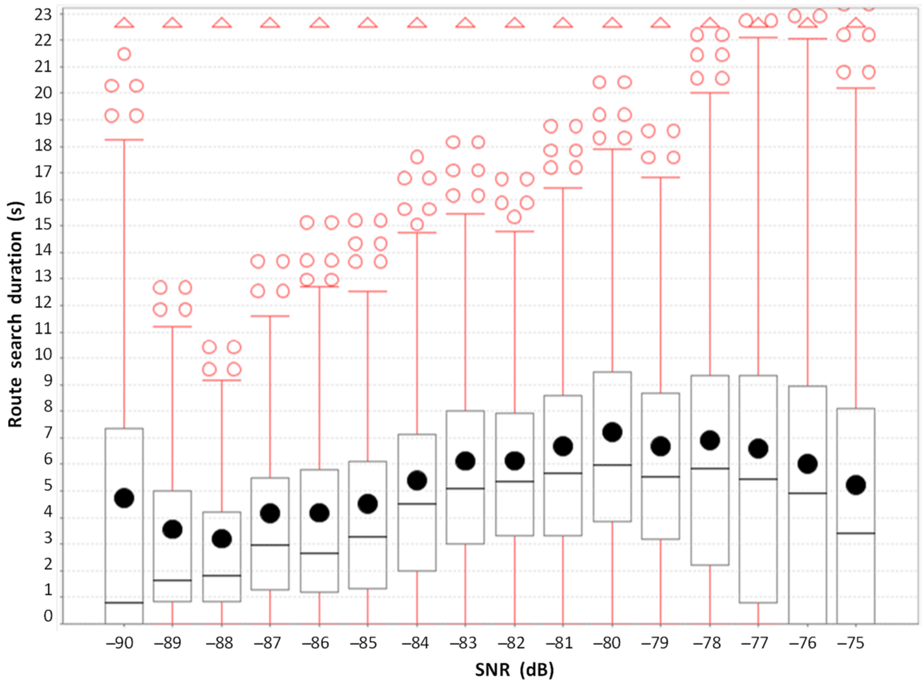


Figure 17. Clusters of a 30 node network formed after using the improved k-means clustering algorithm.

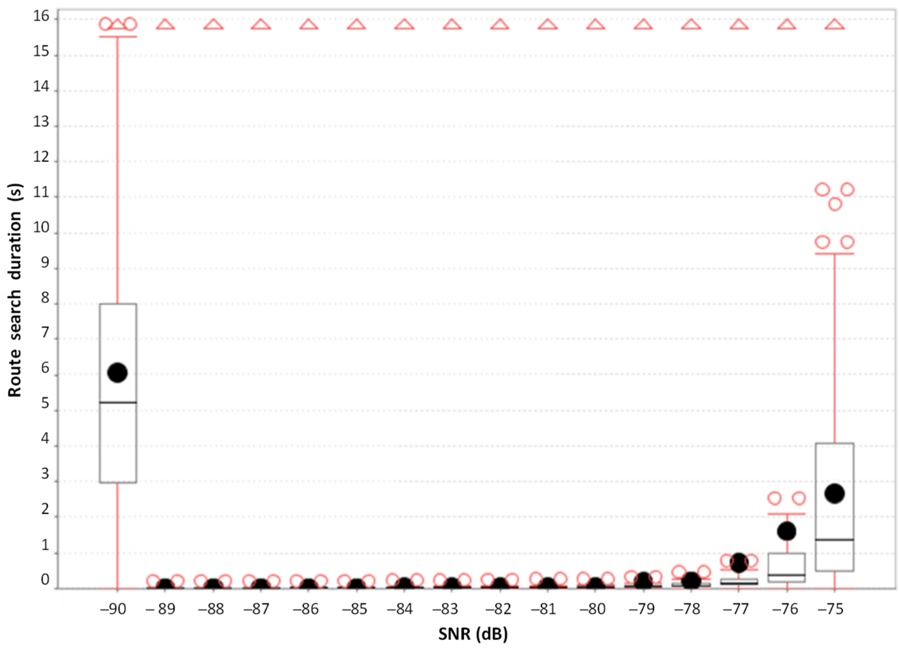
Figure 18a shows a graph of the dependence of the route search duration in the wireless self-organizing network on the radio channel parameters (triangles denote the threshold value, the circles denote the number of transit nodes) using the classical greedy routing algorithm, the mathematical apparatus of which is well known [31], and the improved clustering algorithm. The proposed routing method was compared to greedy routing to evaluate its effectiveness, since it is one of the simplest types of routing based on the Euclidean distance to the destination. The research was also conducted for the same network with 30 nodes using the developed routing method based on natural mechanisms, i.e., the behavior of an ant colony and simulation of the physical annealing process and the improved k-means clustering algorithm, the results of which are shown in Figure 18b.

