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RESEARCH OF APPROACHES TO THE DEVELOPMENT OF THE ORBITAL COMPUTING NETWORK FOR THE SATELLITE SYSTEM OF INTERNET OF THINGS

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ДОСЛІДЖЕННЯ ПІДХОДІВ ДО ПОБУДОВИ ОРБІТАЛЬНОЇ ОБЧИСЛЮВАЛЬНОЇ МЕРЕЖІ СУПУТНИКОВОЇ СИСТЕМИ ІНТЕРНЕТУ РЕЧЕЙ

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Abstract. *There are considered issues of building a Low-Earth-Orbit Satellite System designed to provide the Internet of Things services and adapted to the features of the services and systems of the Internet of Things. The considered system provides the creation of the necessary telecommunication infrastructure on the basis of the Low-Earth-Orbit Broadband Access Satellite System and places Computational Facilities into the Low-Earth-Orbit to ensure the processing of Internet of Things devices and systems information, and perform computations. The architecture of a "Distributed Satellite" was chosen to construct the telecommunications part of the Internets of Things Satellite System. The chosen architecture allows, on the one hand, to ensure the full functionality of complex telecommunication systems, and on the other hand, to use spacecraft of the form factor nano-satellite/cub-sat. The using of the cube-sat spacecraft for development of the satellite-based system allows to reduce significantly the cost of development of the system and the time of the system deploying. A promising direction in the development of the Internet of Things systems is the implementation of the concept of "Fog Computing" for processing Internet of Things information. In order to implement "Fog Computing", it was proposed to include into the composition of each "Distributed Satellite" a separate Satellite-Computer, and to build an Orbital Distributed Network on the basis of Satellite-Computers. The issues of the inter-satellite connectivity are considered taking into account ensuring connection between Satellites-Computers in framework of the Orbital Distributed Computer Network using inter-satellite links between Distributed Satellites, the characteristics of the orbital construction of the Satellite System Constellation. It was proposed to create and deploy the Distributed Localized Database on the basis of the Orbital Distributed Computer Network, to ensure the continuous provision of Internet of Things services, taking into account the movement of spacecraft* in *the orbital plane and the rotation of the Earth. It was shown the direction of transmission of the operational part of a Localized Distributed Database. Proposals are made on the distribution of the excess computational load arising in certain regions of the satellite telecommunications system's service area, involving the resource of neighboring satellite computers in its orbital plane and in neighboring orbital planes. An algorithm is proposed for moving the excess computational load to the polar and oceanic regions.*

Keywords*: LEO Satellite Communication System, Internet of Things, Distributed Computer Network.*

Анотація. *Розглянуті питання побудови низькоорбітальної супутникової системи, яка призначена для надання послуг Інтернету Речей і адаптована до особливостей послуг та систем Інтернету Речей. Розглянута система забезпечує формування необхідної телекомунікаційної інфраструктури на базі низькоорбітальної супутникової системи широкосмугового доступу, і розташованих на низькій навколоземній орбіті обчислювальних засобів, які забезпечують проведення обробки інформації пристроїв та систем Інтернету Речей, і виконання необхідних обчислень. Для побудови телекомунікаційної частини супутникової системи Інтернету Речей вибрана архітектура «розподіленого супутника», яка дозволяє с одного боку забезпечити повну функціональність складної телекомунікаційної системи, а з іншого боку - використовувати космічні апарати форм-фактору нано-супутник/куб-сат. Використання для побудови супутникової системи космічних апаратів типу куб-сат дозволяє суттєво скоротити витрати на створення і час на розгортання системи. Перспективним напрямком розвитку систем Інтернету Речей є реалізація концепції «туманних обчислень» для обробки інформації пристроїв Інтернету Речей. Для реалізації «туманних обчислень» запропоновано включити до складу кожного «розподіленого супутника» окремий супутник-обчислювач, та побудувати на основі супутників-обчислювачів орбітальну розподілену обчислювальну мережу. Розглянуті питання забезпечення зв'язності між супутниками-обчислювачами у складі орбітальної розподіленої обчислювальної мережі за допомогою ліній зв'язку між розподіленими супутниками із врахуванням особливостей орбітальної побудови супутникової системи. Для забезпечення безперервного надання послуг Інтернету Речей запропоновано створення і розміщення на базі орбітальної обчислювальної мережі розподіленої локалізованої бази даних, показано напрямки передач оперативної частини локалізованої розподіленої бази даних із врахуванням руху космічних апаратів в орбітальній площині та обертання Землі. Представлені пропозиції щодо розподілення надлишкового обчислювального навантаження, яке виникає в окремих регіонах зони обслуговування супутникової телекомунікаційної в системи, із залученням ресурсу сусідніх супутників-обчислювачів в своїй орбітальній площині і в сусідніх орбітальних площинах. Запропоновано алгоритм переміщення надлишкового обчислювального навантаження в приполярні та океанічні райони.*

