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HEURISTIC ALGORITHMS FOR FINDING THE MINIMUM STEINER TREE IN THE PROBLEM OF OPTIMIZING THE DEPLOYMENT AND MOTION CONTROL OF SEVERAL FLYING INFORMATION AND TELECOMMUNICATION ROBOTS

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Background. The article explores the problem of combining the motion control of existing FITRs and the deployment of new FITRs so that the number of new FITRs deployed to support the communication of terrestrial subscribers can be minimized. This problem is formulated as the Steiner Minimum Tree Problem (SMT) with existing mobile Steiner points with a constraint on the edges length of the network graph.

Objective. Improve the mathematical model for ensuring the connectivity of episodic radio networks using FITRs and improve the algorithms for providing the connectivity of episodic radio networks using FITRs.

Methods. The two algorithms (deploying new FITRs before moving existing FITRs, and moving existing FITRs before deployment of new FITRs) separate the problem and solve the deployment problem, the movement one after the other. In contrast, the algorithm for deploying new FITRs while moving existing FITRs optimizes the deployment problem and the control of movement across and solves these two problems simultaneously.

Results. A proposed method includes three heuristic algorithms for placing new FITRs, taking into account the movement of existing FITRs (that is, considering scenarios for moving existing FITRs: deploying new FITRs before, after, or during the movement of existing FITRs) for the SMT problem with existing mobile Steiner points with a constraint on the edges length of the network graph.

Conclusions. Evaluation of the effectiveness of the proposed algorithms in various scenarios shows that algorithms taking into account the movement of existing FITRs are always more efficient (in terms of the number of newly added FITRs) than an algorithm without taking into account the movement of existing FITRs.

Keywords: *flying information and telecommunication robots; mobile episodic radio network; algorithm; topology; location.*

Introduction

The movement of terrestrial mobile subscribers leads to a rapid and unpredictable change in the topology of episodic radio networks, which can lead to disruption of network connectivity and loss of communication be-tween some subscribers. Increasing the connectivity of such networks is possible by introducing new additional air-based nodes (FITRs), which have a large radio coverage area and unite disconnected sections of the network. However, to date, the problem of optimal control of the position of such FITRs has not been sufficiently solved, namely, the problem of combining the traffic control of existing FITRs and the deployment of new FITRs so that the number of newly deployed FITRs to maintain communication with terrestrial subscribers can be minimized.

The works of Lysenko O.I., Romaniuk V.A., Chumachenko S.M., and Valuiskyi S.V. are devoted to theoretical and practical research on methods for increasing the throughput of episodic radio networks with position control of telecommunication air platforms [1-3]. In [4], the authors also explore the problem of increasing the connectivity of mobile episodic radio networks by placing new and moving existing FITRs. Still, the mathematical model does not consider the air-to-air communication range, which will be considered in this work.

The task is to improve the mathematical model for ensuring the connectivity of episodic radio networks using FITRs and improve the algorithms for providing the connectivity of episodic radio networks using FITRs.

Practical Value of FITRs

FITRs have several unique characteristics suitable for providing packet relay in mobile episodic radio networks.

First, the flexibility of FITRs movement can expand the scope of terrestrial network application, especially in obstacle scenarios.

Second, FITRs can communicate with ground nodes in line of sight, improving bandwidth connectivity between ground nodes.

Last but not least, FITRs are integrated with communication system, computing system and control system of various sensors; they can explore the environment and adaptively control their movement. The adaptability of FITRs makes them suitable for providing relay services for mobile episodic radio networks with a dynamic network topology.

Problem of deploying new FITRs

In the existing works, when deploying FITRs, the situation that some FITRs have already been deployed in the field is not considered. The movement of terrestrial mobile subscribers of episodic radio networks may lead to the fact that existing FITRs do not provide connectivity to all terrestrial nodes. Therefore, it is necessary to bring out new FITRs to support the communication of terrestrial subscribers. But to minimize the number of new FITRs added, it is essential to consider both the movement of existing FITRs and the deployment of new FITRs. This is a joint optimization problem that optimizes both the deployment and motion control of multiple FITRs.

