

Research Article

An Efficient Method for Choosing Digital Cluster Size in Ultralow Latency Networks

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Received 9 August 2021; Accepted 17 September 2021; Published 4 October 2021

Academic Editor: Deepak Gupta

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The paper proposes a solution to the problem of choosing the size of a cluster in an ultralow latency network. This work is aimed at designing a method for choosing the size of the digital cluster in an ultralow latency network taking into account the lengths of connecting lines. If the linear dimension calculation is based only on the latency requirements without specifics of building the communication line, it negatively affects timing characteristics. This paper shows the method taking into account the communication line features and basing on the fractal dimension estimation of the road network. The proposed method could be used in planning and designing networks with ultralow latencies. Finally, a numerical experiment was carried out, based on the data of electronic maps, which showed that the assessment of the fractal dimension of roads in the network's service area makes it possible to increase the accuracy of the size of the formed cluster. Moreover, the proposed method can allow you to reduce the error in estimating the length of connecting lines, which without using it can be on average about 30%.

1. Introduction

The development of services with high latency requirements of data delivery in the network leads to a change of approaches to determining the network structure. As shown in works, [1, 2] describe in detail the reasons leading to an increase in the requirements for the value of the delay in the delivery of packets in promising communication networks. In [1], the tasks of the Tactile Internet and target requirements for the amount of latency are given; in [2], a structure with the use of border calculations is proposed, which provides a decrease in latency. In [3], the prospects for the application of edge

computing in sixth-generation networks are considered. The paper [4] presents the results of an analysis of the use of d2d technologies for direct connections to devices, which can also serve as a means of reducing the delay. In [5], the author proposes a territorial division into digital clusters according to the distribution of users. There should be a data center at the center of such clusters. In [6], the authors propose the use of multiple computing systems and the distribution of tasks between them. In [7], a method for the formation of digital clusters in networks of the first and subsequent generations is proposed. In [8], the use of edge computing for blockchain implementation is considered.

Mentioned above requires a change in the network structure, as the numerical values of the delay are already commensurate with the propagation time of an electromagnetic or optical signal [9, 10]. This limitation necessitates shifting the service point provision closer to the end-user. It is possible by promising communication networks by organizing local cloud services located at a sufficiently small distance from users, making it possible to meet the requirements for data delivery time [11, 12].

As the works [2, 4, 5] show, the formation of such structure is associated with the task of allocating a certain number of user clusters in the serviced area according to the cluster size, and access points (service provision) can then be located in the centers of the selected clusters. The work [7] shows that clusters of different sizes can be formed for users with different requirements for latency time. The work proposes a method that considers the road's characteristics and the laying of communication lines on the territory of the cluster.

Depending on the magnitude of the delay, the cluster radius varies from several tens to several hundred kilometers. At such distances, the connection between the point of service provision (the clusters' center) with the elements of the cluster (for example, settlements) is carried out by cable communication lines. The length of these lines determines the real propagation delay of the signal. In most cases, the link is longer than the straight line connecting the points on the map.

Currently, there is an intensive growth of interest in services requiring low and ultralow delays, such as telemedicine, telecontrol of vehicles, and unmanned aerial vehicles. To solve such problems, it is often proposed to use local mobile edge computing nodes (edge computing). However, in many cases, when there is a stable demand for services, it is advisable to build a stationary network structure containing data processing centers located close enough to service consumers. The construction of such a structure requires the development of methods for optimizing the structure in order to increase the efficiency of resource use and ensure the delay requirements for subscribers.

The purpose of this article is to present the method developed for assessing the real length of cable communication lines in digital clusters, which will make it possible to determine the required size of these clusters. The main contributions of this paper are summarized as follows:

- (i) The formation of digital clusters in an ultralow latency network based on the distance from the point of service provision is necessary in order to meet the requirement for the delay introduced by the signal propagation time
- (ii) When forming a cluster, it is necessary to consider the fact that communication lines are laid along roads, which most often differ from straight lines
- (iii) It will be shown in the work that this feature can be taken into account by using the fractal dimension, estimated for the road network in the service area of the communication network

2. Problem Statement

The work [7] proposes to use the FOREL clustering method to solve the problem of choosing positions for placing the service provision points. When using this method, the cluster boundary is defined by a circle of a given radius. In other words, the maximum possible distance of a cluster element from its center does not exceed the specified radius of the circle. Figure 1(a) shows an illustration of the performed clustering, in which two cluster elements are very close to the cluster boundary.

The more significant density (an amount of the elements on the one square unit) corresponds with the higher probability for such an event. That is quite acceptable for modeling, but the distance between the cluster center and the element is determined by the existing cable route in the real condition. Moreover, the cable route is laid along the existed road.