Ключові слова*: низькоорбітальна система супутникового зв'язку, Інтернет речей, розподілена обчислювальна мережа*

INTRODUCTION

IoT is becoming an important factor in modern infocommunication technologies. According to analytical companies forecasts, in 2022 the global market for IoT and related technologies will reach $1.2 trillion and average growth rate will be of 13.6 % [1]. The life of a big city and the work of an enterprise, human-machine interaction, community projects and concern for the welfare of every citizen - all this will be provided on the basis of data from smart sensors and devices [2]. According to Ericsson, in 2023 the number of IoT devices connected to cellular networks will amount to 3.5 billion units [1]. The development of IoT is inextricably linked with an increase in the demand for the capacity of telecommunication systems focused on providing IoT Services. The satellite telecommunication system operators increasing attention is attracted by the small satellite segment: nano-satellites/cube-sat (1–10 kg weight), micro-satellites (10–50 kg), mini-satellites (50–500 kg). According to SpaceWorks company's estimates, the launch of 2,800 nano/micro satellites (1–50 kg weight) to be launched over the next ten years [3]. Only the forecast for 2019 is 294÷393 small satellites will be launched in the frame of this market segment.

The scope of this work is to study the peculiarities of the Satellite Communications System which is adopted to the features of Internet of Things and implements the “Fog Computing” concept [4–5].

FOG COMPUTING

The development of IoT technologies is accompanied by the introduction of IoT devices in stationary/fixed objects and the emergence of a large number of mobile IoT devices. Initially, IoT systems focused on the use of Cloud Computing technologies, but the introduction of mobile IoT devices stimulated the search for more effective solutions.

A method of increasing the efficiency of IoT systems is the transfer of computing capacity to the boundaries of the network and the implementation of the concept of “Fog Computing” (FC) [4, 5]. In this case, unlike cloud architecture, processing of IoT devices information is carried out at the lower and intermediate levels of the hierarchical structure of the information system (see Figure 1). This allows us to free the Communication System from transmission the entire amount of IoT Traffic from IoT Devices located at the lower hierarchical level of the System to the Cloud

Computing Center, which is at the upper hierarchical level, and in the opposite direction. When implementing the FC concept, the results of information processing are transmitted to higher hierarchical levels, which reduces the volume of information transmitted and increases the "value" of this information.