Let's consider using existing FITRs by moving them to appropriate positions to reduce the amount of new FITRs needed. Existing FITRs have a limited movement range, depending on the speed of the FITRs and the charge of the battery. To maintain bi-directional communication between FITRs and ground nodes, we assume that FITRs have the same communication range as ground nodes. Fig. 1 shows an example of how the movement control of existing FITRs can reduce the number of new FITRs needed. Assume two ground nodes and two existing FITRs are deployed in the field. Since the distance between two terrestrial nodes is more significant than their communication range r, the terrestrial mobile episodic radio network is divided into two parts, as shown in Fig. 1 (a).

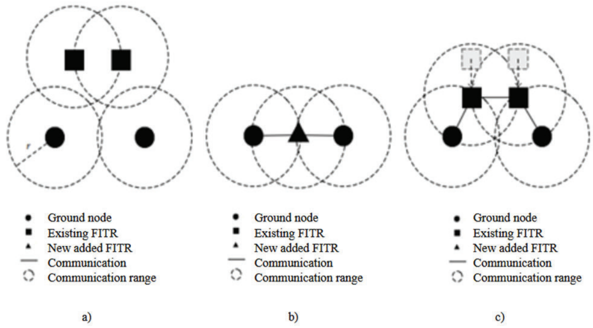

Fig. 1 - An example illustrates the importance of existing FITRs in maintaining the communication of land mobile episodic radio networks

To support the communication of terrestrial subscribers of mobile episodic radio networks, existing methods that do not take into account existing FITRs will add new FITRs to connect the separated parts, as shown in Fig. 1. (b). Here new FITR is added and deployed inside two ground nodes. Therefore, these two ground nodes can now communicate using the new FITR. If we are not considering existing FITRs, at least one additional FITR needs to be deployed to keep ground FITRs connected.

Reducing the number of new FITRs added is advisable to reduce capital costs. In other words, using existing FITRs instead of ignoring them and moving existing FITRs to an appropriate location, and using existing FITRs as repeaters can improve the connectivity of terrestrial FITRs. Fig. 1 (c) shows the movement of two existing FITRs directly to a link consisting of two ground nodes until the distance between the existing FITRs and one ground node is less than the communication range r. A connection is then established between the two ground nodes. In this way, communication of terrestrial subscribers is maintained, and the deployment of new FITRs is not required.

This article addresses the problem of optimizing the deployment and movement control of multiple FITRs according to the criterion of minimizing the number of newly added FITRs that form a connected net-work. Initially, this problem is formulated as the Steiner Minimum Tree Problem (SMT) with existing mobile Steiner points with a constraint on the length of the edges of the network graph. Consider the existing algorithm for placing new FITRs without taking into account the movement of existing FITRs, presented in the work of Valuiskyi S.V. [1], and the proposing three new placement algorithms for both new and existing FITRs:

• Deployment of new FITRs before moving existing FITRs;

• Moving existing FITRs before deploying new FITRs;

• Deployment of new FITRs while moving existing FITRs.

The first two algorithms divide the general problem into the problem of deploying new FITRs and the problem of the movement control of existing FITRs. The algorithm for deploying new FITRs before moving existing FITRs optimizes the deployment of new FITRs before moving existing FITRs. The algorithm for moving existing FITRs before deploying new FITRs solves the problem in reverse. The algorithm for deploying new FITRs while moving existing FITRs is a hybrid algorithm that cross-resolves the problem of moving and deploying. Simulation experiments show that all algorithms for placing new FITRs, taking into account the movement of existing FITRs, have better performance in terms of the number of new FITRs than algorithms without considering the movement of existing FITRs. The algorithm for deploying new FITRs while moving existing FITRs is always better than the algorithms for deploying new FITRs before moving existing FITRs and moving existing FITRs before deploying new FITRs. It can improve performance by up to 70% compared to the algorithm for deploying new FITRs before moving existing FITRs.