Figure 1(b) shows the possible example of choosing the route on the real map (the map was obtained from Google Earth [13]). As you can see from the example, the real route could be significantly different from the straight line connecting the cluster center and the element. The route distance was more considerable than the straight line from 15 to 37%. Also, the length to 3 out of 4 selected for the example points exceeded a radius of 50 km.

Thus, the implementation of the clustering algorithms is complicated by choosing the actual roadways as metrics, but not the straight distance between two points. Of course, there might be more than one option for selecting the route.

Another approach to solving the problem of choosing clusters can be determining a smaller value of the radius R by some value Δ , which would consider the increase in the length of the communication lines due to the choice of routes for their laying.

Even from the given examples, you can notice that the spread of the path length increments is quite large. However, the real situation is far from being limited to this example and can have a greater variety.

This study is aimed at developing a method for choosing the parameters for solving the clustering problem (selecting the size of the cluster), taking into account the peculiarities of the road infrastructure of the target region.

3. Related Work

The clustering task is the most common task when building a communication network. In general, the task of clustering is to divide network objects into groups (clusters) according to some criterion. This general setting is good for any context. However, in practical applications, specific clustering problems differ significantly from each other both in the formulation and in the method of solution.

The statement of the problem and the method of its solution depend on the applied area and the purpose of its solution. The most striking example is the problem of clustering subscribers in a mobile network (in a somewhat simplified interpretation). In this case, the number of clusters will be equal to the number of base stations, and the criterion is the

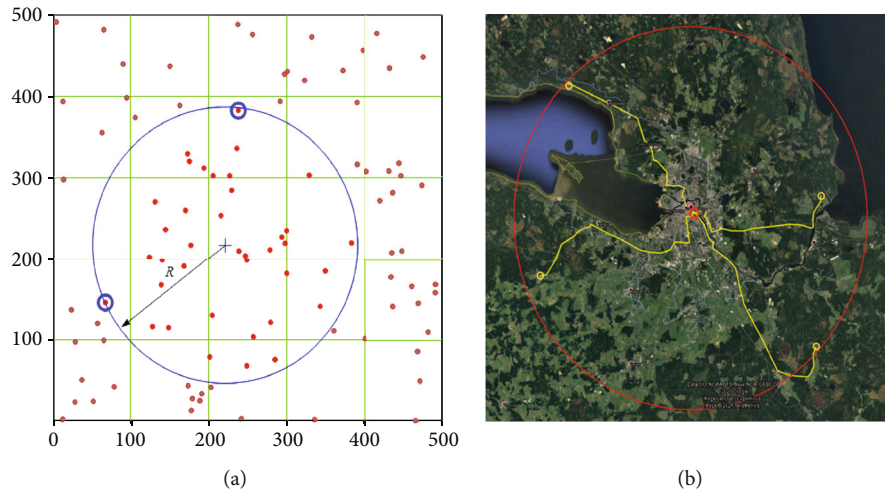


FIGURE 1: Example of applying the FOREL clustering method.

highest quality of service. In this case, a cluster is understood as a group of subscriber units served by one base station [14].

A second example of clustering would be the distribution of users across access nodes, for example, on an access network in a large apartment building. In this case, the criterion can be both the length of the subscriber line and the bandwidth guaranteed to the user. It should be noted that despite the existence of many approaches and methods for solving these problems, one cannot be completely sure that the problems are solved in an optimal way. In general, these problems are multiobjective optimization problems and their exact solution is often unattainable. Most of the methods used make it possible to obtain partial solutions that are not the worst or close to optimal ones. In this sense, clustering problems always attract the attention of researchers.

Device clustering is also used when using direct connections between devices (D2D connections) [4, 15, 16]. In this case, it is also required to select a group of users by the criterion of traffic quality of service, only one of the users of the group, which has a connection with the base station, acting as an access point. Other scenarios for forming a group of D2D users are also possible, but in any case, one of the criteria is the quality of service.

In this paper, the clustering problem is considered in relation to the problem of minimizing the data delivery delay. The component of the delay introduced by the propagation time of an electromagnetic or optical signal in the propagation medium is specifically considered. We consider cable communication lines, most likely optical lines, as a distribution medium. In advanced communication systems, signal propagation time is important for the organization of connections with ultralow URLLC delays. Such connections are required to provide services with increased latency requirements, such as telecontrol, telemedicine (in terms of medical equipment control), and the industrial Internet of things. The solution of the clustering problem according to the propagation delay criterion is practically equivalent to its solution according to the distance criterion; however, the complexity of the solution lies in the fact that the distance, defined as the geometrical or geographical distance

between points on a plane or a geographic map, does not give an unambiguous characteristic of the length of the communication line between the points under consideration. The reason for this is that cable lines are laid along existing roads that cannot be described by a straight line. In this sense, it is also not efficient to determine, for example, the length of the route between points, since there is absolutely no certainty that the route of the communication line will be close to this route.

