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DEVISING A METHOD FOR FORMING A STABLE MOBILE CLUSTER OF THE INTERNET OF THINGS FOG LAYER

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The object of this study is the process of clustering the fog layer of the Internet of Things (IoT) with high and ultra-high density.

The task to increase the stability of mobile components in the fog layer has been solved by modifying the clustering method.

In the process of conducting research, an approach was devised to form the architecture of the mobile component in the fog layer of the IoT. The development took into account the decentralization of the fog layer and the specific features of mobile IoT devices. This has made it possible to propose a four-level architecture, which, unlike the standard one, contains separate mobile clusters at the lower level of fog devices.

A model of a mobile cluster of the fog layer has been proposed, which takes into account the randomness of the mobile IoT devices movement and is based on the Thomas point process. Unlike existing models, it takes into account both spatial and stability indicators of mobile cluster components. This model has made it possible to modify the standard FOREL clustering algorithm. The modification was carried out by introducing weight coefficients when finding the position of the center of the mobile cluster.

The proposed method increases the stability of a mobile cluster of the IoT fog layer with high and ultra-high density. Studies of the proposed method have shown that with an increase in the average relative deviation of IoT devices from the planned movement, the stability of the mobile cluster structure increases.

The research results can be explained by the approach of the center of the mobile cluster to its most unstable components. The proposed method could be used in the clustering of the IoT fog layer with mobile components. The method is effective when the average deviation of the movement of IoT mobile devices from the planned movement is no more than 20 % of the cluster radius

Keywords: Internet of Things, clustering, mobile device, stability, ultra-high density, cloud infrastructure, fog computing

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1. Introduction

The Internet of Things (IoT) is increasingly becoming part of everyday life and is showing rapid technological growth [1, 2]. The IoT ecosystem includes a number of Internet-enabled devices that use embedded systems. These may include processors, sensors, and communication equipment to collect, send, and process the received data [3]. IoT data is analyzed on-site or sent to the cloud for analysis.

The Internet of Things is based on cloud computing technology [4]. However, in recent years, difficulties have arisen due to the following factors [5]:

– the geographical distribution of IoT components;
– increasing network latency;
– the high cost of communication channels;
– the mobility of IoT devices.

Most of these difficulties have been solved by introducing an additional layer, which has been termed fog computing [6].

Fog computing is a decentralized sub-network of the IoT ecosystem, located at the most efficient point between data sources and the cloud. Fog computing is a promising concept that involves bringing data processing closer to the end devices of networks and is a further development of the cloud concept [7]. Fog layer devices are used where data needs to be analyzed very quickly. Fog nodes provide partial processing and temporary storage of data before sending it to the cloud. A fog computing environment can use many devices and targets depending on the supported IoT system.

Fog computing also provides data analysis under a mode close to real-time, which is a primary need to minimize latency. In addition, any fog node could be implemented using a mobile IoT device [8]. Typically, mobile IoT devices are subject to a set of rules. But in most cases, the trajectory of their movement is a random variable.

In high- and ultra-high-density IoT networks, the fog layer is divided into a number of clusters [9]. Typically, the main criterion for clustering is the proximity of the fog nodes that are part of the cluster. But if there are mobile nodes in the fog infrastructure, the cluster structure may be disrupted due to the departure of a mobile node outside the cluster [10]. This will lead to unforeseen delays in processing IoT data. Therefore, for high- and ultra-high-density IoT systems, when performing clustering, it is necessary to take into account such a criterion as the stability of the cluster structure.

So, to eliminate unforeseen time delays in processing high-density IoT data, it is necessary to form stable mobile clusters in the fog layer. Therefore, the issue of devising a method for forming a stable mobile cluster of the fog layer of the Internet of Things is relevant.

2. Literature review and problem statement

The fog layer of the Internet of Things support network in most cases has a distributed decentralized structure. Therefore, when forming the architecture of the fog layer, its computing components are usually clustered. This task is significantly complicated in the case of mobile fog components.

In [11], the results of research on the use of fog mobile components for the implementation of intelligent applications are reported. However, issues related to the stability of mobile components remain unresolved. The reason for this is the focus of the research on the security of the mobile elements involved. One of the possible options for taking into account the stability of mobile components is proposed in [12]. In the study, the distributed mobile component of the fog layer is used to solve operational tasks of industrial IoT (IIoT). At the same time, one of the main indicators of the effectiveness of the proposed approach is the stability of the distributed components of the mobile component. However, the probable deviation of the involved mobile IIoT devices from the planned movement is not taken into account. This could lead to the destruction of the structure of the mobile component. Similar problems are possible when implementing the access control system for mobile components of the fog layer, proposed in [13].

In addition, in the considered works, the studies are based on static clustering, which is performed on a territorial basis. In this case, the formed clusters were not previously analyzed for stability.

