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VIRTUAL REALITY SIMULATION SERVICE ON SDN SOFTWARE UNDER A LIMITED RESOURCE 5G MOBILE TERMINAL

This article develops a hierarchical structure of data placement in the augmented reality service system and examines the advantages of using this structure.

The article develops and investigates a set of models and methods for virtual reality, including models of VR services, the interaction of the main elements in the provision of VR services and a model of a mobile user of a VR service.

Keywords: *Virtual Reality (VR); D2D (Device-to-Device); 5G; server request processing time; M/G/1 queuing system; Pollachek-Khinchin formula; RTT round-trip delay; Internet of Things; multilevel mobile edge computing (MM-MEC).*

Fig.: 6. References: 28.

Urgency of the research. Virtual reality services are the next step in the development of mobile services. The combination of the properties of the terminal's mobility, its computing capabilities, ways of interacting with the environment (recognizing video, sound and tactile images, calculating coordinates and orientation in space), as well as a modern communication network allow realizing a qualitatively new level of services with a high degree of interactivity [1-3]. In particular, these are augmented reality services. Today, such services as interactive maps of cities and towns, the starry sky, various kinds of guidebooks, applications for ordering goods and services are already widely known and popular. However, if we imagine how much traffic all these applications generate in the network, it becomes obvious that it is necessary to change the existing network structures and traffic distribution mechanisms in the network. When providing augmented reality services, one can often observe close interaction with IoT devices, which also generate quite an impressive amount of traffic [2; 4]. It is clear that the structure of the service, in which the call goes to some server in the network, is not applicable with so many devices. Thus, knowing the geographic coordinates of the user, it is possible to upload information about the surrounding objects to his terminal using, among other things, free terminals of other users or other devices located in the user's area of perception. This reduces the response time of the system to changes in the user's environment, which significantly increases the timeliness of displaying information about objects. For the proposed new structure, a method for unloading the traffic of augmented reality applications has been developed, which allows for the energy efficient operation of the network when operating such applications as streaming video with a 360° view, web applications, and multiplayer games [5]. For the proposed method, modeling and performance evaluation were carried out for various scenarios.

It should be noted that the issue of identifying objects of augmented reality and the Internet of Things also affects the quality of the provision of services and the structure of the organization of the service. The advantage and convenience for users of most augmented reality applications is the ability to visually identify objects. It means that the user wearing augmented reality glasses looks at an object and is provided with information about this object or its state changes, so the user does not perform any actions to obtain information and control the object. This paper proposes a system for identifying devices of the Internet of Things using virtual reality technology and cloud services. For the developed system, a model network was created, on the basis of which the assessment of the system's operation and compliance with the quality indicators of perception were carried out.

Target setting. The main tasks include the development of a model of behavior of a mobile user of a virtual reality service, moving in the environment of devices of the Internet of Things, which differs from the known ones in that the user is presented as a queuing system M / G / 1, and the incoming stream is formed from available to the user services, including video, text, graphics, speech, music, tactile sensations, etc., which makes it possible to calculate such systems using the queuing theory apparatus.

Actual scientific researches and issues analysis. There are many theoretical and experimental works in the field of 5G communication networks, which characterize 5G as communication networks with ultra-high reliability and ultra-low latency [6]. Scientists have made a decisive contribution to the study of such networks. Among them are V. M. Vishnevsky, Yu. V. Gaidamak, B. S. Goldstein, V. G. Kartashevsky, R. V. Kirichek, A. E. Kucheryavy, E. A. Kucheryavy, A. I. Paramonov, A. P. Pshenichnikov, V. K. Saryan, S. N. Stepanov, K. E. Samuilov, M. A. Sievers, N. A. Sokolov, V. O. Tikhvinsky, M. A. Schneps-Schneppe, M. Dohler, G. Fettweis, J. Hosek, A. A. Ateya, M. Maier, M. Z. Shafig and others.

The problems of resource allocation in heterogeneous 5G communication networks and traffic offloading are among the most significant for the planning of networks and their sustainable operation [7-8]. The works of S. A. Andreeva, A. I. Vybornova, M. O. Kolbaneva, E. A. Kucheryavy, A. E. Kucheryavy, K. E. Samuylova, A. K. Kanaeva, A. V. Roslyakova, A. S. A. Muthanny, A. M. Tyurlikova, A. Aijaz, A. A. Ateya, M. Dohler, G. Fettweis, M. Simsek, R. S. Schmoll and others are very well-known this area of research. At the same time, almost all work in the field of resource allocation and traffic offloading is devoted to machine-to-machine interactions M2M (Machine-to-Machine) and the Tactile Internet [8].

Obviously, in the works of these authors there was no methodology for representing user traffic, based on three interrelated models: a service space model, a user perception area model, which is a part of the service space, and a mobile user behavior model characterizing changes in his position and activity area. The model of behavior of a mobile augmented reality user includes not only the relatively well-known characteristics from traffic studies in 5G communication networks, such as device density, but also the previously unexplored characteristics of the user's viewing angle and the angular rate of rotation, which have a very significant impact on the quality of service parameters and the quality of perception for the user of augmented reality [8; 9; 10].