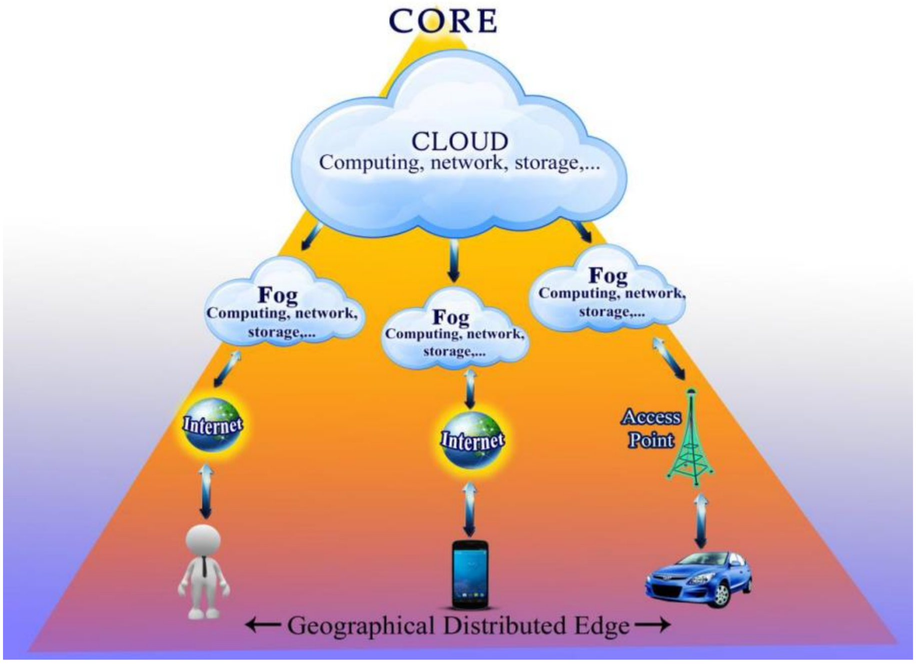

Figure 1 – Cloud & Fog Computing

A communications system designed to provide IoT services and supporting the FC concept must have computing capacity located as close to the network edge as possible and provide these computing capacity to IoT systems [6]. The LEO Satellite Communications System designed to support IoT systems must take into account the specifics of implementing the concepts of "Fog Computing" and provide the IoT consumers with the computing capacity they need.

Thus, the issue of research can be defined as follows: to determine the possibility of placing computing capacity in the space segment and to consider the features of the functioning of computing capacity, taking into account the use of the simplest architectural solutions and design features of the satellite buses of the CubeSat or nano-satellite form factor.

PLACING OF COMPUTING CAPACITY IN THE SATELLITE SYSTEM BASED ON THE DISTRIBUTED SATELLITE ARCHITECTURE

The issue to place own Computing Capacity in the LEO Communication System based on the Distributed Satellite (DS) Architecture [7] could be solved by including a separate particular Edge Satellite – Satellite-Computer (SC) into each DS (see Figure 2).

Similarly, to Edge Satellite-Repeater (SR), the SC is built on the base of CubeSat satellite bus. The payload of such a satellite is the Computing Module (CM).

The Distributed Satellite Concept allows to redirect the power generated by the on-board power supply system of the nano-satellite, and direct it to ensure the operation of the payload. At the same time, that part of the on-board consumers that are not used after the nano-satellite enters into the Distributed Satellite radio network is disconnected. These systems include, at a minimum: the on-board command-telemetric radio line RF equipment, the payload information transmission radio line RF equipment (which is determined by the functional purpose of the system), and the on-board GPS receiver. All the functions of transmitting command-telemetric information and payload information, measuring the motion parameters of a nano-satellite and determining its position in the orbit are performed by the internal radio network of the Distributed Satellite.

