Research of optimal structure for autonomous earth-moving and construction machines’ communication system

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Abstract— The paper presents research results of the optimal structure for constructing an autonomous earth-moving and construction machine complex’s data transfer system**.** The mathematical model of the optimal placement task of mobile communication base stations of an autonomous system was developed. The solution was made for the concrete example of the optimal placement task. The specific number and location of the base mobile stations were determined in the optimal structure for constructing a communication system of autonomous earth-moving and construction machines.

Keywords—autonomous system; base stations; optimal structure; earth-moving and construction machines

I. INTRODUCTION

Research of autonomous vehicles' communication systems are being carried out worldwide. For example, paper [1] presents the IEEE 802.11ah standard research results, which is a promising communication standard. This new communication standard supports a huge number of heterogeneous devices in the Internet of Things (IoT).

Thanks to the promising applications in e-health and entertainment services, a wireless body area network (WBAN) also receives a close attention [2]. One of the most important tasks for WBAN is to monitor and maintain the quality of service (QoS). In the following article, the authors reviewed the probabilities of delivery and delay in a dynamic environment determined by human mobility. The authors also reviewed another important problem - ensuring energy efficiency in such network with limited resources.

The authors published a number of papers [3-10] regarding the research and development of various autonomous earth-moving and construction machine complex’s data transfer system aspects of the operation.

Similar systems are being developed in another area - robotics. For example, paper [11] examines how several cars on the robots' principle travel on paths with limited curvature in a plane that contains a priori unknown areas. There are very few researchers exist who study a movement of earth-moving and construction machines. But there are many researchers who actively study on various areas of research on vehicle movement control. Recent advances in the field of vehicle communications make it possible to implement transport sensor networks [12] - a collaborative environment where mobile vehicles equipped with sensors of a different nature (from toxic detectors to fixed cameras) interact to implement monitoring applications.

One of the important tasks previously unresearched, but which has to be solved when creating an autonomous earth-moving and construction machine complex’s data transfer system, is the optimal placement of base stations (BS) and central station (CS) of the entire system.

II. MAIN PART

It is necessary to solve the following tasks for the BS and CS optimal placement of an autonomous earth-moving and construction machine complex’s data transfer system:

- the choice of an BS optimal number and location. State and location data from sensors of autonomous earth-moving and construction machines will be transferred from each BS to CS. Also BS will transmit reverse control commands;
- the choice of a CS location, which will receive state and location data.

There is a need for technical solution of problems mainly related to the installation and equipping BS and CS with modern communication equipment in a particular mining quarry or on a construction site. Obviously, there will be a need for optimal placement of communication system objects in any quarries or on construction sites. The problem solution, being carried out in the complex of tasks on the communication system formation, allows to use the material resources most effectively for BS and CS building, and also significantly reduces a technical equipment costs.

It is known that the geographic relief of the Republic of Kazakhstan is not homogeneous by the earth surface structure. Some zones occupy vast areas of comparatively flat surface, while others have various hard-to-reach terrain areas. The last ones primarily include seismic regions with a mountainous territory, with densely planted forests, as well as with water basins of lakes and rivers. Therefore, radio and technical equipment installation and delivery to each BS and CS under such conditions in terms of material costs will be different. Of course, the placement of stations in each region is economically unprofitable and here most reasonable way will be to develop some mathematical model. Such a model in an automated radio control system will allow to optimally place these stations. All above causes the need to build such a model.

For example, let's view the following situation in the mining quarry. The CS is located on the quarry northern side, so the number of possible directions of radio signal sources can be reduced to three: south-west, south and south-east. Thus, the minimum number of BS is $N_{min} = 3$, one on each direction. But in case of failure of some block on one of base stations, this station becomes unworkable. So if during that time on this direction any autonomous machine, located in the area of that base station, crashes, then system operator won't know about it, or he finds out about it later. But it will be too late to send any control actions to this or neighboring autonomous machines.

So it is necessary to use the BS redundancy in the radio system by installing additional equipment on the BS or by increasing the number of BS. When choosing a BS redundancy strategy, it is necessary to take into account the data protection and the communication system protection from outside interference (accidental or intentional) as a whole. From this point of view, it will be more optimally to use several additional BS for redundancy purposes, which will operate as main BS.

To choose the number of BS in each of three directions, it is necessary to take into account an external intervention, as a result of which a false data transfer about the status of some autonomous machine or false command transfer can occur. This is an unallowable factor, since false data will lead to accidents and even possibly to human casualties. To exclude the factor of external intervention and to make redundancy for the reliable operation of a communication system, the number of BS on each direction will be chosen below.