In [5, 17], a method of network clustering is proposed, taking into account the signal propagation time, based on the assumption of the presence of direct (rectilinear) connections between network elements. The method considered in the work is based on the use of the FOREL clustering algorithm and allows you to select clusters of elements by the criterion of the distance between these elements and the center of the cluster. In this case, the maximum distance between the center of the cluster and its element is determined along a straight line. This method makes it possible to obtain a solution in which the distances between the centers of the obtained clusters and the most distant elements of these clusters do not exceed a given value.

In [7], a development of the method proposed in the mentioned work is proposed, taking into account the existence of various requirements for the magnitude of the delay, i.e., when providing several time-critical services, the points of provision of which it is desirable to combine in the same network nodes. The proposed by the authors allows you to distinguish clusters of various sizes, depending on the set of services and requirements for the amount of delay. An important feature of this method is that the centers of these clusters are aligned. This is done because when implementing a network, it is advisable to combine the functions of providing several services in one network node. This method, like the one mentioned above, assumes that the points of service are located in the centers of the found clusters.

Both of these methods, as noted above, give a significant overestimation of the cluster sizes, since the actual lengths of the connecting lines will be significantly greater than the linear distances between the points. When choosing the size of

the clusters according to the above methods, the actual lengths of communication lines will exceed the calculated values, which will lead to an overestimation of the delay. In other words, when using them, there is a high probability that the calculated amount of delay will be exceeded. This is an extremely unpleasant situation, since it is possible to reduce the amount of delay only by changing the length of the communication lines, which is associated with significant material costs. Thus, in this case, the quality of solving the clustering problem directly affects the quality of the provision of latency-critical services.

The proposed method makes it possible to take into account the peculiarities of the road network, which make it possible to take into account the “curvature” of existing roads and, on the basis of this knowledge, make adjustments to the solution of the clustering problem. The advantage of the proposed method is that it allows one to obtain a solution that, in terms of the quality of the solution, surpasses the methods described above, due to the fact that the cluster size in this case will be smaller; therefore, the probability of exceeding the delay standard will also be less. The proposed method makes it possible to make a reasonable choice of the cluster size reduction factor.

4. Solution

Assume that cable routes between the service provision point and the endpoint (cluster element) are laid along the existed road. In other words, cable routes are not making a straight line between elements. That the real length of the route L_T will be not smaller than the straight line L_0 that connects the elements:

$$L_T \leq L_0. \quad (1)$$

Also, assume that the road infrastructure is sufficiently developed. So, the cable route still tends to a straight line between points and does not “loop” endlessly within the cluster, for example, like a fractal line [18–21]. This assumption is possible because the points in the model coincide with settlements, each of which is reachable by a route of a finite length.

If L_{\max} is the maximum length of the route, so the following condition must be met: $L_T \leq L_{\max}$. The radius of the assumed cluster should also be less than this value (see Figure 2):

$$R \leq L_{\max}. \quad (2)$$

The value of R should ensure the fulfillment of these conditions. We will proceed from the assumption that the increase in the length of the route is proportional to the fractal dimension of the roads in the territory of the proposed cluster:

$$\Delta L = L_T - L_0 \propto D. \quad (3)$$

Equation (3) shows that D is the fractal dimension. If $L_0 = L_{\max}$, then $\Delta L = \Delta R$.

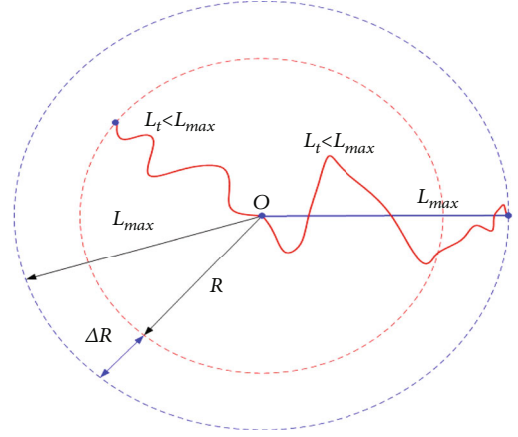


FIGURE 2: Cluster model.

To clarify the method for assessing the fractal dimension, Figure 3 shows an example in which two points located at equal distances are connected in the first case by a straight line and in the second case by an arbitrary curve.