This article assumes that all current locations of ground nodes and existing FITRs are known. It is also believed that no physical interference affects the mobility of FITRs or radio channel. This problem can be de-scribed as follows: given a set of ground nodes and existing FITRs, find new positions for existing FITRs and positions for newly added FITRs to form a tree covering all ground nodes. That the number of newly added FITRs was kept to a minimum.

There are two limitations to this problem. One is the distance between the new position and the current position of each existing FITR, which does not exceed the specified movement range. The other is that the length of each edge in the tree does not exceed the given communication range.

Mathematical formulation of the Steiner minimum tree problem with existing mobile Steiner points with a constraint on the length of edges of the network graph

Since this problem is similar to the Steiner tree problem with the minimum number of Steiner points, in this section, this problem is formulated as the Steiner minimum tree problem with existing mobile Steiner points with a constraint on the length of the edges of the network graph. Steiner points here mean FITRs, and the restriction on the length of the edges of the network graph is the range of the maximum communication range of the network node, determined by the energy of the radio link (transmitter power, receiver sensitivity, antenna characteristics, etc.), terrain and various interferences [7].

A formal definition of the Steiner minimum tree problem with existing mobile Steiner points with a constraint on the length of edges of the network graph is shown as follows:

Let there be a set of ground nodes P, characterized by the current position of each node p, a set of existing FITRs Q, characterized by the current position of each existing FITRs, the movement range of FITRs l, the communication range of the ground node r, the ground-to-air communication range R and the air-to-air communication range D.

In this way $r < R$,

$$P = \{p_1, p_2, \dots, p_n\}, \quad (1)$$
$$Q = \{q_1, q_2, \dots, q_m\},$$

where n - the number of ground nodes, m - the number of existing FITRs.

The new positions of the existing FITRs will make up the set U, the positions of the newly added FITRs – S, and the network graph tree T will consist of the aggregate set of nodes (P, U end S) and the set of edges E:

$$U = \{u_1, u_2, \dots, u_m\},$$
$$S = \{s_1, s_2, \dots, s_k\} \quad (2)$$
$$T = \{P \cup U \cup S, E\}.$$

Then the mathematical formulation of the problem can be formulated as follows: find the minimum number k of new added FITRs, the placement of which will ensure the connectivity of the episodic network

$$min(k) \quad (3)$$

while fulfilling the following restrictions and maintaining the integrity of the network:

$$\Omega_1: |e_i, j| \le r, (e_i, j \in E, i, j \in P),$$
$$\Omega_2: |e_i, j| \le R, (e_i, j \in E, i \in P, j \in U \cup S), \quad (4)$$
$$\Omega_3: |e_i, j| \le D, (e_i, j \in E, i, j \in U \cup S),$$
$$|u_i - q_i| \le l, 1 \le i \le m$$

where $|e_i, j|$ - the length of the edge of the network graph between nodes i and j.

The integrity of the network is understood as the presence of only one component of the connectivity of the network graph. Therefore, checking the integrity of the network is possible by constructing a Steiner minimum tree (SMT) of the graph (for example, according to Prim's algorithm) and checking each edge of the tree for the conditions Ω_1, Ω_2, Ω_3. If the conditions are met, the network is structurally connected at time *t*; otherwise, a management decision is needed (for example, the output of a new (relocation of the existing) FITR.

Algorithm for placing new FITRs without taking into account the movement of existing FITRs

There is already a heuristic algorithm based on the SMT for the Steiner minimal tree problem with existing mobile Steiner points, the worst-case approximation coefficient of which is 4 [7]. Then it divides each edge e in the tree into small pieces of length no more than R, inserting Steiner points number of $\lceil l(e)/R \rceil - 1$, so that all the pieces in the edge e have the same length. Here (e) — is the Euclidean length of the edge *e*.