Uninvestigated parts of general matters defining. The problems of resource allocation in heterogeneous 5G communication networks and traffic estimation are among the most significant for the planning of networks and their sustainable operation [11]. There are some well-known works of E. A. Kucheryavy, A. E. Kucheryavy, K. E. Samuylova, A. K. Kanaeva, A. V. Roslyakova, A. S. A. Muthanny, A. M. Tyurlikova, A. Aijaz, A. A. Ateya, M. Dohler, G. Fettweis, M. Simsek, R. S. Schmoll and others in this area of research. At the same time, almost all works in the field of resource allocation and traffic estimation are devoted to machine-to-machine interactions M2M (Machine-to-Machine) and the Tactile Internet [12]. Only in collaboration between R. S. Schmoll with co-authors, the issues of offloading virtual reality traffic for gaming applications for 5G networks are considered. At the same time, a multi-level system of boundary computing is not used and such key augmented reality applications as circular video streams, multiplayer games and web applications are not considered [12-14].

Also, a unified methodology for representing virtual reality traffic has not been developed and a complex of models and methods for assessing traffic has not been presented, and the assessment of the quality of perception of virtual reality applications for a user has not been investigated.

The research objective. The purpose of the article is achieved by solving the following tasks:

- analysis of the current state of affairs in the field of research of communication networks of the fifth generation and communication networks 2030, the role and place of applications of the augmented reality in the development of networks and communication systems;
- development of the classification of augmented reality applications, taking into account Tactile Internet and Internet Skills;
- development of a methodology for presenting augmented reality user traffic;
- development of a model of the augmented reality user service space;
- development of a model of the user's perception area augmented reality;
- simulation modeling of multimedia content transmission for virtual reality applications based on WI-FI network of mesh topologies (mesh and ad-hoc) in the OMNET + software environment in order to calculate "bottlenecks" in mesh topologies AD-HOC and Mesh.

The statement of basic materials. Service implementation structure. Virtual reality services allow the user to receive the necessary information in a timely manner. At the same time, its selection is performed automatically based on data on its state, for example, its position in space (geographical coordinates), on a map and a plan of the territory (based on geolocation data), on the location of a vehicle, etc. As shown in [15; 16], the implementation of the service requires the organization of data exchange with the service server and / or directly with devices located in the communication area of the subscriber terminal, using D2D technologies [17]. In this case, the time between the request and the delivery of data should not exceed a certain value at which the user still does not feel a decrease in the quality of the service. This time is determined by the time: the request is generated (depends on the implementation of the service), the request is delivered from the terminal to the service server, the request is processed, the data is delivered from the service server to the terminal, and the information is presented to the user. They can be conditionally divided into three groups: the time determined by the processing of data by the user's terminal, the time of data delivery through the communication network, and the time of data processing by the server. In general, these components are mutually dependent.

The process of forming a data request plays an essential role. The request is formed when the user's environment (or the user's state) changes, which can be judged by changing some parameters. These parameters can be sensor data, for example, geographic coordinates, the position of the terminal in space, acceleration, as well as the results of analyzing the image or sound received from the cameras and microphones of the terminal. For example, if the data request is generated based on the results of image recognition (video captured by the terminal camera), then the image recognition functions can be implemented either in the terminal application or on the service server. In the first case, with low computing performance of the terminal, time will be spent on performing the recognition functions by the terminal, in the second - on transmitting video through the communication network and the time it is processed by the server. Obviously, the choice of the first or second option depends on terminal performance, bandwidth (PS) of the communication network, server performance and load, i.e. there is a problem of choosing the optimal option for implementing the service The model described here can be extended by introducing additional parameters, for example, the dependence of the processing time of a request by a service server on the amount of data (database size) and the intensity of requests. In this case, it makes sense to cluster data and organize local service servers.

Considering a promising 5G network, D2D communication technology, and the use of SDN (Software-Defined Network, software-defined networks), the structure of the service implementation which is shown in (Fig. 1) can be made.