When implementing the clustering technique in the fog layer, considered in work [14], the dynamics of mobile nodes of the fog layer are taken into account. In addition, the apparatus of sigmoidal neural networks is used. But the group of mobile devices is not considered separately from static nodes; accordingly, the issues of stability of the formed clusters are not considered. Also, in work [15], clustering issues are not focused on considering the stability of virtual clusters containing mobile IoT devices. In the study, the results of which are reported in [16], a multi-level architecture of a decentralized system is proposed. In this architecture, mobile and static clusters of devices of the fog environment of the IoT could be considered separately. This helps reduce delays in data processing. But the formed clusters do not take into account the probable deviation of mobile elements from the planned movement. Such deviations are taken into account in the study presented in work [17]. The study is aimed at resource management in distributed systems but is focused only on simple system topologies. Therefore, it cannot be used for high- and ultra-high-density IoT systems, as well as the algorithm proposed in [18]. This algorithm takes into account the features of mobile IoT devices, optimizes their performance and energy consumption, and is designed only for simple topologies of the infrastructure under consideration.

The decomposition approach proposed in [19] could be used when clustering the fog layer of high- or ultra-high-density IoT systems. But this approach is implemented only for static infrastructure of the fog environment. To take into account the available mobile components, one could use the algorithm for transferring the computational load given in [20]. This algorithm is focused on reducing delays when performing tasks in distributed systems. But this algorithm does not take into account the specific characteristics of the involved fog layer infrastructure of high- or ultra-high-density IoT systems.

Therefore, the considered scientific works related to clustering the fog layer of the Internet of Things do not take into detailed account the characteristic features of high- and ultra-high-density IoT. In addition, most works for mobile components do not take into account such a criterion as the stability of the fog environment. This could lead to the destruction of the structure of the fog device network. Therefore, it is advisable to conduct a study aimed at increasing the stability of mobile components of the fog layer by modifying the clustering method.

3. The aim and objectives of the study

The aim of our work is to devise a method for forming a stable mobile cluster of the fog layer of the Internet of Things with high and ultra-high density. This will make it possible to increase the stability of a group of mobile IoT devices involved in the fog layer by bringing unstable elements closer to the centers of the clusters.

To achieve this goal, the following tasks were set:

– to devise an approach to forming the architecture of the mobile component of the fog layer of the Internet of Things with high and ultra-high density;

– to build a model of a mobile cluster of the fog layer;

– to devise and investigate a method for ensuring the stability of a mobile cluster of the fog layer of the Internet of Things with high and ultra-high density.

4. The study materials and methods

The object of our study is the process of clustering the fog layer of the Internet of Things with high and ultra-high density. The work considers mobile IoT devices that are components of the fog layer. These devices usually have significantly limited computing resources [21].

The main hypothesis of the study assumes that the implementation of a new method for forming a mobile fog layer cluster, based on the approximation of the cluster center to unstable elements, could make it possible to increase the stability of its structure. This would ensure an increase in the efficiency of the support system for the high or ultra-high density Internet of Things.

When devising the method, the following conditions guided us:

Condition 1. The fog layer contains several territorially separated mobile components consisting of IoT devices.

Condition 2. Mobile IoT devices in the process of movement strive to preserve its parameters.

Condition 3. Almost all mobile IoT devices used in the fog layer have limited computing resources.

Condition 4. The system of IoT devices has a high or ultra-high density in three-dimensional space.

A number of different methods have been applied in the process of clustering the fog layer of the Internet of Things.

When building the fog layer model, the Thomas point field model with random clustering effects was used to describe the relative position of network elements [22]. In this model, it is assumed that in some region of space D, point objects $c_1, c_2, \ldots, c_n$ are randomly distributed. Each of these objects could be considered as a certain cluster center. Accordingly, each cluster center c_i is associated with a certain random variable y_i, which characterizes the number of objects included in it.

Random variables $y_1, y_2, \ldots, y_n$ are usually considered to be mutually independent and equally distributed. The effects of clustering of point objects are usually observed in the vicinity of cluster centers. The position of each element in the cluster is characterized by a three-dimensional normal distribution with some standard deviation from the planned position in the space region D.

When devising a method for ensuring the stability of a fog layer cluster with mobile components, centroid clustering algorithms were considered [23, 24]. When forming a cluster, these algorithms usually use as a criterion the minimization of the value Θ – the total distance from the center of the cluster to its elements:

$$\Theta \underset{pos(C)}{\rightarrow} \min;\ \Theta=\sum_{i=1}^{k} d_{i0},\ pos(C)\in D,\ k\in\overline{1,n},\ i\in\overline{1,k}, \tag{1}$$

where C is the cluster center, d_{i0} is the distance from the i-th element to the cluster center, k is the number of elements in the cluster, n is the number of elements in the set to be clustered.

