Model of a Centralized Strategy for Selecting the Last Mile Access Network

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Abstract. The development of network infrastructure leads to an increase in access options for terminal devices (TD) to global infocommunication resources via terrestrial networks that use a variety of technologies and form a heterogeneous wireless network. Both Always Best Connected concept and the rational use of resources in such a network can be implemented by applying the Vertical Handover (VHO) procedure. The most important part of the VHO procedure is to select the most appropriate access network from among those available to the terminal device at a certain time point at a certain point in space to provide the required connection and services. Nowadays, the corresponding procedures are implemented in a decentralized hardware and software TD, which leads to the complexity and cost of the TD and reduces the use of network resources of the last mile. A new architectural solution is proposed, according to which the selection function is implemented by a dedicated network group device that is located between the physical and channel levels of the access network architecture and makes a decision on the choice of a particular network based on information about the requested service and the status of available access networks. The purpose of the study is to develop a model for managing access to global infocommunication resources at the stage of selecting the best access network. The object of the study is the architecture of the access system at the last mile, and the subject is mathematical models for evaluating the probabilistic and temporal characteristics of the corresponding process. The study analysed the existing solutions for making decisions about the selection of access networks developed by network architecture using a centralized access network selection; the proposed scenario of interaction devices terminals of aggregating devices and access networks; the mathematical model of process of functioning of the aggregation devices; numerical experiments were performed.

Keywords: Wireless communication technologies · Access control model · Heterogeneous network · Access network · Vertical handover.

1 Introduction

The strategic instrument of state policy, indicating the priorities and prospects for the development of end-to-end technologies in the Russian Federation, are the Roadmaps adopted by the Government in October 2019. One of them, dedicated to wireless communication technologies, highlights sub-technologies:

- WLAN (Wireless Local Area Network) – technology of communication networks designed to provide wireless coverage and access within local spaces,

- LPWAN (Low Power Wide Area Network) – technology of energy efficient long-range networks,

- PAN (Personal Area Network) – technology of communication networks connecting devices used by a man as part of his activity and,

- WAN (Wide Area Network) – a global communication network covering large areas and including a large number of communication hubs [1], as the most important for building networks of access to global infocommunication resources.

Standards for each of these sub-technologies are realized by different hardware and software manufacturers, operators and providers of information and communication services.

The Roadmap "wireless access technologies" states that a radio access on the "last mile" must use multiple (multi-station) access procedures to a common channel resource limited by the radio channel spectrum.

The introduction of a wide range of wireless communication systems on the" last mile" according to the principles of the Roadmap [1] leads to a change in one of the inherent properties of fixed networks. Now the mobile terminal in real time at any stage of service can abandon the already established network connection and choose another network to continue the transmission of traffic. Moreover, it can simultaneously interact with several access networks and use the network resources of each of them.

A variety of access networks, created using a variety of radio technologies, together form a heterogeneous wireless network, the rational use of resources which allows you to realize the concept of (Always Best Connected, ABC). The ABC concept implies automatic provision of the subscriber with the best currently available connection to the provider's equipment [2]. The corresponding procedure for transferring the data session of a terminal device from one access network to another without changing the geographical location of the served terminal device is called (Vertical Handover, VHO) [3].

The most important part of the VHO procedure is to select the most appropriate network from number of those available to the mobile device at a certain time period at a certain point in space to provide the required connections and receive the required services. The selection problem can be solved either by the terminal device itself or by a special hardware and software device common to all terminals and connected to both terminals and access networks.

To realize these capabilities, new models and methods of analysis of heterogeneous access networks are needed, such as those that could be used by decision-making procedures for choosing a network for data transmission.

When implementing the VHO procedure in a heterogeneous network, it is necessary to solve the following interrelated problems [4]:

- collection, processing, storage and analysis of information required to make a VHO decision;
- selection one of several available access networks;
- switching the terminal to a new network without loss the connection session.

The aim of the study is to develop a model for managing access to global infocommunication resources at the stage of choosing the best access network.

The object of the study is a set of access networks available to the terminal device on the last mile.

The subject of the study is a model for estimating the probabilistic-time characteristics of the last mile access process.

Solve the problems:

- analysis of existing access network selection solutions;
- development of network architecture with centralized access network selection;
- development of a scenario for interaction between aggregator terminal devices and access networks;
- development of a mathematical model of the process of functioning of the aggregating device;
- conducting numerical experiments.