Since mobile Steiner points are not considered, the SMT heuristic algorithm cannot be used directly for the Steiner minimum tree problem with existing mobile Steiner points with a constraint on the edge length of the network graph. Here, the Lynn and Xue methods are taken as a comparative method. Since this method does not consider existing FITRs, we call this method the algorithm for placing new FITRs without considering the movement of existing FITRs. This algorithm calculates the minimum number of new FITRs required to connect all ground nodes. None of the existing FITRs will be reused to connect mobile terrestrial episodic radio networks. Thus, the number of new FITRs needed to be calculated by this algorithm should be an upper limit of other algorithms considering the placement (relocation) of existing FITRs. This algorithm is shown in Fig. 2.

Algorithm for deploying new FITRs before moving existing FITRs (Algorithm 1)

The first proposed algorithm is an algorithm for deploying new FITRs before moving existing FITRs, which first optimizes the deployment of new FITRs and then optimizes the movement control of existing FITRs.

The basic idea of the algorithm for deploying new FITRs before moving existing FITRs is shown as follows. First, an algorithm for placing new FITRs without considering the movement of existing FITRs is used to create candidate positions for newly added FITRs without considering existing FITRs. We then compare existing FITRs with candidates for newly added FITRs. A match between an existing FITR and a candidate position of a newly added FITR means that an existing FITR will replace the newly added FITR by moving that existing FITR to the candidate position. Because the movement range of existing FITRs is limited, the number of matches is also limited. Here we use an algorithm for deploying new FITRs before moving existing FITRs (DBM) to find the maximum matches so that the number of new needed FITRs can be minimized. The algorithm for deploying new FITRs before moving existing FITRs is shown in Fig. 3.

Algorithm for moving existing FITRs before deploying new FITRs (Algorithm 2)

The main idea of the algorithm for moving existing FITRs before deploying new FITRs is as follows. First, a heuristic function is used to create new positions for existing FITRs $Q`$. Then the set of ground nodes $P$ and the set of existing FITRs with new positions $Q`$ are combined into a large set of nodes $P \cup Q`$. After that, we generate a minimum spanning tree T over the set $P \cup Q`$, and then the process of discarding existing FITRs will be used to cut all existing FITRs under 1 degree in the tree, until all existing FITRs in the tree have at least two neighbouring nodes. Then, for the rest of the subtree $T`$ of $T$ new FITRs will be added to the edges of $T`$, that are longer than *r*.

Algorithm for deploying new FITRs while moving existing FITRs (Algorithm 3)

The main idea of the algorithm for deploying new FITRs when moving existing FITRs is as follows. At first, a complete graph (V, E) is generated on the base nodes, and we sort all the edges E in order of increasing length. Then consider all edges e_i, j in the set E, in which the length of the edge is at most r, and the vertices of the edge belong to different components. After this step, we will have several components consisting of connected grounding nodes. Now we will recursively move the existing FITRs and add new FITRs to connect the separated components until all the separated components are connected into one component. In each loop, we will try to connect all pairs of vertices $V_i$and $V_j$belonging to different components using two different methods. One method uses existing FITRs to establish a link between V_i and V_j by moving the FITRs to specific positions. And new FITRs will be added to chain edges there are longer than r. Another method does not consider existing FITRs and simply tries to set up a connection chain between V_i and V_j by adding new FITRs. The number of newly added FITRs using these two methods will be compared, and the lower number will be written as the minimum number of new FITRs (MNN) for connecting V_i and V_j. The pair of vertices with the minimum MNN will be selected in this loop to connect two separated components. New positions of existing FITRs and positions of newly added FITRs created to connect this pair of vertices will also be recorded as part of the final result. The algorithm for deploying new FITRs when moving existing FITRs is shown in Fig. 5.