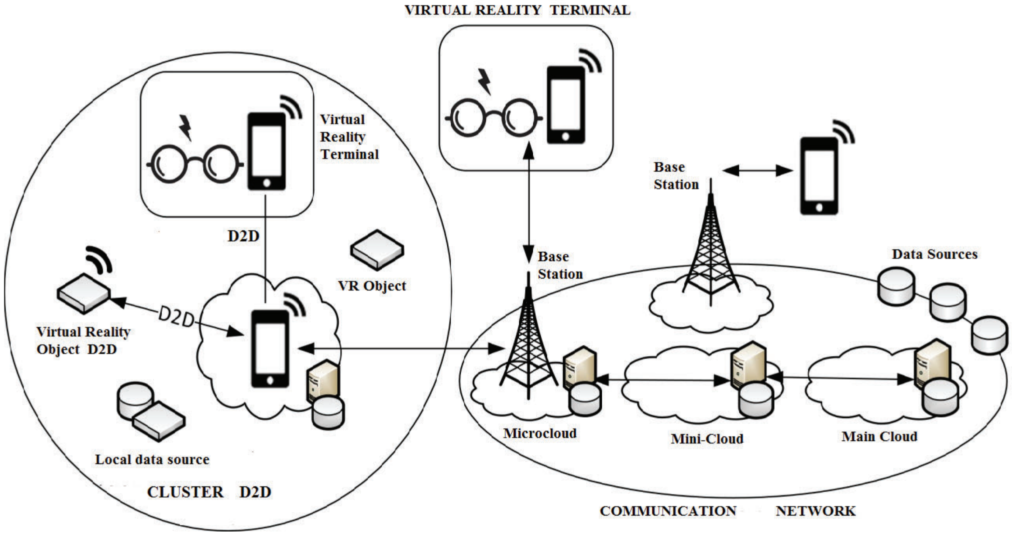

Fig. 1. Possible structure for the implementation of the Virtual Reality service

We believe that the communication network is built using the SDN architecture, in which there are data processing centers (DPC) of various levels [18], which makes it possible to localize traffic and data "closer" to users. In the diagram, these data centers are depicted as micro, mini and base clouds. In a real network, there may be as many such levels as will be necessary for the best implementation of the service. The base station of the network interacts directly with the AR terminal or with a mobile terminal acting as a local cloud, interacting with the AR terminal using D2D technologies, which increases the efficiency of using the radio frequency spectrum [18; 19]. Here, a cloud is understood as a certain amount of computing resources and memory resources that can be used to organize a server and a database (DB) of a service.

As will be shown below, the provision of a service can be implemented at several levels of such servers and databases, which allows, due to the localization of data and traffic, to reduce the requirements for the network's network and to increase the quality indicators of the service. Below, the problem of data clustering and localization of their processing is considered as a problem of resource allocation.

Service model. To build a service model, it is necessary to link the indicators (parameters) characterizing the quality of its provision with the parameters of the communication system. As the main indicator, we will choose the reaction time to a change in the user's environment. We will assume that this time includes all components: the time of recognition of the change and preprocessing by the mobile terminal application tr, the time of data transmission (request) to the service server through the communication network tq, the processing time of the request by the service server ts, the data delivery time through the communication network ta and time of presentation of information to the user by the mobile terminal application td. Augmented reality service presentation model is presented in (Fig. 2).

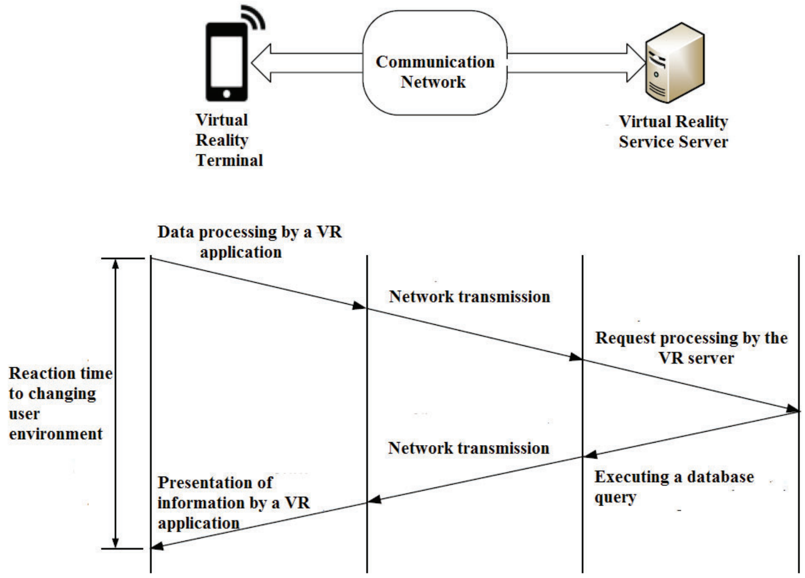

Fig. 2. Virtual Reality Service Delivery Model

The total time can be represented by the arithmetic sum of all components according to the formula (1). It will be assumed that each of them is a random variable. Then, making the assumption about their independence, the average value for the reaction time will be determined as

$$\bar{\tau} = \bar{t_r} + \bar{t_q} + \bar{t_s} + \bar{t_a} + \bar{t_q}. \quad (1)$$

Let's consider each of the components separately. The time for recognizing a change in the user's environment *tr*, in turn, includes all the components associated with detecting this change and collecting information necessary to form a request sent to the service server. Change detection can be realized by analyzing data from various sensors and devices (sensors of the earth's magnetic field, illumination, acceleration, GPS receiver, touch screen, etc.), as well as video cameras and microphones. The analysis can include both relatively simple tasks of comparing several numerical values, and resource-intensive tasks of pattern recognition. Therefore, the numerical value of *tr* depends on the type of service, the method of its implementation and the computing resources of the mobile terminal. Thus, the resources of the mobile terminal affect the quality of the service through the value *tr*. It will be assumed that there is a certain functional relationship between this time and the computing resources of the mobile terminal.

$$\bar{t_r} = f_r(O). \quad (2)$$

In formula (2) O is a parameter characterizing the performance of a mobile terminal, for example, the number of operations or instructions performed per second, the clock speed of the processor, the amount of memory, or some complex metric. The time of transmission of the request to the server of the service tq determined by the volume of transmitted data and the PN of the route between the mobile terminal and the server of the service C. A numerical estimate of this time under the assumption that time is spent only on data transmission (PD), i.e. without taking into account the losses for waiting for transmission at the nodes of the route can be obtained as

$$\bar{t_q} = f_q(C) = \frac{\bar{\nu_q}}{C}. \quad (3)$$

In the formula (3) C is the bandwidth of the route (bit / s);

$\bar{\nu_q}$ - Average amount of data transferred per request (bits).

Average amount of data per request ν_q depends on the type of service and the way it is implemented. For example, if an analysis of images received from the device's video camera is required to identify a change in the environment, then this analysis can be performed both by means of a mobile terminal application and by a server. In the first case, the request will contain relatively little data, which are only identifiers of objects in the service database, information about which is required to be provided. In the second case, it is necessary to transfer all image data (or several images), the analysis of which must be carried out by means of the service server. Intermediate options are also possible, when only a part of the video data will be sent to the server.