As we see, according to the results of the study presented in Figure 18, with increasing noise level, the duration of route search increased. In addition, the use of the developed routing method in combination with the improved k-means clustering algorithm allowed us to reduce the route search duration twice on average, which indicates the feasibility of using the proposed solutions to improve the routing efficiency of information flows in wireless self-organizing networks.

Thus, the proposed method of routing information flows based on a combination of principles of natural mechanisms can be used in wireless networks to reduce the data transfer delay between the source node and the destination node, which will improve the quality of service for end users.



(**a**)



(**b**)

Figure 18. Dependence of the route search duration in a wireless self-organizing network on the radio channel parameters: (**a**) using the classical greedy routing algorithm; (**b**) proposed solution.

7. Conclusions

The processes of signal propagation over the radio channel and the value of the signal-to-noise power ratio in wireless sensor networks have a significant impact on the routing of data; in particular, they can lead to data loss. In this regard, this work proposed improvement of the well-known algorithm k-means by taking into account the Motley signal propagation model in it, resulting in the formation of a cluster, and, accordingly, finding its centroid, which occurs until the moment when it finds all the closest nodes in the distance with the maximum value of the signal strength, which reduces the likelihood of loss of data transmitted in wireless sensor networks.

A characteristic feature of wireless self-organizing networks is dynamically variable topology, which is formed on the basis of autonomous nodes. In this regard, to determine the best information transmission route, especially when there are several such routes, a method for routing information flows based on natural decision-making mechanisms was developed, namely the behavior of an ant colony and the simulation of the physical annealing process. The essence of these processes is to create a set of best routes, the use of which allows you to find the global extremum of some function based on an ordered random search and search for an optimized route with the best value of the parameter QoS by removing/adding node from the route as well as taking into account the heterogeneity in the network.

To research data transmission processes in wireless self-organizing networks, a software simulator was developed, the basis of which is the principle of simulation modeling with discrete events. The simulator allows you to study the behavior of self-organizing networks under conditions of high noise levels and determine the conditions under which the duration of route search and data transfer in the network will be the best.

To verify the effectiveness of the improved clustering algorithm, we conducted a study by using a software simulator, based on the results of which it is shown that its use can reduce the average route search time by up to four times compared to the standard k-means algorithm.

To improve the efficiency of routing information flows in conditions of instability of the noise level in the radio channel, we considered the use of the advanced clustering algorithm k-means and developed the routing method. We showed that their combined use can reduce the average route search time up to two times, which demonstrates the feasibility of their use in wireless self-organizing networks.

In the future, research is planned to focus on assessing the routing of information flows in self-organizing networks based on such QoS parameters as the probability of packet loss and residual node energy.

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References

1. Xu, H.; Przystupa, K.; Fang, C.; Marciniak, A.; Kochan, O.; Beshley, M. A Combination Strategy of Feature Selection Based on an Integrated Optimization Algorithm and Weighted K-Nearest Neighbor to Improve the Performance of Network Intrusion Detection. *Electronics* **2020**, *9*, 1206. [CrossRef]
2. Song, W.; Beshley, M.; Przystupa, K.; Beshley, H.; Kochan, O.; Pryslupskyi, A.; Pieniak, D.; Su, J. A Software Deep Packet Inspection System for Network Traffic Analysis and Anomaly Detection. *Sensors* **2020**, *20*, 1637. [CrossRef] [PubMed]
3. Fang, M.-T.; Przystupa, K.; Chen, Z.-J.; Li, T.; Majka, M.; Kochan, O. Examination of Abnormal Behavior Detection Based on Improved YOLOv3. *Electronics* **2021**, *10*, 197. [CrossRef]