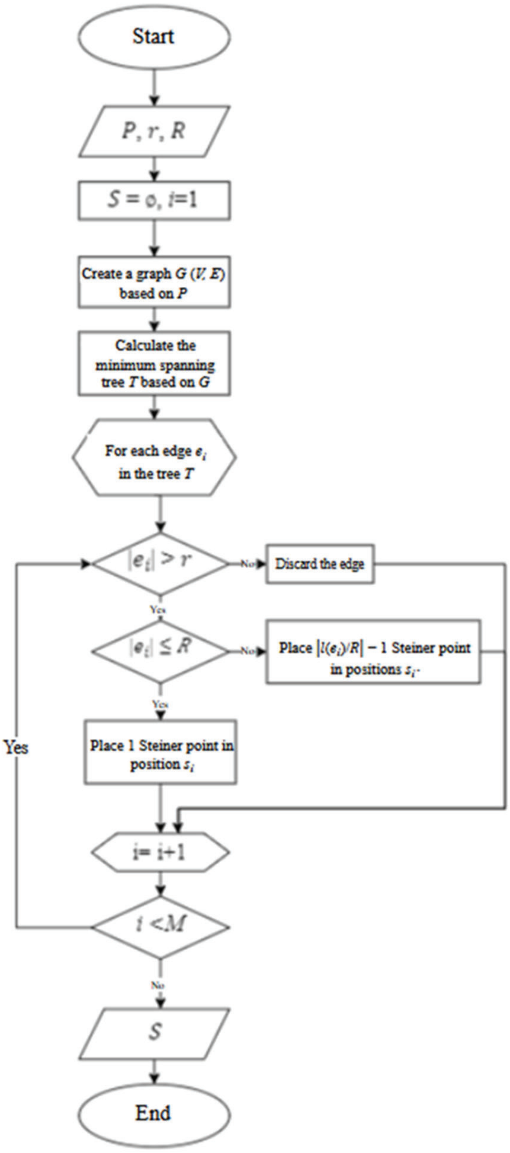

Fig. 2 - Block diagram of the existing algorithm for placing new FITRs without considering the movement of existing FITRs

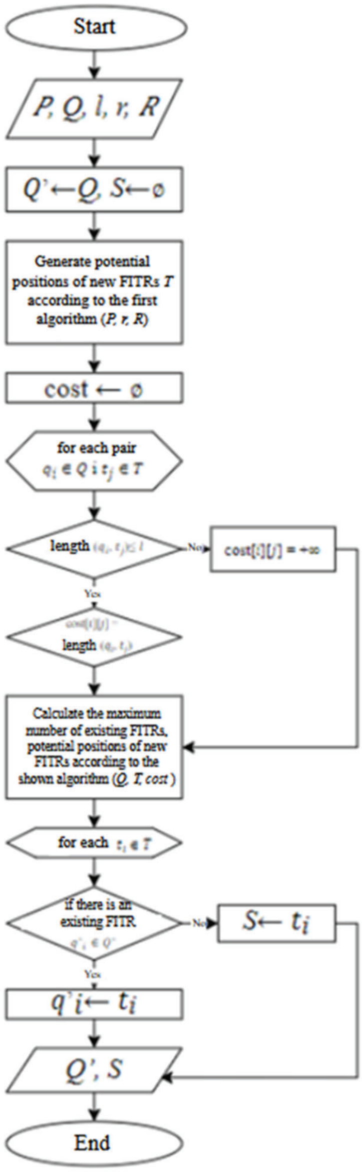

Fig. 3 - Block diagram of the proposed algorithm for deploying new FITRs before moving existing FITRs (Algorithm 1)