Research methods are based on the mathematical apparatus and methodology of queueing theory, probability theory.

2 Materials and Methods

In practice, network operators tend to use a decentralized approach to selecting the last mile access network, in which the decision to select the network is left to the smart TD.

The organization of access with a decentralized approach to selecting the access network for the last mile is shown in Fig. 1.

In this study, we consider another alternative centralized approach to selecting an access network on the last mile, based on the introduction of an aggregating device (AD) – an aggregator of access networks into the architecture of a heterogeneous access network. This is a hardware and software system that serves as an intermediate link between various access networks and terminal devices. Performs two groups of functions:

- managing access to last mile radio networks;
- broadcast packets between TD interfaces and last mile radio network interfaces.

The organization of access with a centralized approach to selecting the access network for the last mile is shown in Fig. 2.

The task of selecting a suitable network for providing a telecommunications service is solved by AD based on consolidated data, connection metrics that can take into account different groups of parameters/criteria:

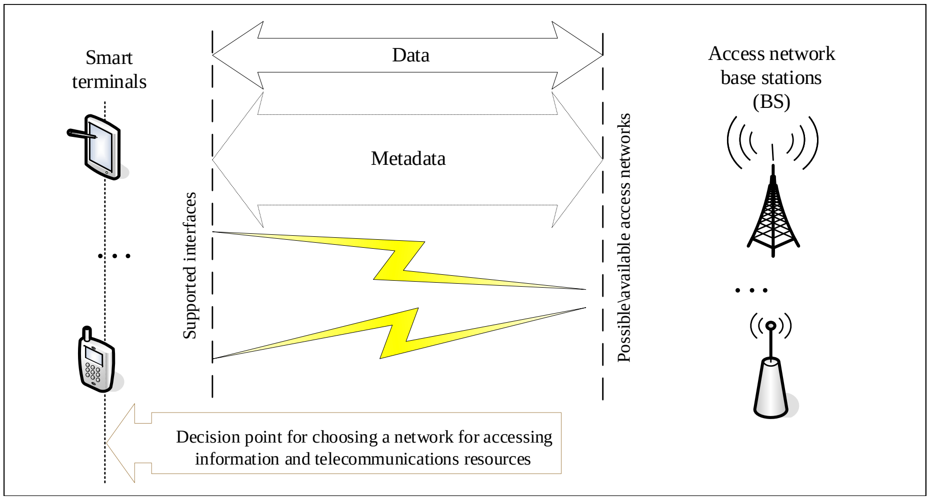

Fig. 1. Organization of access in the case of a decentralized approach to selecting the last mile access network.

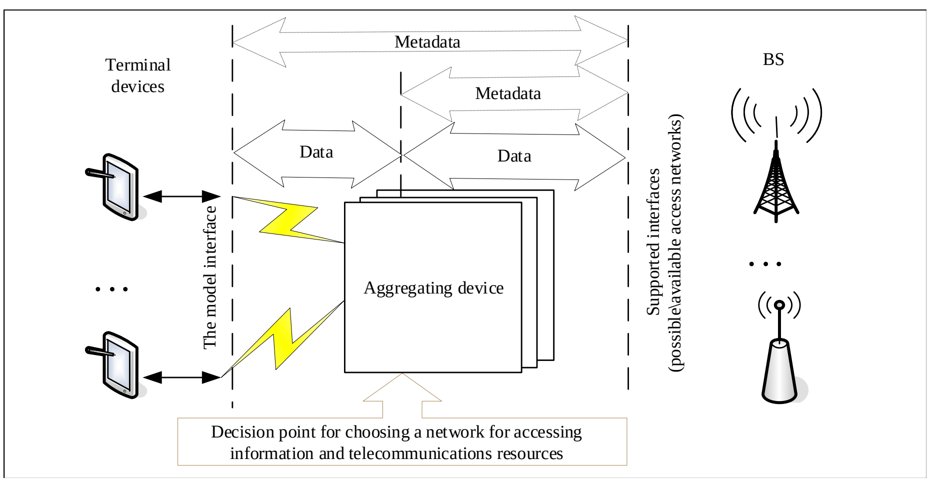

Fig. 2. Organization of access in the case of a centralized approach to selecting the last mile access network.

- available networks (cost, probability-time, energy parameters, etc.);
- parameters of the requested service;
- terminal parameters;
- subscriber profile, etc.