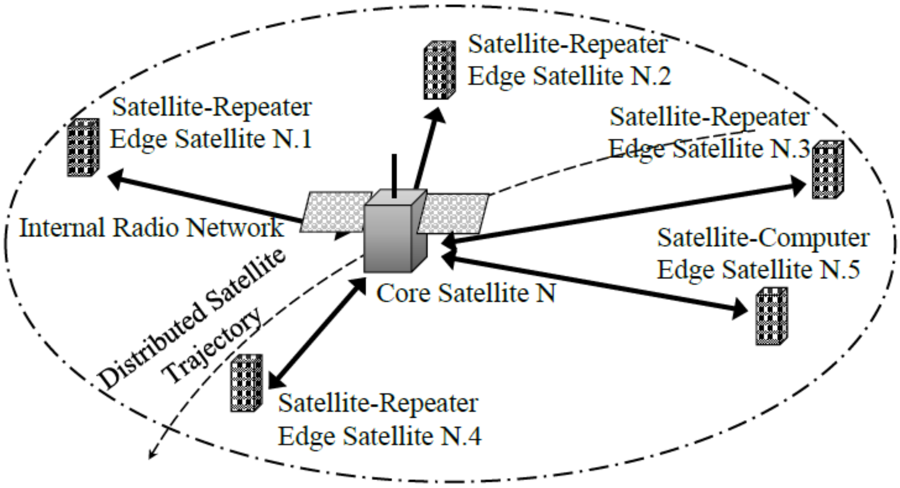

Figure 2 – The Distributed Satellite Architecture. Centralized configuration

The CM is equipped with its own processor and memory CP core performance (computing capacity) is determined on the basis of a trade-off between the following indicators:

- mass-dimensional, energy and thermal performances of the CubeSat satellite bus;
- the number of IoT devices and the characteristics of IoT traffic in the service area of the DS;
- complexity of IoT information processing algorithms, volume of software, IoT information processing time limits.

CP is implemented on the basis of COTS-technologies and related software.

IoT-DEVICES INFORMATION TRANSFER PATH

In the LEO Satellite Communications System, which provides IoT Services, uplink IoT information (from the IoT device to the SC) and in opposite direction are transmitted via the composite path (see Figure 3). The path includes: a radio access network between the IoT device and the VSAT terminal, a satellite link (up-link or down-link) between the VSAT terminal and the SR, and the Internal Radio Network of the DS.