Both lines are covered with some amount of squares with side size τ . There are various methods for estimating the fractal dimension [20]. In particular, circles with the radius τ could be used instead of the square. However, in most practical implementations (programs) of the fractal dimension estimation, the Minkowski method (box-counting) is used, which involves the construction of a grid and counting the cells through which the line $n(\tau)$ passes, which in this case is equivalent to covering with squares.

According to the definition, the fractal dimension (FD) of the line is equal to the following limit [19, 20]:

$$D = \lim_{\tau \rightarrow 0} \frac{\ln n(\tau)}{\ln \tau}, \quad (4)$$

where $n(\tau)$ is the number of elements of the covering of size τ .

Figure 3 shows that the bigger line requires a bigger number of elements to cover. Also, the line size might be measured in the numbers of these elements. The smaller element size brings the smaller measured error $n(\tau)\tau \rightarrow L$.

However, if the measurement is performed for a fractal object (i.e., not a model, but an object of the real world), then, according to the theory of fractals, the number of coverage elements and the total length of the coverage will tend to infinity:

$$n(\tau) \xrightarrow{\tau \rightarrow 0} \infty. \quad (5)$$

The fundamental relation [19, 20] which caused Equation (4) established the correlation between the line length and the size of the coverage element as

$$L \propto \frac{1}{\tau^D}. \quad (6)$$

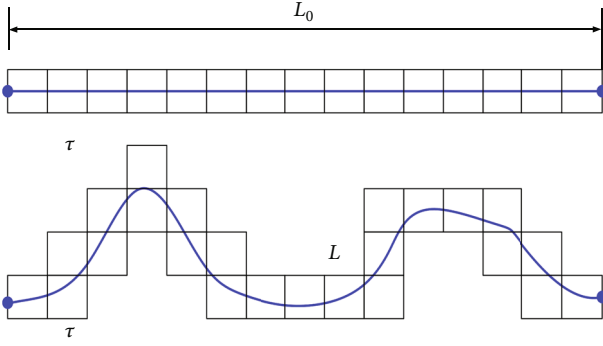


FIGURE 3: The fractal dimension estimation illustration.

Let us introduce the variable a into expression (6) to pass to the equal sign:

$$L = \frac{a}{\tau^D}. \quad (7)$$

It is known from [20] that for a straight line of FD $D = 1$, then based on Formula (7), it is possible to write a system of two equations:

$$\begin{cases} a\tau^{-1} = R, \\ a\tau^{-D} = L_{\max}, \end{cases} \quad (8)$$

where R is the desired cluster radius, L_{\max} is a maximum route length, D is a fractal dimension, and a is an unknown variable.

The first equation in the system is written for a straight line segment connecting the center of the cluster with a point on its edge, i.e., a line whose length equals the radius. Therefore, the exponent t is minus 1, i.e., equal to a straight line's fractal dimension.

The second equation is written for a line, which is a trace with fractal dimension D . In this case, the trace length is equal to the maximum route length L_{\max} .

The system solution is the following:

$$R(D) = L_{\max} \tau^{D-1}, \quad (9)$$

where τ is the coverage element size.

Figure 4 shows two examples: straight routes from the cluster center to the edge (see Figure 4(a)) and joggle lines (see Figure 4(b)). The fractal dimension estimation for Figure 4(a) is $D = 1.002$ and for Figure 4(b) is $D = 1.108$. The fractal dimension was estimated using the program [21].

In the first case (Figure 4(a)), the routes are straight lines, and the FD of straight lines should be equal to one, which is confirmed with sufficiently high accuracy by measurement. In this case, the cluster radius coincides with L_{\max} . In the second case (Figure 4(b)), the FD is greater than one, and according to Equation (9), the radius should be 0.62 of L_{\max} .

Figure 4(b) also shows a circle, which results from a decrease in the cluster size due to the "curvature" of the traces.

For greater generality, let us assume that $L_{\max} = 1$; the dependence of the radius of the assumed cluster on the fractal one will look as shown in Figure 5.

The range of the fractal dimension is selected from 1 to 2, which corresponds to the possible values for the lines, i.e., from a straight line to a line filling the entire plane. As can be seen from the figure, the cluster radius decreases with increasing fractal dimension. It is especially worth noting the role of the τ in this dependence.

In Figure 5, the red curve presents the route length $L_0 = 50$ km at intervals of 1 km ($\tau = 0.02$), the black curve the same route length at intervals of 1 m, and the blue at intervals of 45 km. The dependence on τ is obvious and is explained by the fractal nature of the measured objects.