Traditionally, to assess the effectiveness of information systems, such indicators as transmission channel throughput, probabilistic and time characteristics of information interaction processes [5], reliability and security indicators of information interaction [6, 7, 8], etc. were used.

It is also possible to add probabilistic and energy characteristics that depend on the spatial parameters of the network and the technical characteristics of terminal devices to the previously known and widely used indicators for evaluating the quality of service delivery. For example, in [9, 10], probabilistic-energy characteristics that depend on network parameters at the physical, channel, and network levels are considered.

Fig. 3 shows a scenario for establishing a connection in the case of a centralized approach to selecting an access network on the last mile (using AD).

Mathematical model of the main stage of work

In the process of providing access to global infocommunication resources (see the main stage of work in Fig.3) the following stages can be distinguished: I-Selecting the access network and II-Transmission of user data. A graphical representation of the main stage of work is shown in Fig. 4.

Stage I - Selecting an access network

The incoming request for an infocommunication service of the required quality is processed. AD, evaluates the possibility of providing the service and selects the appropriate access network for the request.

If there are currently no available resources to provide a service of a certain quality, or the predicted values of the probabilistic-time characteristics do not meet the required ones, then the TD either receives a denial of service, or is put in a queue to wait for service.

If a suitable access network is found, resources are reserved for the entire transmission path, and then the service is transferred to the second stage.

Stage II - Transfer of user data

The transmission process in this case can be represented by a two phase QS: Phase 1-transfer of information from/to TD to / from AD; Phase 2-transfer of information from/to AD to/from BS of the selected access network.

We introduce the following notation:

λ – the intensity of the flow of applications from one TD [1/s]

N – the number of TD's that are within the range of one AD

M – the number of AD

B – number of access radio networks

k – the length of transmitted blocks [bit]

P – probability of denial of service

V_1, V_2 – transfer rate at 1 and 2 phases [bit/s]

T_{a1}, T_{a2} – average the allowed aging time of information in phase 1 and 2 [s]

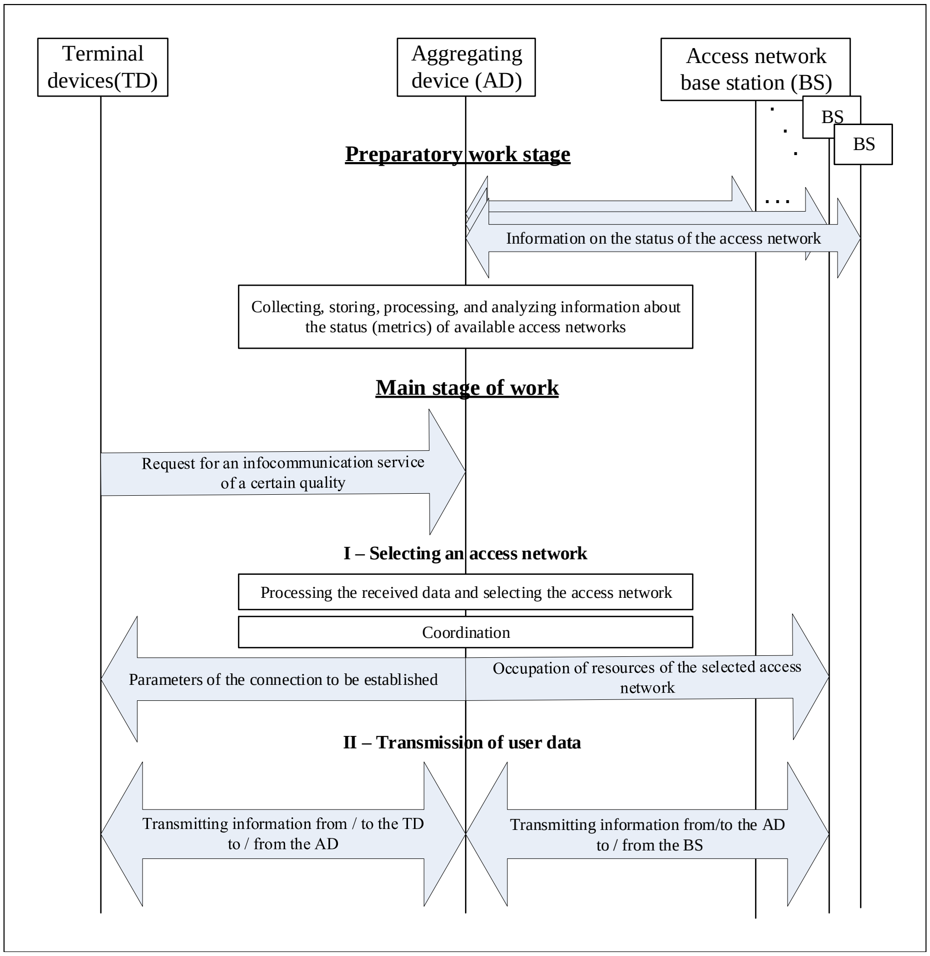

Fig. 3. A script to establish the connection in case of a centralized approach to the selection of access network for last mile.