The minimization of function (1) is carried out by selecting the cluster centers, which are defined as the coordinates of the center of mass in the following way:

$$C=\left(x_c,y_c,z_c\right),\ x_c=\frac{1}{k}\sum_{i=1}^{k}x_{i0};$$

$$y_{jc}=\frac{1}{k}\sum_{i=1}^{k}y_{i0};\ z_{jc}=\frac{1}{k}\sum_{i=1}^{k}z_{i0}, \tag{2}$$

where (x_{i0}, y_{i0}, z_{i0}) are the spatial coordinates of the i-th element of the cluster.

The FOREL centroid algorithm, which is used in many IoT support systems [25], was considered as the basic clustering algorithm. The algorithm provides the ability to perform operations on the centers of clusters, which are known during the algorithm's operation. After executing the algorithm, some actions could be performed on the set of obtained clusters. For example, one could select the most representative objects from each cluster. One could select the centers of clusters or several objects from each cluster, taking into account a priori knowledge about the required representativeness of the sample. Therefore, from the finished clustering we have the opportunity to build the most representative sample. It is also possible to reshape the obtained set of clusters into a multilevel structure using the shortest open path method [26].

The main property of the algorithm is that the number of clusters is not predetermined. Each cluster is a layer whose radius is predetermined. As a result of the algorithm, each j-th of the m resulting clusters contains k_j elements. The following functional belongs to the minimization:

$$Func=\sum_{j=1}^{m}\sum_{i=1}^{k_j}\rho\left(e_i,C_j\right)\underset{\forall\left(e_i,C_j\right)}{\rightarrow}\min, \tag{3}$$

where $\rho(e_i, C_j)$ is the distance of the element e_i from the center of the cluster C_j to which it belongs in the current distribution.

The algorithm of the method is described by the following steps:

Step 0. The input value of the radius R is given.

Step 1. An arbitrary point in space is selected and a new object F is added.

Step 2. The current set K is formed, consisting of all objects to which the distance from F is less than R.

Step 3. The center of mass of all objects from the set K is found (card $K=k$), which will coincide for IoT objects with the center of mass, i.e.:

$$x_A=\sum_{e\in K}x_e\Big/k,\ y_A=\sum_{e\in K}y_e\Big/k,\ z_A=\sum_{e\in K}z_e\Big/k. \tag{4}$$

The object F is transferred to the obtained new center of mass. The value of the radius R is adjusted using the coefficient β $(0.5<\beta\leq 1)$: $R=\beta\cdot R$. The transition to step 2 is performed. The cycle of steps 2 and 3 is repeated until the set K stabilizes.

Step 4. When the set K stabilizes, it is declared a new cluster. Objects that fall into K are removed for consideration from the sample being clustered.

Step 5. If the considered set of IoT objects is not empty, the transition to step 1 is performed with the restoration of the value of the radius R. Otherwise, this algorithm ends.

To assess the effectiveness of clustering, the stability index of the system of m mobile clusters was used [27]:

$$\eta=\max\left(P_j^{-}\middle|\, j\in\overline{1,m}\right), \tag{5}$$

where P_j^{-} is the probability that the structure of the j-th cluster will be destroyed in a fixed period of time, that is, the smaller this indicator, the more stable the system will be.

5. Results of devising and investigating a method for increasing the stability of the mobile component of the fog layer of the Internet of Things

5.1. Formation of the architecture of the mobile component of the fog layer

The rapid development of the Internet of Things has led to the vertical expansion of the IoT concept by introducing an additional fog layer [28]. This layer is intermediate between the data processing centers (DPC) of the cloud layer and the sensors and IoT devices. The cloud layer receives pre-formatted data and can store it for a long time, analyze it, etc. The fog layer contains routers, gateways, routers, individual servers, some IoT devices. They can partially process information before sending it to the cloud or urgently to operational control points. The IoT layer contains things, that is, all sensors, mobile devices, cameras that collect the necessary information.

Such vertical integration of IoT infrastructure has a number of advantages [29]:

– low response time for operational IoT transactions (the fog layer is territorially closer to users and is able to provide instant response);

– reduced requirements for the bandwidth of communication channels with the cloud due to the possibility of distributed aggregation of information flows;

– reduced probability of loss of connection due to the presence of parallel communication channels;

– increased data security, since data is processed by a huge number of nodes in a complex distributed system;

– improved user interface due to instant response and no downtime;

– increased energy efficiency, because a number of fog nodes use high-performance protocols such as Bluetooth, Zigbee, Z-wave.

The general principles of building a cloud computing architecture to support the Internet of Things have been preserved for the concept of fog computing [30]. But for fog computing this is a more difficult task. The reason is not only the decentralized nature of the fog layer but also the limited computing and network resources.