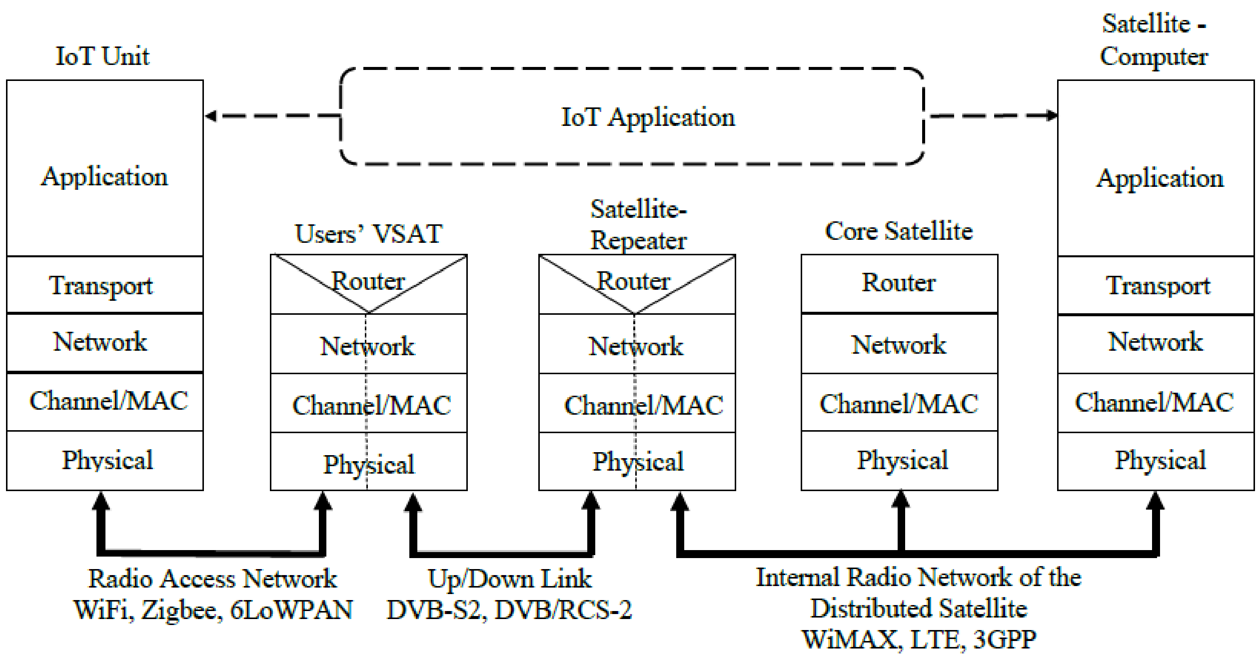

Figure 3 – IoT information transfer path between IoT device and SC

The IoT service software is loaded at the TCP/IP application level in storage of an IoT device, an information source – a sensor, or a actuator – an executive device, and in storage of a SC.

IoT device – the information source (sensor) forms the IoT device information burst in accordance with the IoT Service algorithm. IoT device burst is transmitted via internal interfaces through lower layers: transport, network, data link, to the physical layer for transmission through the radio interface. The procedure for encapsulating an IoT bursts is defined by the terrestrial radio access network standard. The ground network can be built on the basis of standards focused on low power consumption by terminal devices, for example: WiFi, Zigbee, 6LoWPAN, LoRaWAN.

The central station of the ground access network is combined with the VSAT-terminal, where IoT burst is routed and the formation/processing of the up- and downstream is performed. As an implementation, the DVB/RCS-2 standard is considered. Perhaps the use of other technologies offered by developers. It should be noted that, despite the differences in the names of the proposed technologies of VSAT networks of various developers, they all use the DVB-S2 standard and its continuation DVB-S2x in the Down-Link. The differences concern only to organization of the Up-Link.

DS/SR receives the Up-Link transport stream from Up-Link and transmits IoT burst to the Internal Radio Network of the DS. SR provides the conversion of the stream format on the Up-Link to the format of the DS Internal Radio Network. The DS Internal Radio Network considers IoT Systems features and operates on the basis of one of the standards of the broadband terrestrial radio network, taking into account its adaptation to the specifics of functioning in the space system. For example, the 3GPP standard, which is used for 4G, 5G networks, can be selected as the base.

IoT information burst is transmitted to the Router of DS Core Satellite (CS) via the Internal Radio Network and then to the SC, where information is processed and necessary calculations are performed according to the algorithm of the IoT System (see Figure 2).

The processing result is transmitted to the IoT device actuator in the opposite direction.

The generalized results of the IoT devices bursts processing are transmitted to the Cloud Computing Center (see Figure 1) along the path that includes the SC / CS – Inter-Satellite Links between DS – CS / SR – VSAT terminal of the Cloud Computing Center.

The round trip time (RTT) for IoT System, or the response time of IoT System, taking into account delay in satellite segment and realizing of FC concept is

$$T_{\mathrm{IoT}} = t_{\mathrm{S\text{-}C}} + t_{\mathrm{comp}} + t_{\mathrm{C\text{-}R}}$$

where $t_{\mathrm{S\text{-}C}}$ is the delay in the IoT burst transmission from the IoT device to the SC; t_{comp} is the IoT device burst processing time in CS; $t_{\mathrm{C\text{-}R}}$ is the delay in response transmission (the result of the IoT information processing) to the IoT actuator device.

The delay in the IoT information transmission from IoT device to the SC is

$$t_{\mathrm{S\text{-}C}} = t_{\mathrm{IoT1}} + t_{\mathrm{WiFi}} + t_{\mathrm{VSAT_{up}}} + t_{\mathrm{up}} + t_{\mathrm{ST_1}} + t_{\mathrm{SN_1}} + t_{\mathrm{CS}} + t_{\mathrm{SN_2}},$$