The cable route is outwardly different from the coastline, but this difference does not affect the essence, i.e., these objects are objects of the surrounding world. Therefore, the "coastline paradox" [19, 20, 22], which consists in the fact that when the length of the metric τ decreases, its length tends to infinity, to the same extent, applies to this problem.

This is shown in Figure 5. When $\tau = 1$, i.e., when the length of the metric is equal to the length L_0 , naturally, there is no dependence; the graph will coincide with the abscissa axis.

With the length of the metric $\tau \rightarrow 0$, the cluster size also tends to zero $R(\tau) \rightarrow 0$. So, by definition, the length of the fractal line tends to infinity.

All applications essential for practice must operate with τ values between these boundaries. In other words, it is necessary to determine such a value τ that corresponds to the real possibilities and needs for each task. Within the framework of this work, it is advisable to choose t , proceeding from the permissible error in estimating the magnitude of the delay.

If the permissible error in estimating the delay is Δt , then, this will correspond to the value of the permissible error in a distance equal to

$$d = \Delta t C, \quad (10)$$

where C is the speed of light propagation (m/sec).

Then, it is advisable to choose τ based on the d value since this is the size of the metric, and the error is equal to 1/2 of this value. We get the following:

$$\tau = \frac{2d}{L_0}. \quad (11)$$

For example, at $L_0 = 50000$ m, $\Delta t = 1 \mu\text{s}$, $d \approx 600$ m, and $\tau \approx 0.012$. But if we increase $\Delta t = 10 \mu\text{s}$, then $d \approx 6000$ m, and $\tau \approx 0.12$.

Figure 6 illustrates these results.

As shown in Figure 6, with real values of the fractal dimension (1-1.3), the cluster size can be more than half the line length L_{\max} .

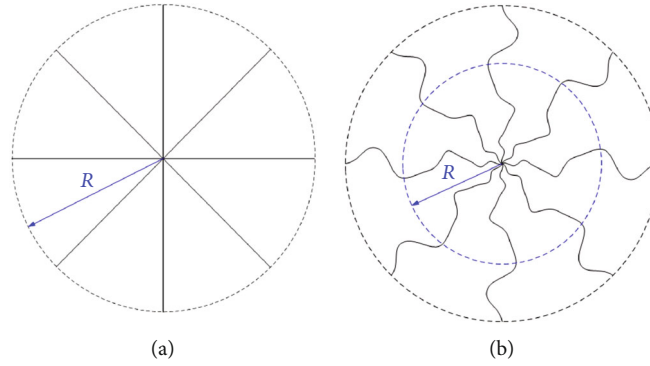


FIGURE 4: Examples of various cluster structures.

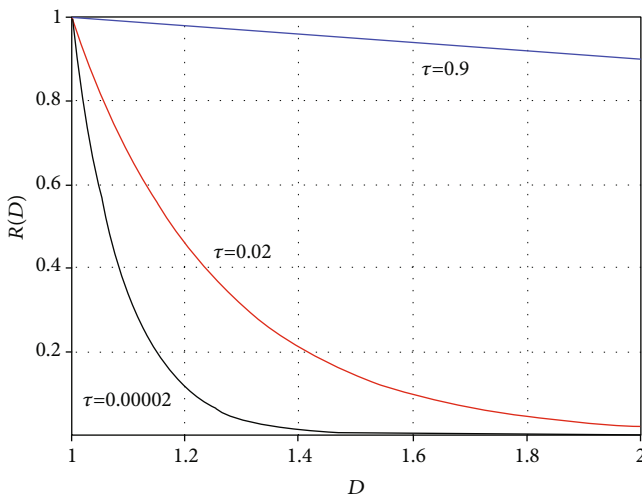
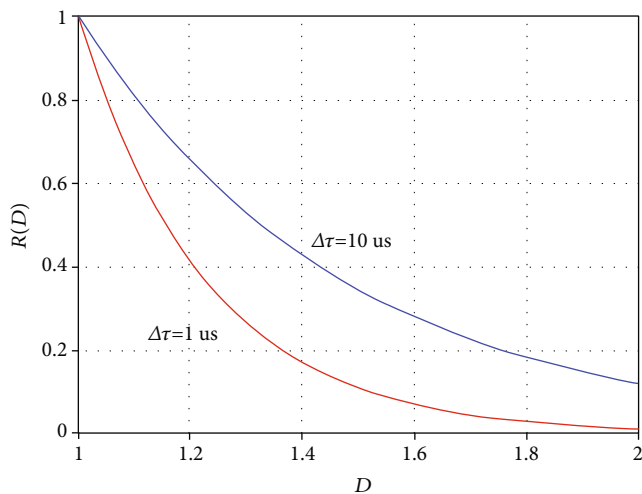


FIGURE 5: The dependence of the cluster radius on the fractal dimension (FD).