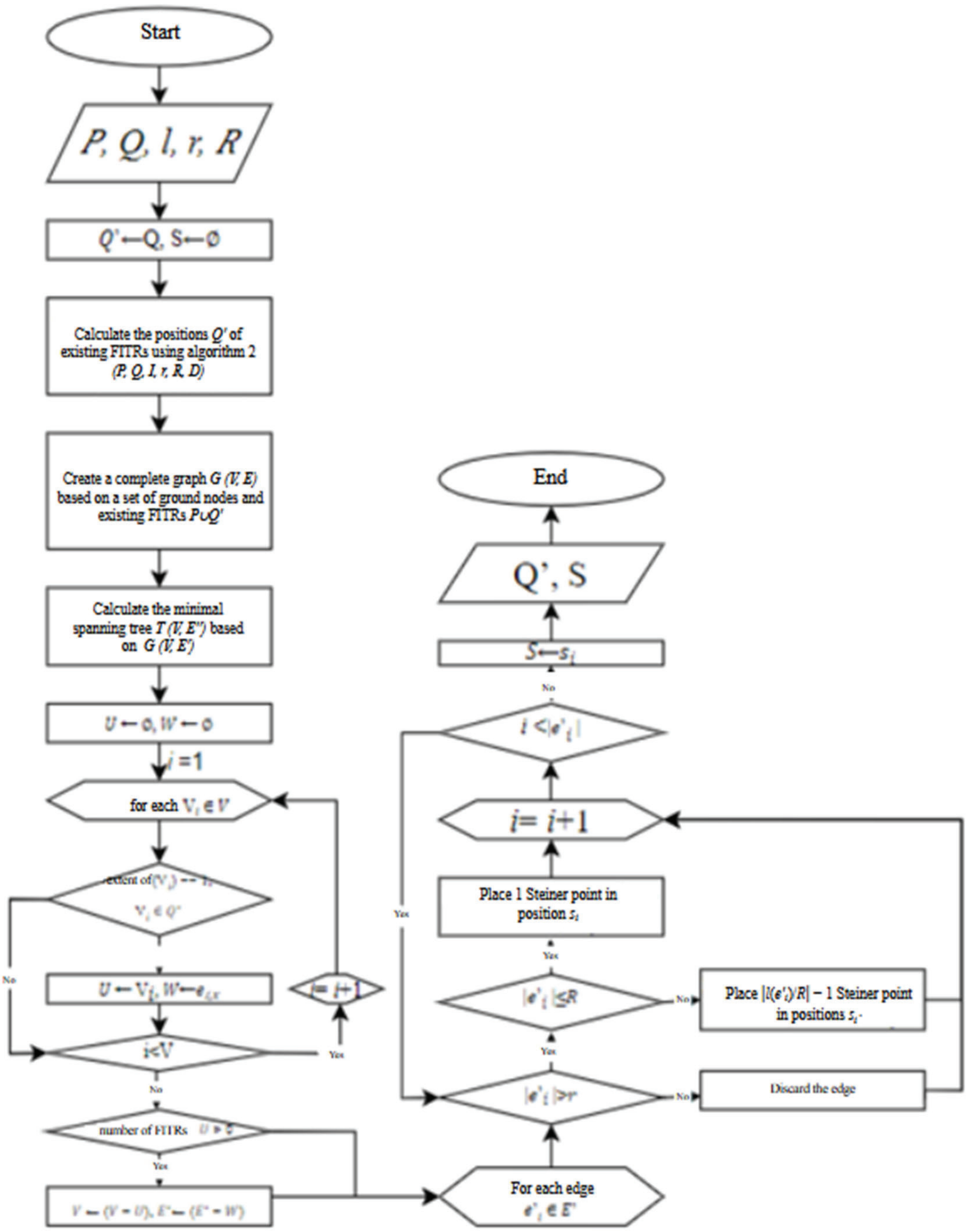

Fig. 4 - Block diagram of the proposed algorithm for moving existing FITRs before deploying new FITRs (Algorithm 2)