We will study and develop a mathematical model for BS and CS optimal placement task of the communication system. After we solve optimal placement task, we will determine the specific number of BS and the BS and CS location.

It is assumed that some topological structure of mining quarry is known. Let's define S as an area of the region geographical territory. S includes a number of regions S={S_i}, $i = \underline{1, n}$, where n - the number of regions. In each region a BS can be located, which is able to control the operation and movement of autonomous earth-moving machines not only in its region, but also in neighboring regions bordering it. It is assumed that each BS is equipped by modern technical equipment which is able to record changes in the operation of all units of autonomous earth-moving machines automatically and to send data to the central station timely. At the same time, the source radio signal from the BS propagates in a certain radio frequency range and has a fixed action range.

As mentioned, the material costs for building each BS are different. Obviously, the location of the BS in each region is economically impractical in terms of material costs for the communications equipment delivery. Thereby, the following problem occurs: to determine the minimal number of BS and location of BS in the regions in order to minimize installation costs and at the same time to provide control the operation and movement of all autonomous earth-moving machines throughout S area.

Let's formalize this problem: we define each region territory as graph vertex Si and connect only those vertices that correspond to the neighboring regions. Then the initial problem in the graph-theoretical interpretation will be to determine the minimal dominating set in this graph.

In the graph $G = (V, E)$, where $V = \{vi\}$, $i = \overline{1, n}$ - is the set of its vertices, E is the set of its edges, the dominating set is a such vertex set $S \subseteq V$, that for each vertex $v_j \notin S$ the arc exists, which goes from some vertex of the set S to the vertex v_j.

Thus, S is the dominating vertex set if

$$S \cup G(S) = V \quad (1)$$

A dominating set is called minimal if there is no other dominating set contained in it.

In other words, the set S is the minimal dominating set for the graph $G = (V, E)$ if it corresponds to the condition (1) and has no own subset that corresponds to a similar condition (1). Note that a graph may have several dominating sets, and they do not necessarily contain the same number of vertices.

If P is the family of all minimal dominating sets of the graph, then the number

$$\beta|G| = \min_{S \in P}|S| \quad (2)$$

is called the domination number of the graph G, and the set S^*, on which the minimum is achieved, is called the minimal dominating set. The problem of finding the minimal dominating set of the graph G in graph theory is closely related with the problem of the minimal covering, which is described in detail below.

Thus, the initial problem of the BS optimal placement can be reduced to the problem of constructing a minimal graph covering.

The main functions of assigning a central station (CS) are: timely receiving of radio signals from one or more BS and prompt decision-making on the implementation of a number of urgent measures, which are necessary to avoid accidents and human casualties. Such activities primarily include: timely notification of an accident possibility on the basis of autonomous earth-moving and construction machines' sensor data; an emergency stopping of autonomous earth-moving and construction machines; an emergency change in the movement trajectory of both autonomous machines themselves and its elements (buckets, etc.).

Obviously, all above measures make sense only if the radio signal propagation from BS to CS is carried out without interference and stay stable at any time. Each BS controls the operation of autonomous earth-moving and construction machines in several regions and has the same action range of radio signal. At the same time, the action range of BS radio signal is the maximum distance where CS is capable to receive this signal and have enough time to make a decision.

In relation to the above, there is a problem of CS optimal placement in the mining quarry. Obviously, the CS installation within the action range of each BS is economically unprofitable. At the same time, as in the BS placement task, while determining the CS location, the geographical features and area inaccessibility must be taken into account.

Let's assume that the BS locations are known and n - the number of BS locations. Each BS has action range of radio signal r. CS optimal location task is defined as follows: It is necessary, using the minimum number of CS, to place them so that the distance from any BS to at least one of the CS would not exceed a given value of r and the installation cost of all the CS points would be the minimal.

In general, the initial problem can be understood as one of the non-linear programming tasks with a goal function of the form

$$W(\tilde{\lambda}_1, \dots \tilde{\lambda}_m) = A \sum_{i=1}^{n} \prod_{j=1}^{m} \omega\left(\lambda_1 - \tilde{\lambda}_j\right) + B * m, \quad (3)$$

where $\lambda_1, \tilde{\lambda}_j$ - accordingly, vectors of objects' and service points' coordinates;

m - number of points;

$\omega(\lambda)$ - rectangular function given by condition

$$\omega(\lambda) = \begin{cases} 0, \|\lambda\| \le r, \\ 1, \|\lambda\| > r, \end{cases} \quad (4)$$

$\|\lambda\|$ - a vector norm λ in Euclidean space;

A, B are constant coefficients.