Communication with data centers is supported using a distributed decentralized core of the fog layer [31]. The fog layer unites all devices into a single access and aggregation network with IoT nodes that have computing resources that are not fully used.

The fog layer architecture of the IoT support network contains the following modules [32]:

– hardware platform modules that must provide stable network connectivity via wired and wireless technologies;

– accelerators, which are built-in modules installed on the hardware platform of fog computing;

– computing modules that provide the necessary computing power of the devices;

– memory modules that are a standard part of the computing system;

– security modules;

– control modules that are responsible for managing other modules of the hardware platform of fog computing;

– modules that provide virtualization or containerization of all hardware platform resources to initialize virtual machines or containers for deploying fog computing services.

Due to the modularity of the cloud computing platform and the separation of levels, it is possible to supplement the architecture both vertically and horizontally. The integration of fog computing in the communication network significantly improves existing IoT models in terms of quality of service (QoS) requirements.

When forming the architecture of the fog layer, it is also necessary to take into account the specific features of some types of modern IoT systems. The use of devices with small amounts of computing and network resources as computing nodes of a fog network cluster is becoming increasingly widespread. High- and ultra-high-density Internet of Things networks are also becoming increasingly popular. Typically, such networks are territorially distributed and spatial. Clustering fog layer devices for IoT increases the efficiency of the IoT system.

In addition, a certain physical feature of promising IoT networks should be taken into account – the mobility of a number of devices or network segments, that is, their ability to move in space. There are many examples that suggest placing fog nodes on mobile platforms that could move in space. This, for example, is the use of unmanned aerial vehicles as either IoT nodes or fog cluster nodes.

One of the tasks of research in the area of fog computing is to study fog taking into account the mobility of Fog devices. Fog devices could be both "last mile" network devices, user devices, and Internet of Things devices. This helps strengthen network slicing. Each of the mobile fog computing clusters could be defined by some essential criteria. This could be, for example, the mobility of the devices that make it up (speed and motion vector), or the time it takes to perform a computational task on the cluster devices.

Therefore, when designing an ultra-high-density fog layer architecture for the Internet of Things with mobile components, the following levels are required:

– the highest, cloud level, which performs centralized processing of IoT data using the corresponding DPCs;

– the level of ensuring the interaction of the IoT system with cloud components, which consists of the fog layer core servers;

– the level of fog layer devices combined into clusters that support interaction with any of the fog layer core servers;

– the lower level of the IoT system, which consists of devices for directly obtaining information from physical objects.

A fragment of the proposed architecture is shown in Fig. 1.

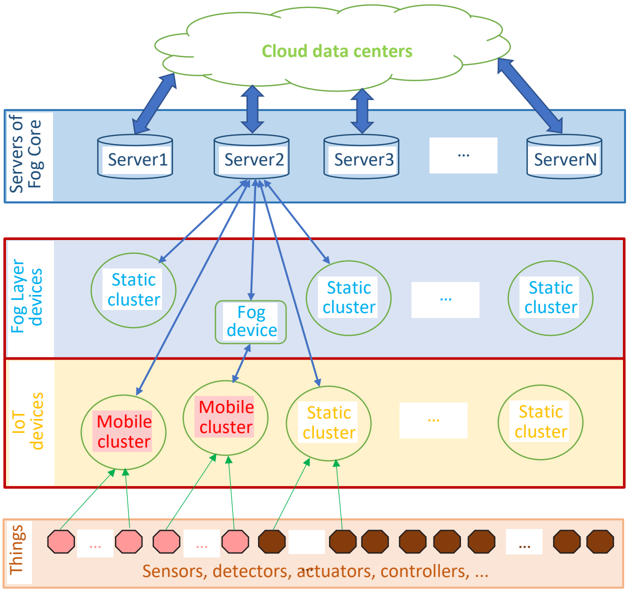

Fig. 1. Fragment of an ultra-high-density IoT fog layer architecture with mobile components

The efficiency of the IoT system with high and ultra-high density significantly depends on the quality of the clustering performed. The division of fog devices into clusters affects QoS indicators, especially when performing operational transactions, for which time criteria are the main ones. In turn, the processing time of an IoT transaction for static clusters mainly depends on the characteristics of intra-cluster communication channels. But for mobile clusters, the stability indicators of the cluster structure come to the fore, for the study of which it is necessary to build an appropriate model.

5. 2. Mobile fog layer cluster model

In many cases, the arrangement of fog layer devices in a high- and ultra-high-density IoT network is characterized by a limited volume. In this case, fog devices are placed at a relatively small distance from each other. The size of such a distance, for example, could be determined by the communication range provided by the access network standard. In addition, the network structure is significantly affected by the mutual location of fog devices. It is also necessary to take into account the mobility of the fog devices themselves, as a result of which the architecture and mutual location of the devices may change. In addition, the exit of a mobile device involved in the fog layer from the communication zone leads to partial destruction of the fog structure. This, in turn, leads to unplanned delays in processing information coming from IoT sensors and a decrease in QoS indicators.