FIGURE 6: The dependence of the cluster radius to the fractal dimension (FD) (with a permissible error of the delay estimation of 1 and 10 μ s).

The redundancy of the trace length is assumed to be unchanged when the size (radius) of the cluster changes and the fractal dimension of the roads. With the uneven distribution of road properties within the original cluster, after adjusting its size (9), the length of the tracks may be underestimated or overestimated. To reduce the error, it is advisable to assess the fractal dimension in the cluster before adjusting the size and taking the fractal dimension's average value as the target value.

The model algorithm is shown in Figure 7.

The computational complexity of the given algorithm is determined by the complexity of the operations for estimating the fractal dimension of the road network. In practice, the assessment of the fractal dimension of an image depends on the size of the image (the number of pixels) and the features of the algorithm implementation. For example, for a 1080×720 image, the algorithm can be implemented by organizing cycles of counting the number of squares containing the points of the curves, starting from 72×72 (10 squares along the short side of the image) to 1 by 1 (this is the maximum number of cycles; usually, it is less). Each cycle requires about $1080/s \cdot 720/s$ operations, where s is the size of the side of the square. Then, for given image size, a maximum of about 1.3 million operations will be required.

Taking into account the performance of modern computers, the solution to this problem is not a significant problem. In practice, the time to solve it, when implementing the method for estimating fractal dimension in Java, is about one second.

The presented algorithm allows estimating the cluster size, taking into account the lengths of the existed cable routes. The clustering process itself can be implemented by complementing the method proposed in [7], based on the FOREL algorithm. The additions are to incorporate the above algorithm into the specified method before the next cluster search step. In contrast to the original method, in which the size of the cluster is chosen constant, this addition provides for the adaptation (change) of the size of each formed cluster, taking into account the peculiarities of the terrain in order to meet the requirements for the amount of delay.

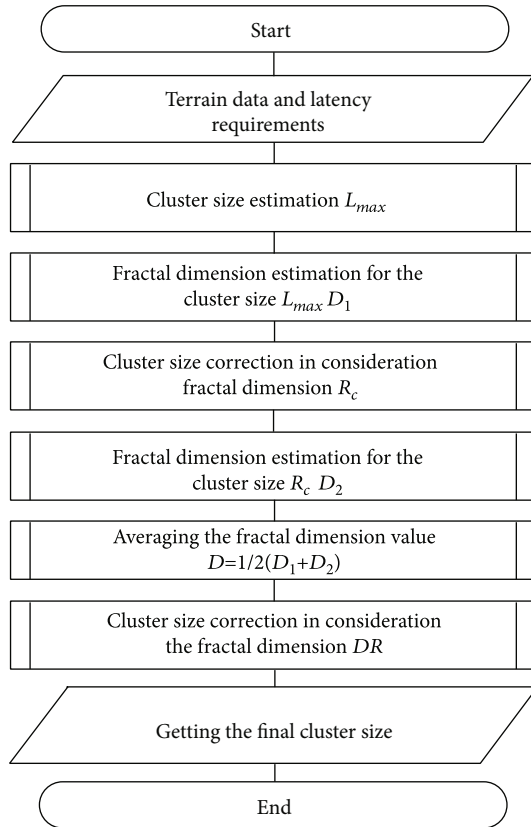


FIGURE 7: Cluster estimation algorithm.

The parameters of the proposed algorithm are selected in accordance with the requirements for the accuracy of estimating the delay value. According to the analysis and modeling performed, the following numerical values of the parameters can be recommended, which can be used in solving most practical problems. The parameter values are given in Table 1.

The proposed algorithm in Figure 7 contains two modules that require a significant investment of time: a block for estimating the size of a cluster and a block for estimating a fractal dimension. Cluster size estimation includes the clustering method, which in the worst case requires n^3 operations, where n is the number of clustered objects. The complexity of the fractal dimension estimation method depends on the image parameters and does not exceed d^2 , where d is the number of pixels.

Furthermore, this algorithm is applicable in cases where the area under consideration already contains a sufficiently developed network of roads. This condition is quite natural, since the method and algorithm are based on the assumption of cable laying along existing roads. If the considered area is devoid of roads or their construction is assumed, then the problem becomes degenerate. In this case, either it is impossible to assume in advance the plan for laying the cable or it is absolutely known, therefore, the solution to the problem is also known. Since the construction of a road network, as a rule, precedes the development of an infocommunication system, this algorithm is applicable in most cases for solving such problems.