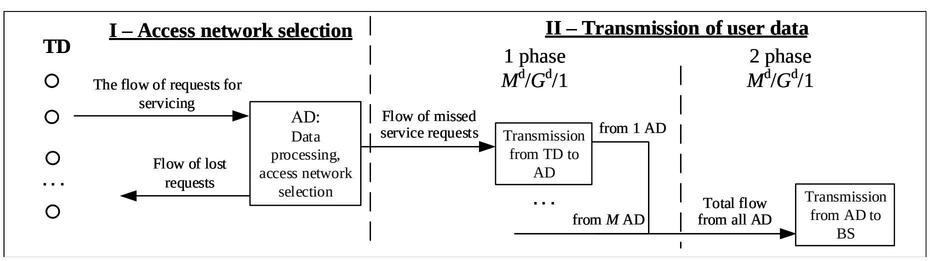

Fig. 4. Graphical representation of the access stage.

Suppose that:

– streams of homogeneous data packets with an intensity of λ [1/s] with a length of k bits, described by the Bernoulli distribution with the parameter q_1 on the T_1 interval, are sent to the TD inputs for transmission. As the minimum clock cycle for modeling the transmission process in the 1st phase, select the interval T_1=1/V_1 [s];

– at the output of each AD for transmission to the BS, a stream of homogeneous packets is formed, described by the Bernoulli distribution with the parameter q_2 on the interval T_2. The minimum clock cycle for modeling the transmission process in the 2nd phase is the interval T_2=1/V_2 [s];

- in phase 1 and 2, Time Division Multiplexing (TDM) technology is used to organize multiple access to the transmission channel);

- direct transmission of data blocks (without feedback) is performed, and data blocks distorted as a result of interference in the radio channel are discarded when receiving.

A mathematical model of the user data transfer process can be represented using an expression for the z-transform of the time delay distribution series for data transfer $f(z)$:

$$f(z) = f_1(z)f_2(z), \tag{1}$$

where $f_1(z)$ and $f_2(z)$ are z-transformations of the distribution series of data block transmission delay times on the 1st and 2nd phase, respectively.

In these assumptions, the 1st and 2nd phases can be represented as the $M^d/G^d/1$.QS. The expression for the z-transform series of the data block transmission time distribution at each phase is given as follows:

$$f_i(z) = \frac{(1-\Theta_i)(1-z)g_i(z)}{1-p_i z - q_i z g_i(z)}, p_i = 1 - q_i, i = \overline{1,2}, \tag{2}$$

$$q_1 = \lambda(1-P)T_1; q_2 = (\lambda(1-P)\Pi_1 N T_2)/B. \tag{3}$$

Π_1 is the probability of timely delivery of the data block in the 1st phase, Θ_1 - the probability of the terminal buffer being busy in the 1st phase; Θ_2 - the probability of the AD buffer being busy in the 2nd phase are defined as follows:

$$\Theta_i = q_i(d/dz^{-1})g_i(z)\Big|_{z=1}, \Theta_i < 1, i = \overline{1,2}. \tag{4}$$

$g_i(z)$ - z-transformations of service interval distribution series in phase 1 and 2, respectively:

$$g_1(z) = z^{-kN}; g_2(z) = z^{-kM}. \tag{5}$$

Taking into account (5), the expression (4) for calculating Θ_1 and Θ_2 takes the following form:

$$\Theta_1 = q_1 kN, \Theta_2 = q_2 kM. \tag{6}$$

The set of the above expressions (1) – (6) defines a mathematical model of the user data transfer process.