Therefore, the mobile cluster model should be focused not only on spatial indicators but also on the stability characteristics of the cluster. The model would describe the functioning of the cluster under conditions of dynamic changes in the architecture due to the movement of fog devices. When building a model, assumptions must be accepted about the nature of the motion of dynamic fog computing devices. In theory, the motion may vary from absolute stillness to Brownian motion.

In most cases, for dynamic fog computing based on mobile IoT devices, groups of devices are operated – swarms. In swarms, devices tend to preserve common parameters of movement.

For example, parameters of car movement are determined by accepted rules and road features. When forming dynamic fog clusters in high-density IoT systems, we select groups of mobile densely placed devices. Such devices try to preserve their position relative to other members of the group.

To describe the mutual position of elements in the dynamic fog computing network supporting the IoT, it is proposed to use the Thomas point process model. For this purpose, the arrangement scheme of a group of mobile IoT devices in three-dimensional space at the beginning of movement is considered (Fig. 2). In this scheme, individual elements of the group of mobile IoT devices $e_1, \ldots, e_k, \ldots$ are included in the cluster K_j and are located in the current positions. These positions are given by the organization rules for IoT devices and are currently fixed relative to the center of this cluster, indicated in the scheme as C_j. All elements of the cluster together can move with equal speeds in the same direction.

Therefore, the distance between the IoT device and the center of the cluster K_j in three-dimensional space could be determined from the following expression:

$$d_{ji0}=\sqrt{\left(x_{ji}-x_{jc}\right)^2+\left(y_{ji}-y_{jc}\right)^2+\left(z_{ji}-z_{jc}\right)^2}, \qquad (6)$$

where x_{ji}, x_{jc}, y_{ji}, y_{jc}, z_{ji}, z_{jc} are the current coordinates of IoT devices and, accordingly, of the cluster coordinator K_j, the point C_j.

At the same time, if the center of the cluster C_j is taken as the origin of coordinates, then the cluster elements will be relatively stationary relative to its center.

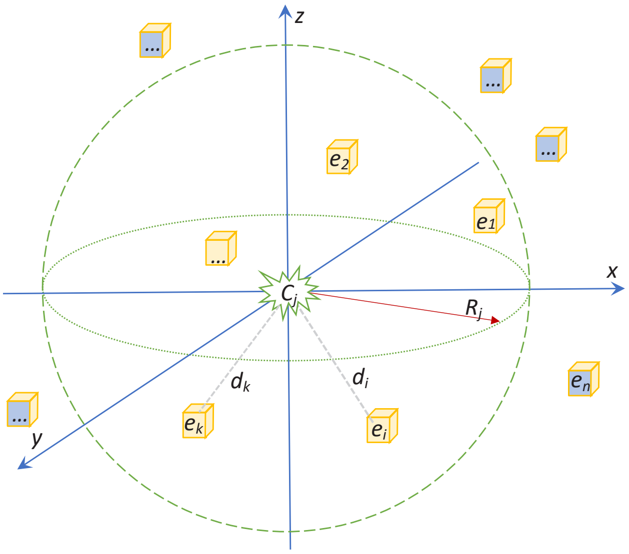

Fig. 2. Layout of a group of IoT devices in three-dimensional space

But in the process of real movement, the speeds and directions of movement of individual mobile elements may differ slightly. This leads to their deviation from the given positions in the cluster. Therefore, the coordinates x_{ji}, y_{ji}, z_{ji} are random variables. Note that mobile IoT devices in most cases maintain their own position relative to other members of the group. Let us assume that the random coordinates of dynamic IoT devices have a normal distribution. Let the initial position of the i-th device in the coordinate system of the cluster K_j be point A_{ji0} $(x_{ji0}, y_{ji0}, z_{ji0})$, and the current position be point A_{ji} (x_{ji}, y_{ji}, z_{ji}). Then the deviation of the device from the initial position is calculated as:

$$\xi_{ji}=\sqrt{\left(x_{ji}-x_{ji0}\right)^2+\left(y_{ji}-y_{ji0}\right)^2+\left(z_{ji}-z_{ji0}\right)^2}. \qquad (7)$$

The ξ_{ji} value does not depend on the choice of coordinate systems, i.e., $\xi_{ji}=\xi_i$ $\forall i$. The deviation ξ_i is a random variable distributed according to the normal law with the probability density function:

$$f\left(\xi_i\right)=\frac{1}{\sigma_i\sqrt{2\pi}}\cdot\exp\left(-\frac{1}{2}\left(\xi_i/\sigma_i\right)^2\right), \qquad (8)$$

where σ_i is the root mean square deviation of the random variable ξ_i from the initial position of the i-th device.