The processing time of the request by the server ts is the most complex characteristic, since it depends on many parameters: the time of the analysis of the request data τ_s, поступающих данных; the intensity of requests from mobile terminals of users λ_s; server performance μs, which, in turn, depends on the size of the database ns:

$$\overline{t_s} = f_s(\tau_s, \lambda_s, \mu_s(n_s)). \quad (4)$$

The server serves requests from many users, the service time of which is determined by the request processing time and the waiting time. The server can be described by the QS model, in which the request servicing time is determined by the size of the service database and the server's performance. The technical implementation of the server may be different, so it makes sense to consider it as a QS with general expectation with one G / G / 1 server. Assuming that the flow of incoming requests can be represented by a model of the simplest flow (M / G / 1), the average delay can be described by the Polyachek-Khinchin formula [20]. With this in mind.

$$\overline{t_s} = \frac{\rho_s}{\mu_s(\nu_s)2(1-\rho_s)}(1 + V_s^2) + \frac{1}{\mu_s(\nu_s)}. \quad (5)$$

In formula (5), the following parameters are applied:

$\rho_s = \frac{\lambda_s}{\mu_s(n_s)}$ – server load;

$V = \sigma_s \mu_s(\nu_s)$ – service time variation coefficient.

σ_s^2 – standard deviation of service time.

The adoption of the simplest flow model is very useful, since it makes it possible to obtain analytical expressions for dependencies, especially when the properties of the real flow are unknown. Server performance, depending on the size of the database DB $\mu_s(n_s)$, is also a kind of dependency and is determined by the way the database is implemented. In particular, the most common models describe this dependence as ln(ns) or nln (ns) operations [21], where n_S is the number of records in the database. Let's take a logarithmic dependence as an example. Taking into account that the service time includes preliminary processing of the request, the average execution time of which τ_s , we obtain the expression (6).

$$\mu_s(\nu_s) = \frac{1}{\eta \ln(\nu_s) + \tau_s}, \quad (6)$$

where η - execution time per record.

The transmission time of the server response t_a, as well as the transmission time of the request, is determined by the volume of transmitted data and the PS of the route between the service server and the mobile terminal C. A numerical [21] estimate of this time under similar assumptions can be written as.

$$\overline{t_a} = f_a(C) = \frac{\overline{\nu_a}}{C}. \quad (7)$$

In formula (7), C is the route PN (bit / s);

$\overline{\nu_a}$ – the average amount of data transmitted in the server response (bits). The average amount of data in a server response $\overline{\nu_a}$ depends on the type of service and the way it is implemented. This data can be transmitted text, raster or vector images, sound, numerical values.

The message submission time t_d includes all components related to the processing and presentation of the data received by the mobile terminal application. In general, the message can be presented visually: in the form of text, pictograms, video or other images; sound - speech or melody; tactile - vibration. We will assume that there is some functional dependence (8) between the time and the computing resources of the mobile terminal:

$$\overline{t_d} = f_d(O) \quad (8)$$

As can be seen from the models selected above, the response time significantly depends on such parameters as the performance of the mobile terminal, the network communication network and the processing time of the request by the server, which is determined by its performance and load [22; 23]. Below, we propose a method for choosing the structure and parameters of equipment to meet the requirements the reaction time for the Virtual Reality service.

Method for choosing the network structure and equipment parameters. Considering the above models, we can say that ensuring an acceptable response time is a problem of choosing the amount of resources (bandwidth, performance and memory), as well as their distribution among the elements of the service system. This is a problem with several variables, the number of which is determined by the models themselves. If we argue from the standpoint of constructing a method of organizing a service, then not all variables may be available for change [24; 25]. For example, if we assume that the performance of the mobile terminal and the characteristics of the server equipment can be taken into account, but cannot be changed within the framework of this problem, then the expression for the response time can be written as.

$$\bar{\tau} = \overline{t_m} + \frac{\overline{v_q} + \overline{v_a}}{C} + \frac{\rho_s}{\mu_s(n_s)2(1-\rho_s)}(1 + V_s^2) + \frac{1}{\mu_s(v_s)}, \quad (9)$$

where $\overline{t_m} = \overline{t_r} + \overline{t_a}$ - the total delay introduced by the mobile terminal application when processing input data and displaying information. Based on (9), you can write down the complete expression (10) This value depends on the terminal performance and the features of the application [26]. We will assume that it is constant, i.e.

$$\bar{\tau} = \overline{t_m} + \frac{\overline{v_q} + \overline{v_a}}{C} + \frac{\lambda_s}{\mu_s(n_s)2(\mu_s(n_s) - \lambda_s)}(1 + V_s^2) \quad (10)$$

Figure 3 shows the dependence obtained using formula (10) for a different number of records in the database. The figure shows that the reaction time increases according to the *1 / (a-x)* law. The constant component of time is due to the time of the PD request to the server and the time of its processing by the server. According to the chosen model according to formula (6), the service time also depends on the number of records in the database.