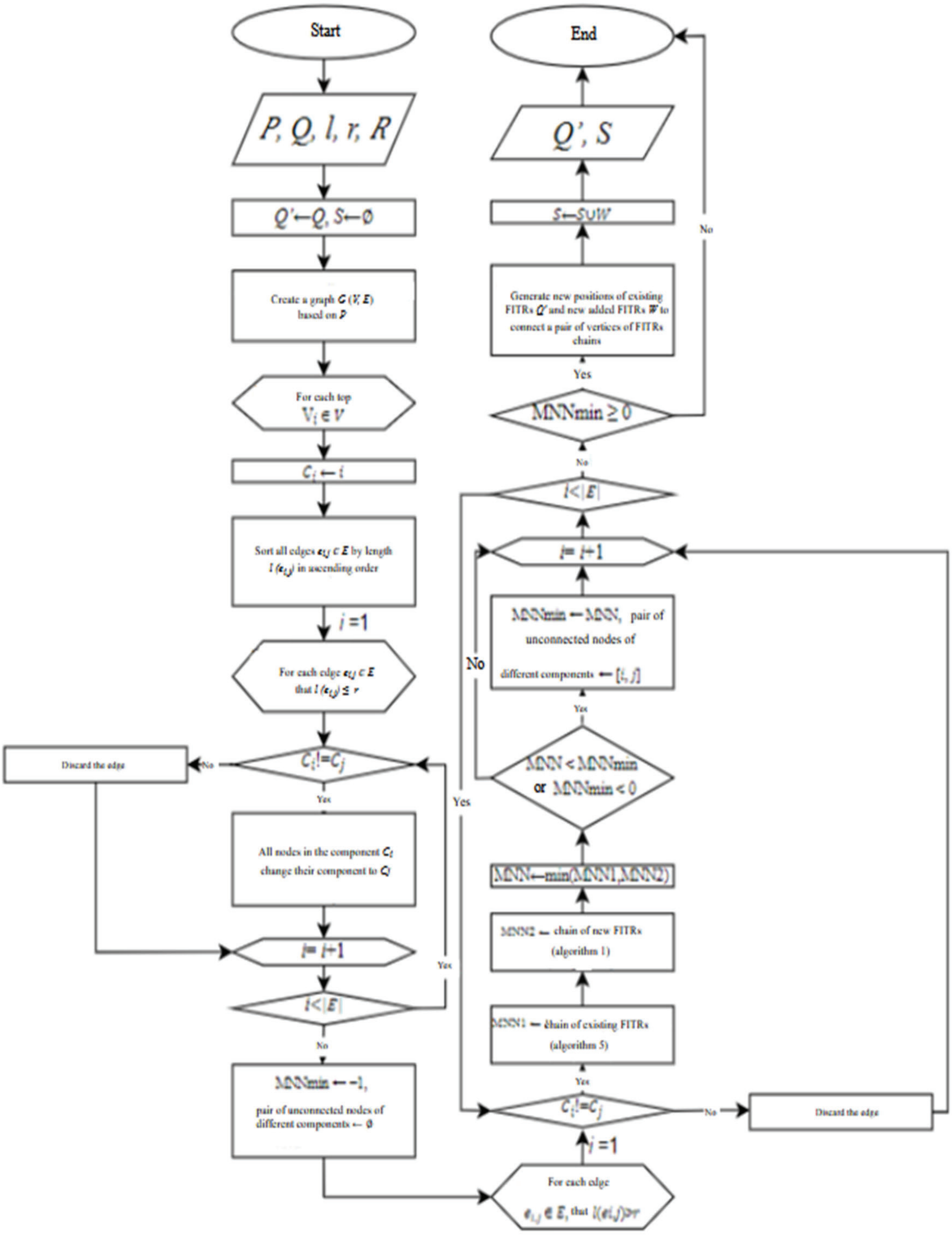

Fig. 5 - Block diagram of the proposed algorithm for deploying new FITRs while moving existing FITRs (Algorithm 3)

Conclusions

The paper explores the problem of using FITRs to maintain communication of terrestrial mobile episodic radio networks. Unlike existing works, this paper considers the condition that some FITRs have already been deployed in the field. However, due to the movement of terrestrial subscribers of mobile episodic radio networks and limited communication range, existing FITRs cannot connect all terrestrial nodes, so new FITRs must be deployed to maintain communication.