where t_{IoT1} is the time of formation of IoT-sensor device burst; t_{WiFi} – delay for transmission in the radio access terrestrial network; $t_{\mathrm{VSAT_{up}}}$ – delay for routing and format conversion in the VSAT terminal; t_{up} is the delay in satellite uplink; $t_{\mathrm{ST_1}}$ is the delay for processing and format conversion to SR; $t_{\mathrm{SN_1}}$ – delay for transmission in the Internal Radio Network; t_{CS} – delay for routing in CS; $t_{\mathrm{SN_2}}$ is the delay for transmission on the Internal Radio Network to the SR. The response transfer delay from the SC to the IoT actuator $t_{\mathrm{S\text{-}C}}$ has the similar components. The difference appears in replacing the t_{up} parameter with the t_{down} parameter – the delay in the satellite downlink. Considering the limited size of the radio access terrestrial network, the Internal Radio

Network of the Distributed Satellite, as well as the rationing in the design and manufacture of delays in equipment generation/processing, formats conversion and information routing, a number of components of the total delay in sending the IoT device burst/command could be considered minimal, without making significant impact on the delay value. These include: t_{IoT1}; t_{WiFi}; $t_{\mathrm{VSAT_{up}}}$; $t_{\mathrm{ST_1}}$; $t_{\mathrm{SN_1}}$; t_{CS}; $t_{\mathrm{SN_2}}$. The most equivocation appears due to $t_{\mathrm{up}}/t_{\mathrm{down}}$.

The delays in the IoT information transmission through satellite uplink t_{up} or in the back way through downlink t_{down} are the random value that depends on the geometric ratio between the VSAT terminal and the SR during the IoT burst/response transmission, and equals [8]:

$$t_{\mathrm{down}}, t_{\mathrm{up}} = \frac{(R_{\mathrm{e}} + h)\cdot \sin\theta}{c\cdot\cos\beta},$$

where R_e is the Earth radius (adopted 6371 km); h is the satellite orbit altitude; θ is the central angle between the sub-satellite point and the VSAT terminal location; β is the elevation angle of the VSAT-terminal beam directed to the satellite; c is the speed of light c = 3108 m/s.

The central angle between the sub-satellite point and the VSAT terminal location is calculated with help of well-known expressions [9]:

$$\theta = \arccos\left(\cos\Delta\lambda_{\text{sat-vsat}} \cos l_{\mathrm{sat}} \cos l_{\mathrm{vsat}} + \sin l_{\mathrm{sat}} \sin l_{\mathrm{vsat}}\right),$$

where $\Delta\lambda_{\text{sat-vsat}}$ is a difference in longitude of the sub-satellite point and the VSAT-terminal; l_{sat} is the latitude of the sub-satellite point; l_{vsat} is the VSAT terminal latitude.

The value of delay for uplink/downlink $t_{\mathrm{up}}/t_{\mathrm{down}}$ are a random value that depends on the height of the orbit h and the current values of the central angle θ and the elevation angle β, and is accurate within

$$\frac{h}{c} \le t_{\mathrm{up}}, t_{\mathrm{down}} \le \frac{(R_{\mathrm{e}} + h)\cdot \sin\theta_{\max}}{c\cdot\cos\beta_{\min}}$$

where $\theta_{\max}$ is the maximum value of the central angle determined by the spacecraft footprint; βmin is the minimum acceptable value of the VSAT terminal beam elevation angle, specified primarily by the QoS requirements for IoT system. For the case of a low-orbit satellite communication system, it could be assumed that the delay in the transmission of the IoT devices burst/response is evenly distributed within these limits. The limits values for even distribution depending on the height of the LEO satellite communication system and the minimum elevation angle limitation of the VSAT terminal beam are given in Table 1.

Table 1 – Limits of Change of Delay on Distribution in Satellite Up/Down Link in the Send/Response IoT-Device Data Transmission Channel.