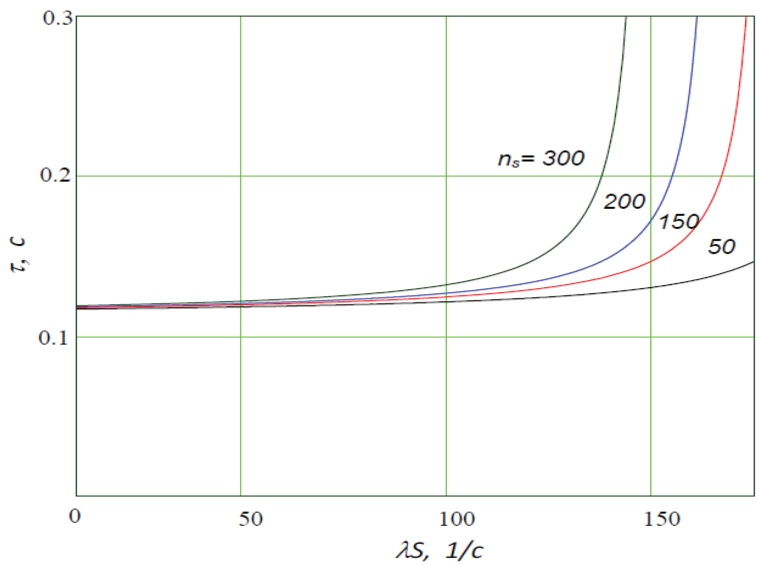

Fig. 3. Response time versus request intensity and the size of the Database

Thus, for the organization of the service, it is necessary to provide the required response time. For this, based on the presented models according to formulas (9) and (10), it is necessary to choose the structure of the service provision network, taking into account the traffic, the volume of the Database and the time of data delivery.

Processing environment data. As noted above, the formation of a query is based on the results of recognizing a change in the environment. Recognition can be based on various data received both from sensors and from video cameras and microphones. In the latter case, the recognition problem can have significant computational complexity, therefore, the time required will be very significant. Therefore, it makes sense to choose a means for solving this problem: a mobile terminal or a service server. If the image is fully processed on the terminal, then a request is sent to the server containing only a relatively small amount of data required to identify the object in the server database. In the case when the image is completely fed to the server for processing, a relatively large amount of data is required to be transferred, which is determined by the resolution of the camera and the format of data presentation. Intermediate solutions are also possible, for example, when the terminal application does not fully identify the object, but highlights the object (payload) in the image. In this case, the server receives only the selected part (s) of the image for further processing. Thus, the transfer of the object recognition work to the user terminal saves the time of data transmission over the channel and the PS resource. Transferring this work to the server allows you to save on the processing time of the image by the terminal, however, it leads to an increase in the transmission delay and the consumption of the PS channel. From the point of view of using network resources, the first option is more profitable, however, when implementing the service, one should take into account the real performance of the mobile terminal, the real channel bandwidth and the requirements for the response time. We describe the above with the following model [26; 27]. The component of the delay caused by the processing of the image in the terminal, the server and the time of the PD to the server is defined as

$$\tau_P = f_r(O_r) + \frac{\bar{v}}{c} + f_s(O_s). \quad (11)$$

In formula (11) O_r and O_S are the processing time on the mobile terminal and the server based on one bit, respectively;

c – PD speed (bit / s);

$\bar{v}$ – the amount of processed (transmitted) data.

We will assume that the processing time in the mobile terminal and the server linearly depends on the size of the processed data block (image or its part).

$$f(O) = \bar{v}O, \quad (12)$$

where O is the processing time per 1 byte of the image, typical for a mobile terminal or server (for a mobile terminal and a server, these values may differ significantly).

Then

$$\tau_P = \eta_r \frac{\bar{v}}{O_r} + (1 - \eta_r)\left(\frac{\bar{v}}{c} + \frac{\bar{v}}{O_s}\right). \quad (13)$$

In formula (13) η_r is the share of data processed in the mobile terminal.

It can be seen from formula (12) that an increase η_r leads to a decrease τ_P if the processing time in the mobile terminal is less than the sum of the transmission time and the processing time in the server:

$$\frac{\bar{v}}{O_r} < \left(\frac{\bar{v}}{c} + \frac{\bar{v}}{O_s}\right). \quad (14)$$

Guided by expression (14), the service system can distribute data processing functions between the server and the terminal, for example, depending on the server load.

Hierarchical structure of augmented reality service delivery for load and data distribution.

To reduce response times by reducing the load on the service server, you can organize a hierarchical structure that includes several levels of service. The server of each level is available to a different number of users. For example, the server of the first (lower) level can be organized directly in the mobile terminal and have a single user. A call to a higher-level server occurs when the required information is not found in the database of lower-level servers. The server database for each of the levels contains information about the environment of each of the users for whom this server is available, as well as information demanded by users, and the probability of this demand is p.

Consider a service delivery model. Upon detecting a change in the environment, the user terminal transmits data (possibly already generated request) to the 1st level service server. The server processes the data and the request. Upon successful processing and data availability, the server sends a response to the user terminal. If for some reason the request is not fulfilled by the server of this level, the request is passed to the server of the next level, and so on. Failure may be due to lack of required data at the current service level. The construction of a hierarchical model of service provision allows, by distributing traffic and data between levels, to provide the required indicators of the quality of service provision [28].

The service time of a request in a network with several servers can be described as

$$\bar{\tau} = \bar{t_r} + \sum_{j=1}^{k} p_j \sum_{i=1}^{j} \left(\bar{t_q} + \bar{t_s}\right) + \bar{t_a} + \bar{t_d}. \tag{15}$$

In formula (15) p_j is the probability that the requested data is in the server database of the j-th level;

k is the number of levels on each of which there is a VR service server according to the hierarchical structure.