4. Jun, S.; Przystupa, K.; Beshley, M.; Kochan, O.; Beshley, H.; Klymash, M.; Wang, J.; Pieniak, D. A Cost-Efficient Software Based Router and Traffic Generator for Simulation and Testing of IP Network. *Electronics* **2019**, *9*, 40. [CrossRef]
5. Tang, L.; Lu, Z.; Cai, J.; Yan, J. An Equilibrium Strategy-Based Routing Optimization Algorithm for Wireless Sensor Networks. *Sensors* **2018**, *18*, 3477. [CrossRef] [PubMed]
6. Del-Valle-Soto, C.; Mex-Perera, C.; Nolazco-Flores, J.A.; Velázquez, R.; Rossa-Sierra, A. Wireless Sensor Network Energy Model and Its Use in the Optimization of Routing Protocols. *Electronics* **2020**, *13*, 728. [CrossRef]
7. Zhang, T.; Chen, G.; Zeng, Q.; Song, G.; Li, C.; Duan, H. Routing Clustering Protocol for 3D Wireless Sensor Networks Based on Fragile Collection Ant Colony Algorithm. *IEEE Access* **2020**, *8*, 58874–58888. [CrossRef]
8. Tsado, Y.; Gamage, K.A.A.; Adebisi, B.; Lund, D.; Rabie, K.M.; Ikpehai, A. Improving the Reliability of Optimised Link State Routing in a Smart Grid Neighbour Area Network based Wireless Mesh Network Using Multiple Metrics. *Energies* **2017**, *10*, 287. [CrossRef]
9. Durairaj, U.M.; Selvaraj, S. Two-Level Clustering and Routing Algorithms to Prolong the Lifetime of Wind Farm-Based WSN. *IEEE Sens. J.* **2021**, *21*, 857–867. [CrossRef]
10. Xiao, X.; Huang, H. A Clustering Routing Algorithm Based on Improved Ant Colony Optimization Algorithms for Underwater Wireless Sensor Networks. *Algorithms* **2020**, *13*, 250. [CrossRef]
11. Ajeil, F.H.; Ibraheem, I.K.; Azar, A.T.; Humaidi, A.J. Grid-Based Mobile Robot Path Planning Using Aging-Based Ant Colony Optimization Algorithm in Static and Dynamic Environments. *Sensors* **2020**, *20*, 1880. [CrossRef] [PubMed]
12. Li, X.; Keegan, B.; Mtenzi, F. Energy Efficient Hybrid Routing Protocol Based on the Artificial Fish Swarm Algorithm and Ant Colony Optimisation for WSNs. *Sensors* **2018**, *18*, 3351. [CrossRef] [PubMed]
13. Sinde, R.; Begum, F.; Njau, K.; Kaijage, S. Refining Network Lifetime of Wireless Sensor Network Using Energy-Efficient Clustering and DRL-Based Sleep Scheduling. *Sensors* **2020**, *20*, 1540. [CrossRef] [PubMed]
14. Kim, J.-Y.; Sharma, T.; Kumar, B.; Tomar, G.S.; Berry, K.; Lee, W.-H. Intercluster Ant Colony Optimization Algorithm for Wireless Sensor Network in Dense Environment. *Int. J. Distrib. Sens. Netw.* **2014**, *10*, 457402. [CrossRef]
15. Saha, B.K.; Misra, S.; Pal, S. SeeR: Simulated Annealing-Based Routing in Opportunistic Mobile Networks. *IEEE Trans. Mob. Comput.* **2017**, *16*, 2876–2888. [CrossRef]
16. lhan, İ. A Population Based Simulated Annealing Algorithm for Capacitated Vehiclerouting Problem. *Turk. J. Electr. Eng. Comput. Sci.* **2020**, *28*, 1217–1235.
17. Redi, A.A.N.P.; Jewpanya, P.; Kurniawan, A.C.; Persada, S.F.; Nadlifatin, R.; Dewi, O.A.C. A Simulated Annealing Algorithm for Solving Two-Echelon Vehicle Routing Problem with Locker Facilities. *Algorithms* **2020**, *13*, 218. [CrossRef]
18. He, W. Energy-Saving Algorithm and Simulation of Wireless Sensor Networks Based on Clustering Routing Protocol. *IEEE Access* **2019**, *7*, 172505–172514. [CrossRef]