BS is an object, CS is a service point.

Minimization (3) must be performed both by coordinate values $\lambda_1, \dots, \lambda_m$, and by their number m.

The coefficients A and B characterize respectively the losses from not maintaining one object and the cost of one service point. Obviously, when A>B, the minimum (3) is ensured in the case when all objects are serviced and the number of points is minimal.

Let's construct a graph on a given set of points (objects), taking last ones as vertices and drawing an edge between two vertices only if the distance between them does not exceed 2 r.

Let's define the coverage of given graph as set of circles of radius r where each graph vertex falls into at least one of these circles. Coverage is considered as minimal if there is no other coverage with fewer circles. Obviously, coordinates of the circles' centers, forming the minimal coverage, can be taken as the coordinates of the service points in given task.

Let's now construct minimal coverage. First let's note that any two vertices of an existing graph belonging to different connected components wittingly can't be covered by the same circle, since the distance between them exceeds the diameter of the circle. Therefore, coverage can be constructed independently for various connected components, and in paper it will be enough to study only one connected graph.

Let's view a vertices group of connected graph that can be covered by one circle, and we associate a circle covering it with such a group. Then the choice of the group, that includes all the graph vertices, will determine some graph coverage, in which the number of circles is equal to the number of groups in the set. Let's construct minimal coverage by searching such sets. Obviously, the minimal coverage will correspond to the set of the minimal number of groups.

Here are some considerations that allow us to reduce the number of sets being analyzed. Let's denote graph vertices as $e_1, \dots, e_k$. Let's define group of vertices ($e_i, \dots, e_k$) as maximal if it is covered by one circle and there is no such new vertex e_e ($e \neq i, \dots, k$) that group $e_i, \dots, e_k$ also is covered by one circle.

Let's suppose that some minimal graph coverage U is constructed, and that a some circle $S \in U$ covers the vertices $e_i, \dots, e_j$ (and only these vertices), and the group $e_i, \dots, e_j$ is not a maximal.

Obviously, there is a maximal group $e_i, \dots, e_j, \dots, e_k$ containing $e_i, \dots, e_j$. Let's assume, that S' - a circle covering this maximal group. By condition, the circle S' does not belong to U. Let's construct a new graph coverage U' that differs from U in that S' is taken instead of S. The number of circles in the coverage U' is equal to their number in U, i.e. U' is the minimal coverage. Thus, there is always a minimal coverage originated by set of maximal groups, and while solving tasks it is enough to restrict ourselves to analyze the set only from maximal groups.

Now let's define the basic steps of the algorithm for constructing a minimal coverage:

- to determine maximum groups;
- to construct sets of maximal groups containing all graph vertices; to find out a set with the minimal number of groups;
- to calculate coordinates of circles' centers covering the groups of the last set.

It should be noted that in 2nd step of the algorithm it is enough to restrict ourselves to construct only such sets, in which each group enters at least one new element (vertex), compared to the combination of other groups of the set. It will bring to the deviation from the optimality because the presence of vertex simultanuosly in several maximal groups means that it will be covered with several circles while in order to solve the task it should be enough a single coverage. Finally, some circles of the minimal coverage can be found out without searching. Let's assume that some graph vertex enters only to one maximal group. This group will enter into every set, that is constructed according to the 2nd step of the algorithm and, therefore, the circle covering it is the circle of minimal coverage. If we find these circles on the first calculation step then we can exclude vertices covered with these circles from the review and build the minimal coverage only for the remaining graph. If we add selected circles to the coverage we found then we'll get a task solution. The examples of vertices that enter only into single maximal group are vertices of the 1st and 2nd level.

The above results allow to create a flowchart of the task solving algorithm (Figure 1).

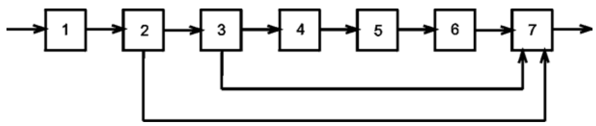


Fig. 1. Flowchart of the algorithm

A graph is being constructed on a given set of points in block 1. In block 2 the vertices of level 0 are being selected. The vertices of level 1 and all vertices connected with it are being selected in block 3. Their coordinates are being transmitted into block 7 to calculate their centers. In block 4 the graph, remaining after exclusion of the vertices that were processed in blocks 2 and 3, is being divided on several connected components. Different connected components are being processed independently.