Also, three algorithms are proposed: 1) an algorithm for deploying new FITRs before moving existing FITRs, 2) an algorithm for moving existing FITRs before deploying new FITRs and 3) an algorithm for deploying new FITRs when moving existing FITRs for the SMT problem with existing Steiner Mobile Points with the constraint of the length of the edges of the network graph.

After testing the performance of the proposed algorithms in various scenarios with changing simulation parameters (including the number of ground nodes, the number of existing FITRs, the communication range and the movement distance), it can be concluded that the algorithms considering the movement of existing FITRs always have better performance than the method without considering the movement of existing FITRs in terms of the number of new added FITRs. Among the three algorithms for deploying new FITRs considering the movement of existing FITRs, the algorithm for moving existing FITRs before deploying new FITRs is better than the algorithm for deploying new FITRs before moving existing FITRs in most scenarios. The algorithm for deploying new FITRs while moving existing FITRs always has the best performance during all scenarios. In some scenarios, the algorithm for deploying new FITRs while moving existing FITRs can reduce a maximum of 70% of new FITRs compared to the algorithm for deploying new FITRs before moving existing FITRs.

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Евристичні алгоритми пошуку мінімального дерева Штейнера в задачі оптимізації розгортання та керування рухом кількох літаючих інформаційно-телекомунікаційних роботів

Проблематика. У статті досліджено проблему поєднання управління рухом існуючих літаючих інформаційно-телекомунікаційних роботів (ЛІТР), мобільна епізодична радіомережа, алгоритм, топологія, розміщення ЛІТР та розгортання нових ЛІТР, щоб кількість нових розгорнутих ЛІТР для підтримки зв’язку наземних абонентів могла бути мінімізована. Дана проблема сформульована, як проблема мінімального дерева Штейнера з існуючими мобільними точками Штейнера із обмеженням довжини ребер графу мережі.

Мета дослідження. Удосконалити математичну модель забезпечення зв'язку епізодичних радіомереж з використанням ЛІТР та вдосконалити алгоритми забезпечення зв'язку епізодичних радіомереж із використанням ЛІТР.

Методика реалізації. Два алгоритми: розгортання нових ЛІТР до початку переміщення існуючих ЛІТР і переміщення існуючих ЛІТР до початку розгортання нових ЛІТР розділяють проблему та вирішують проблему розгортання, переміщення одна за одною, тоді як алгоритм розгортання нових ЛІТР під час переміщення існуючих ЛІТР оптимізує проблему розгортання та керування рухом поперек і вирішує ці дві проблеми одночасно.

Результати дослідження. Запропоновано метод, який включає три евристичні алгоритми розміщення нових ЛІТР з урахуванням переміщення існуючих ЛІТР для задачі МДШ з існуючими мобільними точками Штейнера із обмеженням довжини ребер графу мережі: алгоритми розгортання нових ЛІТР до початку переміщення існуючих ЛІТР, переміщення існуючих ЛІТР до початку розгортання нових ЛІТР і розгортання нових ЛІТР під час переміщення існуючих ЛІТР.

Висновки. Оцінка ефективності запропонованих алгоритмів у різних сценаріях свідчить, що алгоритми з урахуванням переміщення існуючих ЛІТР завжди мають кращу продуктивність, ніж алгоритм без урахування переміщення існуючих ЛІТР з точки зору кількості нових доданих ЛІТР. Серед трьох алгоритмів розміщення нових ЛІТР з урахуванням переміщення існуючих ЛІТР, алгоритм переміщення існуючих ЛІТР до початку розгортання нових ЛІТР кращий за алгоритм розгортання нових ЛІТР до початку переміщення існуючих ЛІТР у більшості сценаріїв, а алгоритм розгортання нових ЛІТР під час переміщення існуючих ЛІТР завжди має найкращу ефективність у всіх сценаріях.

Ключові слова: *літаючі інформаційно-телекомунікаційні роботи; мобільна епізодична радіомережа; алгоритм; топологія; розміщення.*