Expressions for calculating probabilistic-time characteristics

Probability of timely delivery of the data block. Consider the case of a stochastic restriction on the allowed delivery time of a data block in the 1st and 2nd phases with the parameter Q_{ai}:

$$Q_{ai} = 1 - \frac{T_i}{T_{ai}}, i = \overline{1,2}. \tag{7}$$

In this case, the probability of timely delivery can be found as follows:

$$\Pi = \Pi_1 \Pi_2, \Pi_i = f_i(z)\Big|_{z=Q_{ai}^{-1}}, i = \overline{1,2}, \tag{8}$$

where $f_i(z) - z$ is the transformation of the delay time distribution series in the QS at phase 1 and 2 (2).

The average delivery time of a data block from TD to BS will be determined as follows:

$$\overline{t} = \overline{t_1} + \overline{t_2}, \tag{9}$$

where $\overline{t_1}$ $\overline{t_2}$ - the average delay time of data block transmission in phase 1 and 2 is determined by the Hinchen-Polacek formula

$$\overline{t_i} = \overline{n_i} T_i, \overline{n_i} = g_i'(1) + \frac{q_1 g_i''(1)}{2(1-\Theta_i)}, i = \overline{1,2}, \tag{10}$$

$$g_i'(1) = (d/dz^{-1}) g_i(z)\Big|_{z=1}, g_i''(1) = (d/dz^{-2}) g_i(z)\Big|_{z=1}, i = \overline{1,2}, \tag{11}$$

where $g_i(z)$ is the z-transform of the service interval distribution series for the i-th phase ($i = \overline{1,2}$) is defined from (5).

The real-time information rate shows how much traffic is actually transmitted in the access network per unit of time [s], i.e. it takes into account the losses associated with failures at the 1st stage of service, as well as the losses that occur due to late delivery of data blocks in the 1st and 2nd phases of transmission

$$R^{RT} = k\lambda(1-P)\Pi, \tag{12}$$

where Π is the probability of timely delivery of the data block from the BS terminal device is determined from (8).

Numerical experiments were performed with the following initial data: $M = 4$ – the number of AD; $B = 5$ – number of available access radio networks; $N = 100; 200$ – the number of terminals in the area of one AD; $k = 256$ [bit] is the length of transmitted data blocks; $V_1 = 2 * 10^7$[bit/s], $V_2 = 8 * 10^7$[bit/s] - transmission rates for phase 1 and 2; $T_{a1} = 0.05$[s]; $T_{a2} = 0.05$[s] – the average allowable aging time of information in phase 1 and 2; $P = 0; 0,1; 0,3$ and the probability of denial of service.

Figure 5-7 shows the results of numerical experiments. The study of the influence of the number of nodes in the AD area, the probability of service failure at stage 1 on the probabilistic and temporal characteristics of the data block transmission process in the access network: the probability of timely delivery of

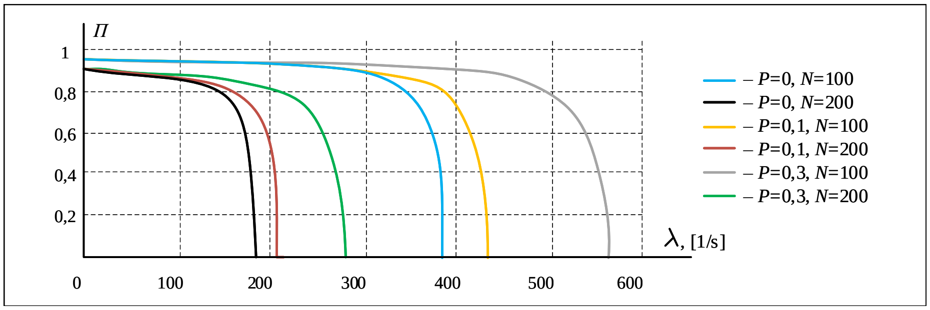

Fig. 5. Dependence of the probability of timely delivery of data blocks on the intensity of their receipt for different probabilities of denial of service and different number of TD.

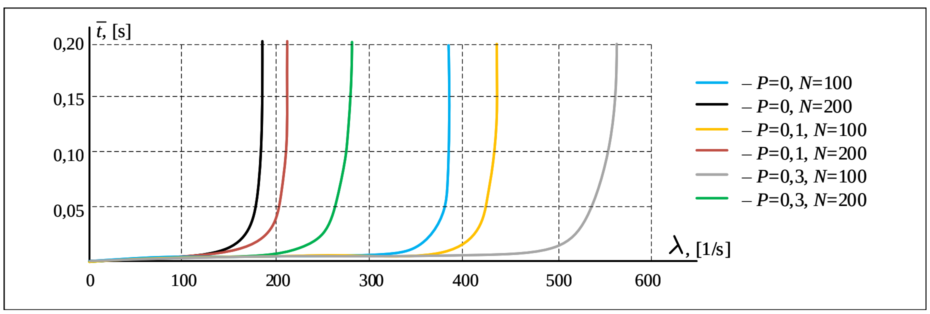

Fig. 6. Dependence of the average delay time on the intensity of data blocks received for transmission with different probabilities of denial of service and different number of TD.