Next, we consider an IoT device e_i, which belongs to the cluster K_j with a radius of the reachable zone R_j. Let d_{ji0} be the distance between the initial position e_i and the center of the cluster K_j. In the process of movement, the device e_i can practically deviate from the initial position by no more than $3\sigma_i$. Therefore, all current positions of the device must be in a sphere with a radius R_j centered at the initial position. The exit of any mobile device outside this sphere will lead to the destruction of the structure of the cluster K_j.

The probability that the IoT device e_i will be in the reachable zone of the cluster K_j is as follows:

$$P_{ji}^{+} \to P_{ji}^{(theor+)} = \\ = \begin{cases} 1, & \text{else} \quad 3\sigma_i + d_{ji0} \le R_j; \\ 0.5 + \Phi\left(3\sigma_i + d_{ji0} - R_j\right), & \text{else} \quad 3\sigma_i + d_{ji0} > R_j, \end{cases} \tag{9}$$

where $\Phi\left(\xi_i\right) = \frac{1}{\sqrt{2\pi}} \int\limits_0^{\xi_i} \exp\left(-\frac{t^2}{2}\right) \mathrm{dt}$ is the value of the Laplace function for distribution (8).

Then the probability that the cluster K_j structure will be destroyed, that is, at least one of the devices will go beyond the coordinator's reach, will equal:

$$P_j^{-} = 1 - \sum_{i=1}^{k_j} P_{ji}^{+}, \tag{10}$$

where k_j is the number of cluster K_j elements.

As a criterion for forming a mobile cluster, we shall take the maximum stability of the cluster of fog computing. By the stability of the cluster, we shall understand the probability of preserving its structure, that is, the probability of the presence of a connection between the central device and all cluster elements. Then the objective function when forming a cluster structure is the following expression:

$$\max_j \left(\min_{pos\left(C_j\right)} \left(1 - \sum_{i=1}^{k_j} P_{ji}^{+} \right) \right), \; pos\left(C_j\right) \in D, \; k_j \in \overline{1,n}, \tag{11}$$

where D is the IoT service area; $pos\ (C_j)$ is the position of the center of the cluster K_j in three-dimensional space; n is the size of the group of mobile devices of the IoT system being clustered.

5. 3. Devising and investigating the effectiveness of a method for ensuring the stability of a mobile cluster of the fog layer

The stability of a cluster consisting of mobile IoT devices is ensured by preserving its structure. When deploying fog computing based on ground mobile systems, the main coordinating device could be the network device of the air segment of the IoT. It should have such a position in the cluster that would maximally ensure the stability of the cluster when the group of mobile devices of the fog layer moves. Therefore, it is necessary to minimize the probability of any device leaving the cluster during random movements of IoT devices.

When clustering devices of the fog layer of the Internet of Things with high and ultra-high density, centroid clustering algorithms are usually used. These algorithms minimize the total distance from fog devices to the centers of clusters in accordance with expression (1).

For clustering a group of mobile devices D, the centroid FOREL algorithm was chosen, which provides the ability to vary the parameters of clusters and their centers. The FOREL algorithm is based on the principle of cluster formation in places of concentration of IoT objects. According to this algorithm and expression (1), for group D during clustering the functional Θ is minimized:

$$\Theta \underset{pos\left(C_j\right)}{\to} \min;$$

$$\Theta = \sum_{j=1}^{m} \sum_{i=1}^{k_j} d_{ji0}, \; pos\left(C_j\right) \in D, \; k_j \in \overline{1,n}, \; j \in \overline{1,m}, \tag{12}$$

where m is the number of clusters in the group of dynamic IoT devices obtained after executing the FOREL algorithm.

The stability of a mobile cluster increases as the center of a mobile fog device approaches the center of the cluster. Therefore, it is desirable to move the center of the cluster closer to the cluster of devices. This could be done by introducing weight coefficients that affect the position of the cluster center. The weight coefficient is related to the conditional mass of the corresponding fog device. If the weight coefficient of an element is much larger than the weight coefficients of other elements, then the center of the cluster will shift to this element.

The coordinates of the center of mass of the cluster taking into account the weight coefficients and formula (2) will be as follows:

$$C_j = \left(x_{jc}, y_{jc}, z_{jc}\right); \; x_{jc} = \frac{1}{k_j} \sum_{i=1}^{k_j} \gamma_i x_{ji0};$$

$$y_{jc} = \frac{1}{k_j} \sum_{i=1}^{k_j} \gamma_i y_{ji0}; \;\; z_{jc} = \frac{1}{k_j} \sum_{i=1}^{k_j} \gamma_i z_{ji0}, \tag{13}$$

where γ_i is the weight coefficient of the mobile IoT device e_i.