TABLE 1: Algorithm parameters.

Fractal dimension	R reducing factor		
	Delay error ($\Delta = 10 \mu s$)	Delay error ($\Delta = 5 \mu s$)	Delay error ($\Delta = 1 \mu s$)
1.2	0.654	0.573	0.413
1.4	0.428	0.329	0.170
1.6	0.280	0.189	0.070
1.8	0.183	0.108	0.029
2.0	0.120	0.062	0.012

5. Experimental Environment and Setup

To carry out this work, we used Google Earth electronic maps [13], the Image Processing and Analysis in Java program for image processing and fractal dimension estimation [23], and the Mathcad program.

They were obtaining digital images of the plan of the area where the construction of a communication network is supposed to be realized by various means. These can be scans of paper maps or plans of the area or digital images obtained in another way. The simplest and most affordable way to obtain digital images, at present, is the use of digital maps of the area. Google Earth is perhaps the most advanced geographic system available. It allows you to receive images of various scales, make measurements, and enable or disable various map elements. However, in most cases, the resulting digital images require additional processing. The fact is that the parameters of the road structure are subject to assessment, but the digital image also contains other map elements. These elements must be excluded when evaluating the fractal dimension. When performing the experiments, the results of which were given above; we used Google Earth processing tools, a graphics editor, and an image processing program [23]. The processing process was not fully formalized. At the first step, on the digital image, the roads were highlighted in color, which was taken into consideration. Also, all labels and unrelated map elements were turned off on the map, which could be excluded by means of Google Earth. A digital image was formed in the form of a separate graphic file. On the second template, this image was processed in a graphical editor, where the roads were highlighted, and all other elements of the map were deleted. At the third stage, the Image Processing and Analysis in Java program [23] was used, in which the final image processing (setting the contrast threshold) and the evaluation of the fractal dimension were performed.

It should be noted that the process described above is not entirely formal since the second step is human editing of the image. The amount of uncertainty introduced by the actions of the editor is very small, since these actions are aimed at highlighting well-defined objects and removing unnecessary objects in the image and are mainly determined by erroneous actions. To a greater extent, this process is reflected in the complexity, which is determined by the stage of manual editing. Note also that the entire described sequence of operations can be fully formalized and implemented in the form of software. This will eliminate the factor of errors introduced by

manual image editing. Since this work was research work, such a task was not set in it.

Full formalization of image processing will be implemented in the course of further work.

The analytical dependencies shown in Figures 5 and 6 were obtained using the Mathcad program.

6. Conclusions

Choosing the cluster size of an ultralow latency network, one should consider the specifics of laying communication lines between the point of service provision and the points of connection of users. This feature, as a rule, consists in the fact that the route of laying communication lines runs along existing roads. Therefore, the structure of the existing road route influences the choice of routes for laying communication lines. Given this feature, the length of the communication line, in most cases, turns out to be greater than the distance between the connected points. For a cluster, this leads to an overestimation of the delay relative to the target values. In addition, it is necessary to select the cluster size to consider the length of the cable routing to avoid overestimating the delay. The proposed algorithm assesses the cluster size and considers route lengths based on assessing the fractal dimension of the road in the area. The value of the fractal dimension makes it possible to assess the degree of difference between the laying routes and straight lines and, as a result, determine the coefficient by which it is necessary to reduce the size of the assumed cluster. Moreover, the road's route unevenness may affect the underestimation or overestimation of the cluster size. It is essential to estimate the fractal dimension for the initial and corrected cluster sizes for its compensation. Then, use the averaged value of the fractal dimension for the final estimate of the cluster size.

Although the fractal dimension is estimated to improve the accuracy of the formation of digital clusters, its value significantly depends on the image processing method. Theretofore, in ongoing and future work, the proposed method will be further improved to include the processing of digital images with the objective of maximizing the formalization of the method to highlight roads as lines and exclude the influence of other image elements.

Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research is based on the Applied Scientific Research under the SPbSUT state assignment 2021.