In block 5, for each vertex of a given connected component, maximal groups containing this vertex are being constructed. The search of maximum groups and identification of groups from maximum coverage for remaining graph is being carried out in block 6. The group set corresponding to the minimal coverage is being transferred to block 7, where centers of circles covering the groups of this set are being determined.

The most time-consuming stage of the construction of a minimal coverage is the allocation of maximal groups. By virtue of the method of graph construction, the necessary condition for the given group of vertices to be covered by one circle is the completeness of the subgraph whose vertices are group elements. The sufficient condition is that the intersection of circles with centers at these vertices should not be empty. To verify this condition, it is necessary to solve the corresponding system of square inequalities. After all vertex groups corresponding to the necessary condition will be tested for sufficient condition, maximum groups are being selected, following the definition given above.

In order to reduce in prospect the number of operations when allocating maximum groups, it is possible to introduce some assumptions that allows to exclude verification of sufficient conditions.

Let's prove that the completeness of the graph constructed by the method specified in step 2 of the algorithm is the sufficient condition for covering its vertices with a single circle with radius $R = 2r/\sqrt{3}$. Let's view at the equilateral triangle ΔABC (Figure 2), length of sides of which is 2r. It is covered by the circle with radius R and center at the point O of medians' intersection. Moreover, this circle covers the sector AB and C, since for any point E of this sector the projection on DC is $|Pr_{DC}OF| \leq DC \leq OC = R$.

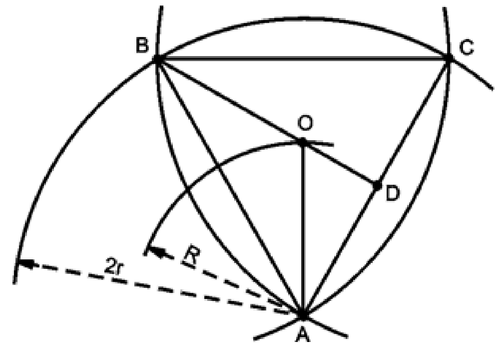


Fig. 2. The coverage by circle with radius R

Let's assume we have a random complete graph with three vertices $A_1B_1C_1$. One of $\Delta A_1B_1C_1$ angles should be no more than $\pi/3$. Let's assume that this angle is $B_1A_1C_1$. Let's combine points A and A_1 so that side A_1B_1 would go along side AB. Since $A_1B_1 \leq AB$, the point B_1 will be on AB side. At the same time, $\angle B_1A_1C_1 \leq \angle BAC$, therefore, the side$A_1C_1$ will go (with the appropriate orientation of planes) inside ∠BAC. Since $A_1C_1 \leq AC$, the point C_1 will be within the AB and C. Thus,$\Delta A_1B_1C_1$ is placed in the sector AB and C, which is covered by a circle with radius R, and the graph with vertices A_1, B_1 and C_1 is covered by a circle with radius R.

The initial data in the algorithm for optimal placement of service points are coordinates of objects and the service radius r. While making up the algorithm, assumptions made at the end of previous section were used. The formula chart of the algorithm is shown in Figure 1.

Depending on the number of earth-moving and construction machines connected to each BS, their action range (radius), we will construct an algorithm for the BS optimal placement on the territory of the proposed "a", based on the above-described method. To do this, it is necessary to split the area being studied into a number of regions in which BS can be located. The procedure for finding such a number of splits into regions is as follows.

For the simplicity of the following calculations, let's represent a controlled mining quarry in the rectangle form, the length of which is a kilometers and width is b kilometers. Then the square of this territory part will be: $S = \mathrm{a} * \mathrm{b}$.

Let's split this area into n regions, in the center of each of which only one BS can be located. At the same time, we assume that all areas are the same in their topological and surface structure and have the square shape with a side equal to l kilometers. Then the square of each region will be l^2 kilometers. Let's assume that each BS has a certain action radius r, value of which depends on the range of radio channels. At the same time, as follows from figure 3, value of r is $\frac{3}{2} * l$.