The cluster stability criterion is taken into account using the weight coefficient of the mobile IoT device e_i:

$$w_i = \sigma_i^s, \; 0 \le s \le 1, \tag{14}$$

where s is a coefficient that determines the sensitivity of the method to random deviations of cluster elements from the initial position.

The choice of the value of this coefficient is determined by the significance of the cluster stability criterion for the problem being solved. When $s=0$, cluster stability is not taken into account as a criterion. When $s=1$, the cluster stability criterion has the maximum impact on the cluster formation process.

In addition to introducing weighting coefficients, step 2 of the FOREL algorithm is modified. At this step, only those mobile IoT objects are selected for the current cluster for which the condition $P_{ji}^{(theor+)} = 1$ is met. This makes the probability of any mobile object leaving the cluster minimal. Of course, the number of clusters may increase, but the stability of the resulting clusters will increase significantly.

For the clustering task using the modified FOREL algorithm, additional input data is required:

– initial coordinates of the elements of the group of mobile IoT devices, which are mathematical expectations of the coordinates of the elements;

– root mean square deviations of the positions of mobile IoT devices.

Such data could be obtained by collecting relevant statistics over a sufficient time interval.

To assess the effectiveness of the modified method, a simulation model was used. The elements of the mobile device group in the model formed heterogeneous clusters, i.e., different in composition and nature of placement. The coordinates of mobile devices were considered as values of random variables distributed according to the normal law. The parameters of the corresponding normal distributions for each element e_i were given by the zero mathematical expectation $\mu_i=0$ and the standard deviation σ_i. The spread of deviations of elements from the initial positions was different for different elements. The following restriction was imposed on the standard deviation: $R/60 < \sigma_i < R/12$, which is dictated by the characteristics of mobile IoT devices.

The effectiveness of the modified method is assessed in comparison with the cluster formation method, which is based only on the distance criterion between elements. The assessment was carried out using the system stability indicator calculated from expression (9). During modeling, the coefficient s, which determines the sensitivity of the method to random deviations, changed discretely with a step of 0.2. Different variants of the size of the group of mobile devices were simulated: $n \in \{50, 150, 300\}$. The model also used the indicator of the average statistical limit of possible deviations of mobile devices from the planned trajectories:

$$\sigma = 3\sum_{i=1}^{n} \sigma_i \Big/ n. \qquad (15)$$

The generalized modeling results are given in Table 1.

Table 1

Generalized probabilities of destruction of a mobile structure

σ/R	m, s n	m_0	$s=0$	$s=0.2$	$s=0.4$	$s=0.6$	$s=0.8$	$s=1.0$	m_1
0.05	50	4	0.004	0.004	0.003	0.003	0.003	0.002	4
	150	9	0.022	0.017	0.012	0.010	0.007	0.005	10
	300	14	0.034	0.027	0.021	0.017	0.013	0.010	19
0.10	50	4	0.036	0.028	0.021	0.016	0.011	0.005	6
	150	9	0.105	0.079	0.053	0.031	0.019	0.008	14
	300	15	0.217	0.129	0.070	0.053	0.028	0.013	37
0.25	50	4	0.276	0.180	0.101	0.068	0.027	0.009	11
	150	10	0.320	0.147	0.088	0.052	0.033	0.011	34
	300	16	0.445	0.299	0.118	0.091	0.070	0.019	87

In Table 1, the column "$s=0$" corresponds to clustering in which the deviations of mobile elements of the fog layer are not taken into account. The number of clusters obtained in such clustering is given in the column "m_0". The column "$s=1$" corresponds to clustering, which is maximally oriented towards the stability of mobile clusters. In this case, the number of clusters obtained is given in the column "m_1".

6. Discussion of results based on devising a method for the virtual clustering of the Internet of Things edge environment

The architecture of the mobile component of the fog layer of the Internet of Things of high or ultra-high density has been designed. The specificity of such components were taken into account during the development. Three main layers of the architecture are highlighted, shown in Fig. 1. The structure of each of the above layers is justified and the relationships between them are shown. Particular attention in the proposed architecture has been paid to mobile components, which consist of the involved IoT devices. The presence of separate mobile components is a significant difference from existing architectural solutions for building fog infrastructure.

A model of a separate mobile cluster of the fog layer has been proposed. The main difference of this model is the orientation not only on spatial indicators but also on the stability characteristics of the cluster. To implement the model, the Thomas point process model was used (Fig. 2, formulas (7), (8)). The probabilistic characteristics of the movement of mobile components of the cluster were taken into account in formulas (9), (10). The objective function for forming the cluster structure was defined in formula (11). This model allowed us to devise a method for ensuring the stability of a mobile cluster of the fog layer. The effectiveness of clustering using the modified centroid algorithm FOREL (formulas (3), (4)) has been proven. This algorithm was modified by introducing weighting factors when finding the position of the center of the mobile cluster (formulas (13), (14)). This has made it possible to bring unstable components closer to the center of the cluster.