Or, taking into account the model according to the formula (5).

$$\bar{\tau} = \overline{t_m} + \sum_{j=1}^{k} p_j \sum_{i=1}^{j} \left(\frac{\overline{v_q} + \overline{v_a}}{C} + \frac{\rho_s}{\mu_s(n_s)2(1-\rho_s)}\left(1 + V_s^2\right) + \frac{1}{\mu_s(\nu_s)}\right). \tag{16}$$

When organizing a service in an SDN network, its functionality can be used to dynamically manage the service by changing the number of service levels, i.e. increasing or decreasing *k* in expressions (15) and (16).

The criterion for making a decision is the response time $\bar{\tau}$, or rather its value in comparison with a certain normative (target) value τ_0 , the value of which is most acceptable for the implementation of the service. Obviously, 0 (zero) can be chosen as the target, but it is obvious that such a goal is not achievable. Reducing processing and delivery delays can be associated with significant financial costs, therefore, the acceptability of the value should be considered as the maximum value at which the desired quality of service (QoS) and user experience (QoE) are provided.

Thus, within the framework of this model, service management consists in maintaining the possible proximity between the real value of the reaction time and its target value, i.e. in providing $\min|\bar{\tau} - \tau_0|$. Then the objective function of this task can be written down at least the difference between the reaction time and the standard. The minimum of the difference can be expressed in terms of the minimum of the square of the difference and the least squares method can be applied. Then the problem can be formulated as an optimization problem with an objective function

$$\{k, p_i\} = \underset{k,p_i}{\operatorname{argmin}} \left\{\sum_{i=1}^{k} (\bar{\tau} - \tau_0)^2\right\} \tag{17}$$

and restrictions

$$k \in N, \quad k \le k_{max}, \quad 0 \le p_i \le 1, \ \bar{\tau} > 0, \ \tau_0 = 0,$$

In the formula (17) $\bar{\tau}$– is determined by expressions according to formulas (15) or (16);

τ_0 – target response time;

k_{max}– the maximum number of service levels allowed. It should be noted that expressions (15) and (16) are only possible models for describing the timing of the service. They can be both analytical and simulation models, which make it possible to adequately assess the parameters of interest.

The above problem by formula (17) is formulated as the problem of finding the optimal number of service levels k and values of pi, which determine not only the composition of the data in the database, but also the traffic share at each of the service levels.

In fact, the composition of data in the database of the level i server can be determined according to the rule: a data block is stored in the database if the share of requests to it exceeds pi. The latter actually means that traffic generated by incoming requests will be closed at this service level.

Thus, the implementation of the augmented reality service presupposes that the service system performs the functions of processing, transferring, storing, retrieving data and presenting information to the user. Each of these functions is costly in time, network bandwidth, server performance, and memory.

Information support of the service (information Virtual Reality) can be formed in various ways, including on the basis of search results for information presented on the global Internet. Data retrieval and storage is performed by the service system, which can have several levels of processing. Their number affects the amount of resources used (network bandwidth, server performance, memory).

The main indicator of the quality of service provision is the response time, i.e. the time from the moment the user's environment changes until the required message is presented to the user. This time depends on the distribution of the functions of providing the service to the executive elements (user terminal, servers, channels of the Data Transmission network). The target value of this time should not exceed the user's reaction time to the submitted message by the Virtual Reality.

To ensure the quality of service perception, the resources of the mobile terminal can be used (reduce the data transfer time), as well as SDN resources, allowing to implement a hierarchical service delivery model. The hierarchical model makes it possible to localize a significant proportion of data and traffic, which saves resources on the bandwidth of the communication network. The parameters of the hierarchical service delivery model include the number of hierarchy levels and the likelihood of accessing each of them. The probability of accessing a certain level can be used as a criterion for the formation of a database (DB). The choice of the number of hierarchy levels in the service delivery model and the probability of calls to each of them is an optimization problem, the purpose of which is to ensure the response time closest to the given value. The solution to this problem allows one to obtain the structural parameters of the service system based on data on user traffic.

Experimental study of multimedia content transfer for virtual reality applications based on WI-FI network of mesh topologies (mesh and ad-hoc). Solutions for virtual reality applications that exist today imply the formation of a request for the output of an auxiliary layer of information based on video analytics. This is possible due to the presence of an external camera on a smartphone or glasses, which takes a picture and in real time forms a request to the database. The existing solution has a number of significant limitations due to the fact that at a distance of more than 10 meters, as well as at night, video analytics usually works incorrectly and does not allow reliable information reading and video analytics. The approach proposed below is fundamentally different from the existing solutions in that to display information about an object, the direct receipt of information from this object over the network is used.

1) Virtual reality application client: traditionally applications are developed for mobile devices (smartphone, smart glasses, etc.). In a situation when an application wants to get information about a particular object, it generates and sends a request to the nearest application service node (Application Point). A wireless access point based on Wi-Fi technology connects the mobile device to the service center annexes.

2) Virtual reality application service node: this node interacts with system elements and supports protocol interaction. The node is served on a publisher-subscriber basis, i.e. the client as a subscriber subscribes to the channels for providing information of objects, then the client can receive data from the objects when the augmented reality application forms a request and expects data to form a visualization layer. Wireless sensor network endpoints acting as publishers send the collected data over these channels. Thus, information about objects can be provided to the client (virtual reality application) as quickly as possible.