Let's assume we have p, q - number of regions located accordingly along the length and width of the part of the region being viewed. Then $a = p^l$, $b = q^l$. Taking into account the value of r, we will obtain:

$$\begin{cases} p = 3a/2r, \\ q = 3b/2r. \end{cases}$$

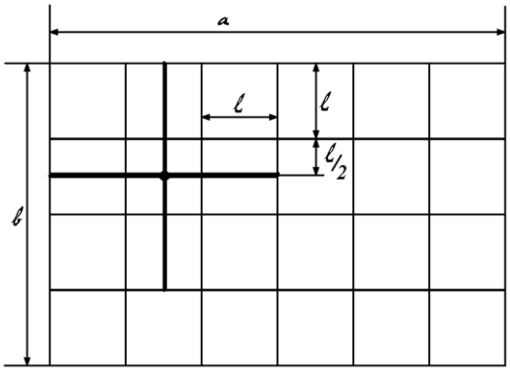


Fig. 3. Finding the distances a and b

In our case, the length and width of the area being researched are 20 and 10 km accordingly, then its square is 3200 km^2. Modern equipment and equipping technology of modern BS allows to control regions within 3.75 km. Then $p = 3 * \frac{20}{2} * 3{,}75 = 8$, $q = 3 * \frac{10}{2} * 3{,}75 = 4$, i.e. number of placement of squares in length will be 8 units, and in width - 4 units, and in the whole territory of the region their number will be 32 units.

Thus, the whole territory of the region is represented by a large square and is divided into 32 districts.

As we previously assumed, further we will view this territory in its geophysical structure as a homogeneous. So we assume that the BS installation costs in each of the 32 regions to be the same and equal to 1, i.e. $C_j = 1, j = \overline{1,32}$. We assume that each BS located in any region can control autonomous earth-moving and construction machines not only within this region, but also in neighboring regions bordering it. In this case the optimal placement task is formulated as follows: it is required to find the minimal possible number of BS, and also to determine places of their location in quarry being studied so that to provide control of the whole region territory. If we will represent each region as the graph vertex and connect only those pairs of vertices that correspond to neighboring regions, we will get the graph shown in Figure 4.

For our case, the linear programming problem (1) - (4) will be written down: to find a vector x = (x1, …, x32), corresponding to the basis condition:

z = (x1 + x2 + x3 + … +x32) → min,

This integer programming problem was solved by the Homori method on the computer. After solving task with the simplex method, we will obtain the following calculation result.

One of solutions of the initial placement problem is the vector:

x = (10001000001000111000100000100010).

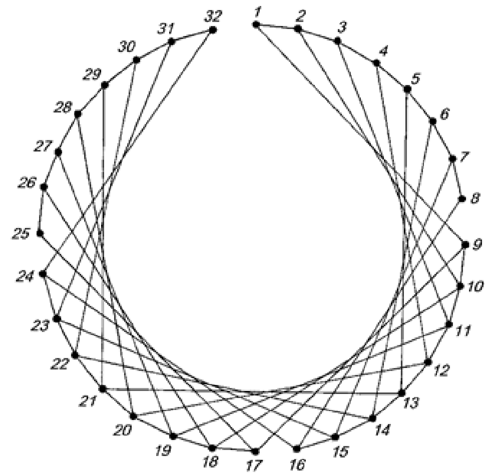
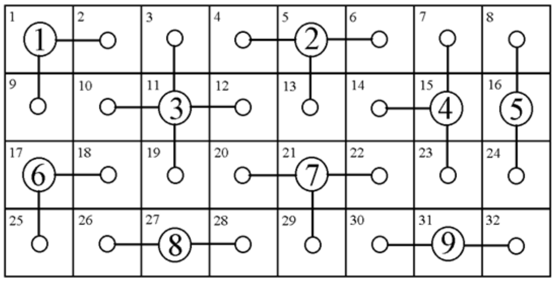


Fig. 4. Graph of the BS optimal placement task

The matrix A^t will look like this:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1

Thus, solution results show that the BS should be located in the regions S_1, S_5, S_{11}, S_{15}, S_{16}, S_{17}, S_{21}, S_{27}, S_{31} (Figure 5). At the same time in Figure 5, large circles, marked with numbers, indicate real locations of the BS, and small circles indicate possible locations. The connecting lines indicate neighboring regions that can be controlled by optimally located BSs.



III. Conclusion

The paper presents the results of research and development of the mathematical model for the optimal placement task of base mobile stations of the communication system of autonomous earth-moving and construction machines. The solution was made for the concrete example of the optimal placement task. The specific number and location of the base mobile stations were determined in the optimal structure for constructing a complex of autonomous earth-moving and construction machines.

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