References

- [1] G. Fettweis, H. Boche, T. Wiegand et al., *The Tactile Internet-ITU-T Technology Watch Report*, Int. Telecom, Union (ITU), Geneva, 2014.
- [2] ITU-T, "Signalling requirements and architecture of intelligent edge computing," <https://www.itu.int/rec/T-REC-Q.5001/en>.
- [3] A. al-Ansi, A. M. al-Ansi, A. Muthanna, I. A. Elgendy, and A. Koucheryavy, "Survey on intelligence edge computing in 6g: characteristics, challenges, potential use cases, and market drivers," *Future Internet*, vol. 13, no. 5, p. 118, 2021.
- [4] A. Muthanna, P. Masek, J. Hosek et al., "Analytical evaluation of d2d connectivity potential in 5g wireless systems," in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*, vol. 9870, pp. 395–403, Springer International Publishing, 2016.
- [5] V. I. Blanutsa, "Territorial structure of the russian digital economy: preliminary delimitation of smart urban agglomerations and regions," *Regional Research of Russia*, vol. 9, no. 4, pp. 318–328, 2019.
- [6] A. Alshahrani, I. A. Elgendy, A. Muthanna, A. M. Alghamdi, and A. Alshamrani, "Efficient multi-player computation offloading for vr edge-cloud computing systems," *Applied Sciences*, vol. 10, no. 16, p. 5515, 2020.
- [7] A. Paramonov, N. Chistova, M. Makolkina, and A. Koucheryavy, "The method of forming the digital clusters for fifth and beyond telecommunication networks structure based on the quality of service," in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*, vol. 12525, pp. 59–70, Springer, 2020.
- [8] A. A. Abd el-Latif, B. Abd-el-Atty, I. Mehmood, K. Muhammad, S. E. Venegas-Andraca, and J. Peng, "Quantum-inspired blockchain-based cybersecurity: securing smart edge utilities in iot-based smart cities," *Information Processing & Management*, vol. 58, no. 4, article 102549, 2021.
- [9] A. A. A. el-Latif, B. Abd-el-Atty, A. Belazi, and A. M. Iliyasu, "Efficient chaos-based substitution-box and its application to image encryption," *Electronics*, vol. 10, no. 12, p. 1392, 2021.
- [10] A. Alanezi, B. Abd-El-Atty, H. Kolivand, and A. A. Abd El-Latif, "Quantum based encryption approach for secure images," in *2021 1st International Conference on Artificial Intelligence and Data Analytics (CAIDA)*, pp. 176–181, Riyadh, Saudi Arabia, 2021.
- [11] I. A. Elgendy, W.-Z. Zhang, H. He, B. B. Gupta, and A. A. Abd El-Latif, "Joint computation offloading and task caching for multi-user and multi-task mec systems: reinforcement learning-based algorithms," *Wireless Networks*, vol. 27, no. 3, pp. 2023–2038, 2021.
- [12] W.-Z. Zhang, I. A. Elgendy, M. Hammad et al., "Secure and optimized load balancing for multitier iot and edge-cloud computing systems," *IEEE Internet of Things Journal*, vol. 8, no. 10, pp. 8119–8132, 2021.
- [13] The world's most detailed globe, "Google earth," <https://earth.google.com/web/>.
- [14] A. Jajszczyk, "Cognitive wireless communication networks (Hossian, E. and Bhargava, V.; 2007) [book review]," *IEEE Communications Magazine*, vol. 46, no. 11, pp. 18–18, 2008.
- [15] A. Paramonov, O. Hussain, K. Samouylov, A. Koucheryavy, R. Kirichek, and Y. Koucheryavy, "Clustering optimization for out-of-band D2D communications," *Wireless*

Communications and Mobile Computing, vol. 2017, Article ID 6747052, 11 pages, 2017.

- [16] R. Kirichek, A. Paramonov, A. Vladyko, and E. Borisov, "Implementation of the communication network for the multi-agent robotic systems," *International Journal of Embedded and Real-Time Communication Systems*, vol. 7, no. 1, pp. 48–63, 2016.
- [17] X. Li, A. Gani, R. Salleh, and O. Zakaria, "The future of mobile wireless communication networks," in *2009 International Conference on Communication Software and Networks*, pp. 554–557, Chengdu, Sichuan, China, 2009.
- [18] A. Paramonov, E. Tonkikh, A. Koucheryavy, and T. M. Tatarnikova, "High density internet of things network analysis," in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*, vol. 12525, pp. 307–316, Springer, 2020.
- [19] B. B. Mandelbrot and B. B. Mandelbrot, *The Fractal Geometry of Nature*, vol. 1, WH Freeman, New York, 1982.
- [20] A. Paramonov, A. Muthanna, O. I. Aboulola et al., "Beyond 5g network architecture study: fractal properties of access network," *Applied Sciences*, vol. 10, no. 20, p. 7191, 2020.
- [21] K. Falconer, *Fractal Geometry: Mathematical Foundations and Applications*, John Wiley & Sons, 2003.
- [22] Wolfram MathWorld Coastline Paradox, "Coastline paradox," <https://mathworld.wolfram.com/CoastlineParadox.html>.
- [23] ImageJ Disclaimer, "Image processing and analysis in java," <https://imagej.nih.gov/ij/>.