3) Wireless sensor network for data collection: As mentioned earlier, a network with ZigBee protocol support is considered as a self-organizing network. Zigbee endpoints are equipped with various sensors and also contain information about the object itself. The collected data is sent at a specified frequency to the gateway or at the request of the client. The gateway then redirects requests to the cloud service and the application service host (Fig. 4) shows a schematic diagram of a network survey.

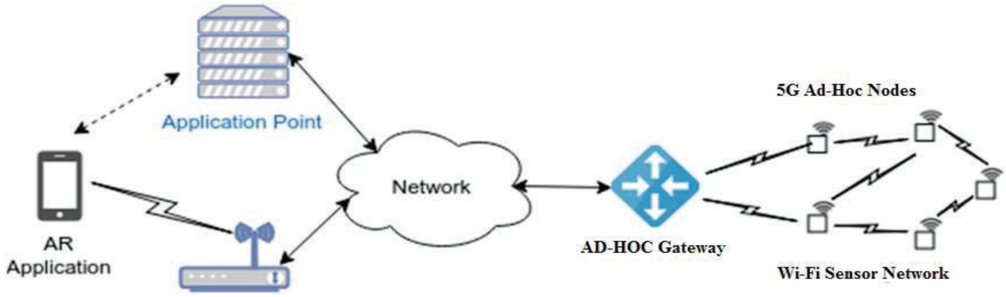

Fig. 4. The structure of the studied network

Let's select Wi-Fi technology for comparison and conduct a study of its potential in an AD-HOC network. For the study, we will use the OMNeT ++ simulation system. We will consider the construction of a model network in a two-dimensional service area, which is a square with a side of 600 m. The size of the service area was selected based on the average estimates of the geographic parameters of the most visited places (squares, recreation areas, train stations, campuses, etc.). We will change the number of network nodes depending on the purpose of the experiment. Each of the network nodes is equipped with a Wi-Fi transceiver and can perform the functions of both an endpoint and a transit node. The specific functionality of the node is determined by the purpose of the experiment. We will consider the case when the network nodes are stationary in the service area. We will consider the use of the TCP and UDP protocols as a transport layer. We will investigate the dependence of the main parameters of the traffic quality of service, such as throughput, message delivery time and the probability of packet loss, on the network configuration and traffic intensity.

In general, the route length depends on the characteristics of a particular network and in practical applications can be up to a dozen transit sections. Consider a network model in which there are two end nodes, one of which acts as a server and the other as a client. The client transfers data in the form of a file to a server running the TCP protocol. Since this protocol provides guaranteed delivery and transfers data at a speed close to the maximum achievable (uses the maximum bandwidth), we will estimate the amount of network throughput based on the analysis of the achievable data transfer rate between the client and the server. The route between the client and the server will contain several hops.

Researches and results of the developed traffic modeling method. Table shows the results of simulation experiments. During the experiments, the outgoing traffic of the client and the incoming traffic of the server were recorded.

Table

Dependence of traffic parameters on the number of transits

Number of transits	Traffic intensity (client), Mbps	Traffic intensity (server), Mbps	RTT, ms
0	8,8	8,8	7,3
1	9,4	4,7	13,6
2	7,3	3,3	19,5
3	7,0	2,9	22,3
4	6,6	2,8	23,2
5	6,2	2,7	24,3
6	6,1	2,6	25,0
7	5,9	2,5	25,5
8	5,7	2,5	25,8
9	5,7	2,5	26,1
10	5,5	2,4	26,5
11	5,2	2,4	27,0

Figure 5 shows the dependence of the throughput on the number of transit nodes in the route, based on the data in (Table 1).

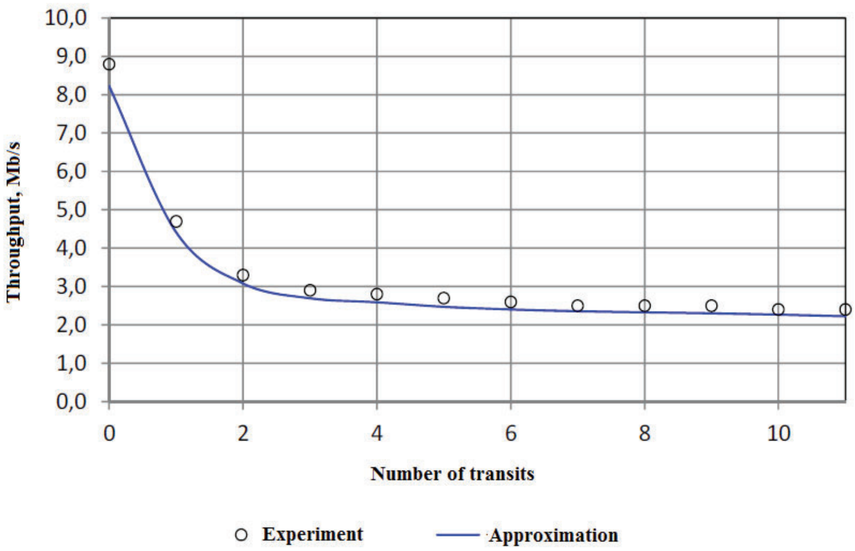

Fig. 5. Dependence of throughput on the number of transits

Figure 5 shows the dependence of the throughput obtained according to the expression

$$b = \frac{W_{nd}}{RTT} \text{ bit/sec.} \tag{18}$$

In formula (18) Wnd is the size of the transmission window (bits),

RTT – response time (ms).