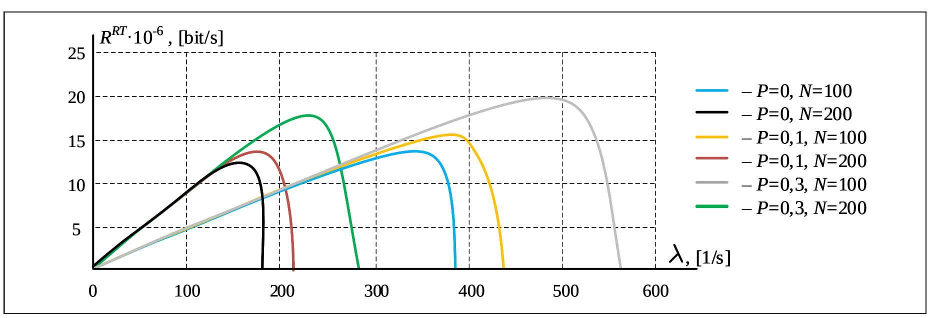

Fig. 7. Dependence of the network's real-time information speed on the intensity of data blocks received for transmission with different probabilities of service failure and different number of TD.

the data block (Fig. 5), the average transmission delay time (Fig. 6), real-time network information speed (Fig. 7).

From the graphs shown in figure 5-7, it can be seen that as the load on the access network increases (i.e., as the number of TD increases and the intensity of data blocks for transmission increases), the probabilistic and temporal characteristics of the transmission process deteriorate. However, sifting through part of the traffic at the first stage of service can generally improve the quality of transmission and significantly increase the operating range of access network performance intensities, i.e., increase their stability.

3 Results

1. A new architecture of the access network is proposed, in which, unlike the known ones, the tasks of vertical handover are solved by a special hardware-software aggregator, which allows to release terminal devices from the corresponding functions and improve the quality of service by rational choice of data transmission paths within the ABC concept.
2. The proposed script of terminal access to global infocommunication resources differs from the known ones by the allocation of a special stage of selecting the best access network, which allows for a comprehensive choice of the network on the "last mile" taking into account the current state of all available access networks and the terminal itself.
3. The developed model of access control to global infocommunication resources displays all the features of the new architecture and script of terminal access to global infocommunication resources, which allows you to choose the best network by a complex criterion that combines probabilistic-time and probabilistic-energy characteristics.
4. A mathematical model of interaction between end terminals and the base station via an aggregating device is obtained. this model allows us to estimate the PTC of the data transfer process from the terminal to the base station.
5. The numerical calculation and analysis of the impact on the probabilistic and time characteristics of the process of transmitting data blocks in the access network of the number of TD, the intensity of their operation and the probability of denial of service.

4 Discussion

The 802.21 "Media independent handover" standard [11] describes the VHO procedure, but does not provide specific recommendations for its implementation.

When using a decentralized approach to VHO organization, the problem of selecting one of several possible access networks on the last mile is solved by a smart TD (see Fig.1), which has the following disadvantages:

- complication of terminals that must support: multiple protocols; complex software for rating and selection of access network;

- with the development of network technologies and the emergence of new technologies and standards, the subscriber has to purchase more complex and expensive terminal devices;

- most of the network resources of the last mile are used not for transmitting user information, but for transmitting service information that supports the decision-making process on choosing an access network, since the smart terminal must interact with the network base station (for example, in the case of 4G, service traffic exceeds the user traffic in volume);

- TD today is not only a human gadget, but also objects of the Internet of things (IoT), for which the complexity and cost increase is often unacceptable.

The key idea of this approach, considered, in particular, in the works [12,13]: the use of a complex/smart terminal-multifunctional device SDR (Software Defined Radio). On the basis of consolidation of known (previously collected/received from operators) values of characteristics of available networks and required quality of service, SDR will select for transmission the most suitable network for access to information and telecommunication resources.