19. Wei, Z.; Liu, F.; Ding, X.; Feng, L.; Lyu, Z.; Shi, L. K-CHRA: A Clustering Hierarchical Routing Algorithm for Wireless Rechargeable Sensor Networks. *IEEE Access* **2019**, *7*, 81859–81874. [CrossRef]
20. Shin, C.; Lee, M. Swarm-Intelligence-Centric Routing Algorithm for Wireless Sensor Networks. *Sensors* **2020**, *20*, 5164. [CrossRef]
21. Chu, K.-C.; Horng, D.-J.; Chang, K.-C. Numerical Optimization of the Energy Consumption for Wireless Sensor Networks Based on an Improved Ant Colony Algorithm. *IEEE Access* **2019**, *7*, 105562–105571. [CrossRef]
22. Nepal, B.; Yamaha, M.; Sahashi, H.; Yokoe, A. Analysis of Building Electricity Use Pattern Using K-Means Clustering Algorithm by Determination of Better Initial Centroids and Number of Clusters. *Energies* **2019**, *12*, 2451. [CrossRef]
23. Motley, A. Indoor Propagation Models, COST Action 231: Digital Mobile Radio Towards Future Generation Systems: Final Report Eur 18957. European Commision EC: Luxemburg, 1999; pp. 175–179.
24. Klymash, Y.; Shpur, O.; Strykhaliuk, I. Investigating Ant Colony Optimization Algorithm for Increasing Routing Efficiency in Self-Organized Networks. In Proceedings of the 2018 International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo), Odessa, Ukraine, 10–14 September 2018; pp. 1–4.
25. Klymash, M.; Pyrih, Y.; Kaidan, M.; Andrushchak, V. A Meta-Heuristic Data Routing Algorithm for Networks with Dynam-ically Variable Structure. In Proceedings of the 2019 IEEE 20th International Conference on Computational Problems of Electrical Engineering (CPEE), Lviv-Slavske, Ukraine, 15–18 September 2019; pp. 1–4.
26. Du, K.-L.; Swamy, M.N.S. Simulated Annealing. In *Search and Optimization by Metaheuristics*; J.B. Metzler: Stuttgard, Germany, 2016; pp. 29–36.
27. Klymash, M.; Pyrih, Y.; Kaidan, M. A Modified Genetic Algorithm for Increasing the Efficiency of Routing in Self-Organized Networks. In Proceedings of the 2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T), Kyiv, Ukraine, 8–11 October 2019; pp. 447–450.
28. Pyrih, Y.; Kaidan, M.; Strykhalyuk, B.; Zhebka, V. A Modified Simulated Annealing Algorithm Based on Principle of the Greedy Algorithm for Networks with Mobile Nodes. In Proceedings of the 2020 IEEE 15th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET), Lviv-Slavske, Ukraine, 25–29 February 2020; pp. 482–485.
29. Hajlaoui, R.; Guyennet, H.; Moulahi, T. A Survey on Heuristic-Based Routing Methods in Vehicular Ad-Hoc Network: Tech-nical Challenges and Future Trends. *IEEE Sens. J.* **2016**, *16*, 6782–6792. [CrossRef]

30. Beshley, M.; Kryvinska, N.; Seliuchenko, M.; Beshley, H.; Shakshuki, E.M.; Yasar, A.-U.-H. End-to-End QoS "Smart Queue" Management Algorithms and Traffic Prioritization Mechanisms for Narrow-Band Internet of Things Services in 4G/5G Networks. *Sensors* **2020**, *20*, 2324. [CrossRef] [PubMed]
31. Samarasinghe, K.; Wehbe, R.A.; Leone, P. Greedy Zone Routing: Robust and Scalable Routing in Wireless Ad-hoc Networks. In Proceedings of the 2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA), Cranz-Montana, Switzerland, 23–25 March 2016; pp. 557–564.