The window size in these experiments was Wnd = 7504 byte.

Figure 5 shows that the data obtained are quite close to the estimates, according to the expression by formula (18). Figure 6 shows the round-trip delay (RTT) versus the number of transit nodes.

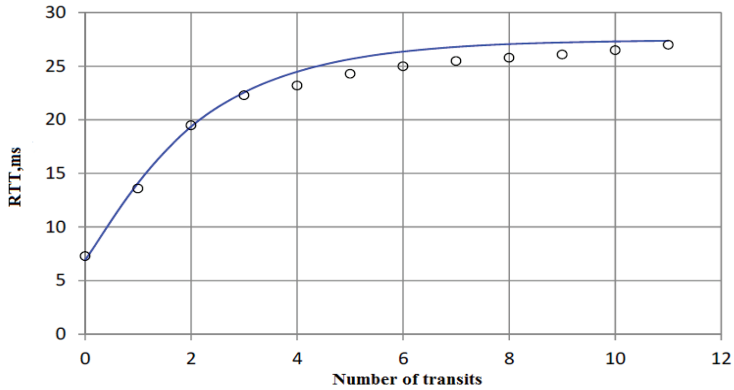

Fig. 6. Dependence of round-trip delay (RTT) on the number of transits

The same figure shows the dependence of RTT, obtained according to the empirical formula.

$$RTT = \frac{W_{nd}}{b_0} + 2b_0(1 - e^{-k}). \quad (19)$$

In formula (19) Wnd is the size of the transmission window (bits),
b_0–in this case the quantity b_0= 11000 bit / s,
k – number of transit sections

Conclusions.

1. It was found that the main indicator of the quality of service provision is the response time, i.e. the time from the moment the user's environment changes until the required message is presented to the user. This time depends on the distribution of functions for the provision of services by executive elements (user terminal, Virtual Reality servers, channels, data transmission networks).

2. In order to minimize the response time to changes in the user's environment, a hierarchical structure of resource allocation is proposed when providing augmented reality services. The hierarchical model makes it possible to localize a significant proportion of data and traffic, which saves resources of communication network bandwidth.

3. A new four-level structure of augmented reality service delivery system has been developed based on a modified multilevel mobile edge computing (MM-MEC) using the Device-to-Device (D2D) interaction technology.

4. It can be seen from the above results that the quality of functioning of a self-organizing network built using Wi-Fi technology significantly depends on its parameters, in particular, on the route length and traffic intensity. However, the numerical values of the throughput and the delay values that occur when the route length and traffic intensity change over a fairly wide range, significantly differ from the values obtained for a network built using AD-HOC or MESH topologies.

5. When carrying out simulation experiments, the value of the round-trip delay RTT did not exceed 30 ms, in the worst case, and the throughput did not decrease below 2 Mbps. From this we can conclude that the use of Wi-Fi standards for building wireless sensor networks, in some cases, acceptable for many augmented reality applications.

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ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ ПОСЛУГИ ВІРТУАЛЬНОЇ РЕАЛЬНОСТІ В ПРОГРАМНО-КОНФІГУРОВАНИХ МЕРЕЖАХ SDN В УМОВАХ ОБМЕЖЕНИХ РЕСУРСІВ МОБІЛЬНОГО ТЕРМІНАЛУ 5G

Основна ідея віртуальної реальності полягає в накладенні тексту, графіки, аудіо, відео, сенсорних даних і відчуттів поверх існуючих об'єктів навколишнього світу в режимі реального часу. Тому відмінною рисою віртуальної реальності є поєднання реальних і віртуальних об'єктів в єдиному просторі, що часто називають новим поняттям «гібридна» реальність, під яким розуміють тривимірне сприйняття об'єктів і наявність інтерактивності, що призводить до високих вимог до затримки передачі по мережі зв'язку.

У цій статті розроблена ієрархічна структура розміщення даних у системі обслуговування віртуальної реальності і досліджуються переваги використання даної структури. Досить велика кількість додатків віртуальної реальності засновано на розпізнаванні об'єктів в оточенні користувача, тобто в поле його зору. Запропонована нова структура системи надання послуг віртуальної реальності (VR) на основі модифікованої багаторівневої системи граничних обчислень, що використовує технологію взаємодії D2D (Device-to-Device).

В основі мереж 5G лежать занадто щільні мережі з ультра малими затримками (τ <1мс.). Останнім часом вимоги до ультрамалих затримок були доповнені вимогами щодо ультрависокої надійності, в результаті чого з'явилися мережі з ультрависокої надійністю і ультра малими затримками URLLC (Ultra Reliable and Low Latency Communications.

У статті розробляється і досліджується комплекс моделей і методів для віртуальної реальності, що включає в себе моделі послуг VR, взаємодії основних елементів при наданні послуг VR, модель мобільного користувача послуги VR, в якій користувач представлений як система масового обслуговування, що дозволяє оцінити потоки і інформацію, яка надходить до системи масового обслуговування.

Ключові слова: *Віртуальна Реальність (VR); D2D (Device-to-Device); 5G; час обробки запиту сервером; система масового обслуговування M / G / 1; формула Поллачека-Хинчина; кругова затримка RTT; Інтернет Речей, багаторівнева система граничних обчислень (MM-MEC).*

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