VHO decision-making based on SDR can be considered as one of the possible solutions to the problem of choosing a network of access to global infocommunication resources. It is suitable for use in special purpose networks functioning, for example, in the interests of national defense, state security, law enforcement [14], where the required quality of communication is determined by the terminal device itself. However, in networks that require complex terminals, it is difficult to ensure efficient operation. This approach does not take into account other alternative methods of improving the efficiency of infocommunication networks, which grows as network resources become larger, multiplexing, multiple access and switching technologies improve.

The present study considers an alternative approach to the selection of access networks on the last mile – centralized (see Fig.2). It is based on the implementation of an aggregating device (AD) – an aggregator of access networks - into the architecture of a heterogeneous access network. Access control consists of selecting the most appropriate network for each communication session.

AD implements the following procedures: collecting, storing and analyzing data on the current state of all available access radio networks, deciding on the appropriate network for each connection, dynamically reallocating connections between end terminals and base stations to prevent failures, consequences of congestion of access networks, and ensuring the best connection available at the moment to the provider's equipment within the ABC concept.

The selection procedure is based on the consolidation of data on the current state of all access radio networks that fall within the coverage area of the service, as well as requirements for the quality of the service provided. TD in this case – simple, inexpensive devices that support a typical (universal) interface for communication with AD. For communication of terminals with BS, signal channels are supported, which transmit service information (geolocation data, etc.). AD for receiving / transmitting data from / to end terminals on the one hand supports standard interfaces, and on the other all interfaces of available radio access networks.

Advantage of the proposed approach to selecting the last mile access network in comparison with a decentralized one:

- simplify and reduce the cost of TD-reduce requirements for hardware and software resources of terminals;

- reducing the amount of service traffic transmitted;

- orientation to the needs of the Internet of things;

- this approach meets the national 5G network implementation programs that focus on: cooperation of Telecom operators, pooling their resources on the last mile, creating telecommunications ecosystems, and striving to simplify and reduce the cost of terminal devices [15];

- this approach meets the requirements of the IEEE 3001 Future Network (FN) concept [16].

Let's take a closer look at the last point: within the framework of the FN concept [16], the main requirements for promising Infocommunications were formulated. Requirements are divided into 4 groups of factors: services, data, environmental and socio-economic factors. The proposed centralized architecture for selecting the last mile access network corresponds to the specified factors. In particular, the FN concept has a socio-economic orientation and provides for the elimination of digital divide (DD) by reducing costs at all stages of the infocommunication service life cycle. The proposed architecture meets this requirement because it is focused on: simplifying and reducing the cost of TD; using standard broadband access; reducing requirements for software and hardware resources of TD. This solution is generally more cost-effective than the SDR approach shown in Fig.1, if you estimate the total cost of terminals and network equipment. Separately, we note that the disposal of complex smart TD is more expensive than simple devices. This fact is also consistent with another environmental factor of the FN concept. Networks should be environmentally safe for the environment, and the technical solutions used to create them should minimize the impact on the ecosystem and reduce the consumption of all resources, especially energy. In the proposed approach to VHO organization (see Fig.2) it is assumed: reducing the volume of service traffic between the terminal and the network, reducing the procedure for probing the radio frequency spectrum to find available networks, etc. all this together leads to a decrease in power consumption of the TD, which is especially important for Autonomous IOT devices that work for a long time without charging.

Implementing the proposed new architecture of the TD access system to global infocommunication resources on the last mile is not an easy task, requiring the development of new hardware solutions, as well as specific software. Before conducting this development, it is advisable to assess the expected effect of its implementation.

5 Conclusion

The strategy of choosing a network of access to global infocommunication resources studied in this paper corresponds to the laws of development of telecommunication networks – consolidation leads to increased efficiency. It seems appropriate to develop a way that focuses on the cooperation of Telecom operators, combining their resources in the last mile, creating telecommunications ecosystems, and striving to simplify and reduce the cost of terminal devices.

The developed architecture, access scenario, and VHO process model can be applied in public communication networks and can improve the efficiency of the corresponding procedures.

In Russia, the movement in this direction can be observed when creating 5G networks. mobile operators are considering creating a single infrastructure for the development of fifth – generation networks in all frequency bands below 6 GHz- a Single infrastructure operator [15]. A technical and economic analysis of such a 5G deployment scenario in Russia has shown that "the Single infrastructure operator option is the least expensive in terms of total capital expenditures for both network deployment and operation" [15].

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