The simulation results showed that the effectiveness of the proposed method increases in the following cases:

– an increase in the values of the root mean square deviations (RMSD) of mobile devices from the planned trajectories of movement;

– an increase in the number of mobile devices used as elements of the fog layer.

This is explained by the fact that the clustering algorithm selects the position of the cluster center by bringing the center closer to the most unstable elements.

The effectiveness of the proposed method for ensuring the stability of a mobile cluster of the fog layer of the Internet of Things of high or ultra-high density was investigated. Comparative testing of the standard and modified methods (Table 1) showed the following results:

– with an increase in the RMS values of deviations of mobile devices from the planned trajectories of movement, the stability of the mobile cluster increases;

– with a ratio value of σ/R from 0.05 to 0.2, the use of the modified method makes it possible to increase the stability of the mobile structure by up to 20 %;

– with $\sigma/R > 0.2$, the use of the modified method is impractical due to the complication of controlling the components of the fog layer;

– with $\sigma/R < 0.05$, the stability of the mobile structure increases by no more than 5 %.

Our results based on investigating the method for ensuring the stability of the mobile cluster could be explained by approaching the centers of mobile clusters to unstable components.

Unlike [12], in which the structure of the mobile component of the IoT fog layer was proposed, our method for ensuring stability makes it possible to obtain a more stable structure. This becomes possible due to the consideration of the probable deviation of the involved mobile IoT devices from the planned movement when building a mobile cluster. Unlike [14], in which the clustering method in the fog layer was proposed, the modified architecture (Fig. 1) allowed us to increase the stability of mobile clusters. This becomes possible due to the allocation of separate territorially distributed groups of IoT mobile devices, the computational resources of which are involved in fog computing.

Therefore, the results allowed us to increase the stability of mobile components of the IoT fog layer of high or ultra-high density in terms of the probability of preserving its structure. Depending on the number and characteristics and the level of territorial separation of the groups of mobile devices, the stability of the mobile cluster increased by up to 20 %. This is explained by the consideration of the random movement of the involved mobile devices in the process of forming a mobile cluster.

But we note that at relatively large values of RMS, the number of clusters in comparison with the standard method begins to increase. This significantly complicates control over the fog layer components. Therefore, the proposed results should be applied when $\sigma/R < 0.2$. In addition, a significant limitation of the study is the presence of a system of IoT devices of high or ultra-high density. The study was conducted under conditions of territorial separation of mobile device groups.

A drawback of this study worth noting is that there is no restriction on the number of mobile clusters in the clustering process when unstable components increase. To eliminate this drawback, it is necessary to conduct additional studies on the influence of the size of the current radius of the mobile sphere on the reduction of the number of cluster elements.

As a future prospect, the following should be noted.

First, when the instability of the group of mobile IoT devices increases, some devices become isolated, that is, they are not included in the formed clusters. Additional research should be conducted on isolated components in the group of mobile clusters.

Second, it is necessary to add the possibility of unification or joint management for territorially close mobile clusters. This would simplify the process of managing unstable groups of mobile devices.

7. Conclusions

1. An approach to forming the architecture of the mobile component of the fog layer of the Internet of Things of high or ultra-high density has been devised. Our development process took into account the specific features of mobile IoT devices used as dynamic nodes of the fog layer. This has made it possible to propose a three-level architecture of the fog infrastructure, in which mobile clusters are separate components.

2. A model of a separate mobile cluster of the fog layer has been built, which takes into account the randomness of the movement of mobile IoT devices and is based on the Thomas point process. The main difference of this model from existing ones is the focus not only on spatial indicators but also on the stability characteristics of the cluster components. This model allowed us to devise a method for ensuring the stability of the mobile cluster of the fog layer based on the proposed architecture of the mobile component of the fog layer of the Internet of Things.

3. A method for ensuring the stability of the mobile cluster of the fog layer supporting the Internet of Things of high or ultra-high density has been devised and investigated. The increase in stability is achieved by iteratively approaching the cluster center to its most unstable components. The results of the study allowed us to compare the stability of mobile clusters built by standard and modified methods. When the average relative deviation of cluster elements from the planned movement is less than 0.05, the modified method has no advantage in stability over the standard one. If the average relative deviation of cluster elements is in the range from 0.05 to 0.2, then the stability could increase to 20 %. It was also proven that when the average relative deviation is more than 0.2, the use of the modified method is impractical due to the complexity of controlling the components of the fog layer.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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