The height of the orbit, *h* km	Minimum delay, ms	Maximum delay, ms		
		β_{min} = 40°	β_{min} = 50°	β_{min} = 60°
500	1.67	2.47	2.13	1.9
800	2.67	3.86	3.35	3.03
1100	3.67	5.2	4.56	4.13

Orbital distributed peer-to-peer computer network

The orbital segment of the Low-Earth-Orbit Satellite Internet of Things System (LEO IoT System) consists of N orbital planes, each of which contains M Satellites, which is a traditional pattern for such systems [10,11]. The number of orbital planes and satellites in each orbital plane depends on the height of the orbit, the latitude of the boundary of continuous service zone, the minimum elevation angle for the user's VSAT terminal. Each satellite is connected with two neighboring satellites in its orbital plane and with one nearest satellite in two neighboring orbital planes by communication links. In the LEO IoT System, each satellite represents a “Distributed Satellite” (DS) micro-constellation with one core satellite and a number of edge satellites [7].

The CS from LEO Satellite System DS forms a peer-to-peer Orbital Distributed Computer Network (ODCN), which structure is shown on Figure 4. The CS provides necessary calculations for IoT devices operation in the DS Service Area. The connectivity of the peer-to-peer ODCN is ensured by the combination of the DS Internal Radio Network and the set of Inter-Satellite Links between DSs.

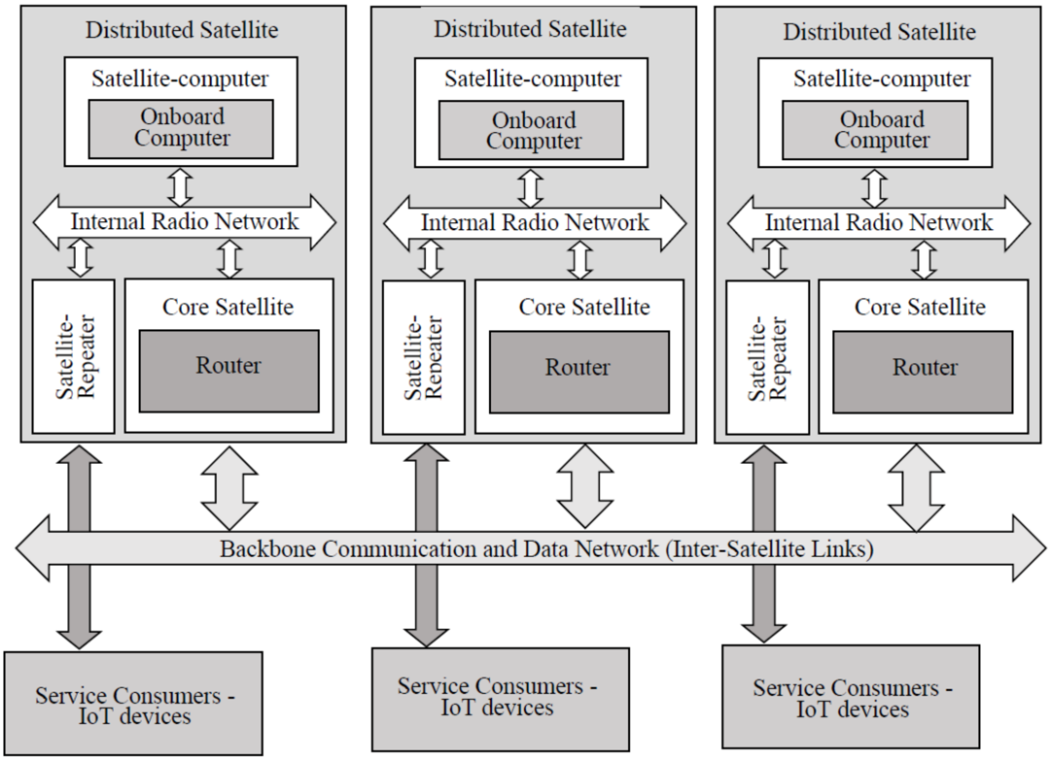

Figure 4 – Peer-to-peer Orbital Distributed Computer Network (ODCN)

Satellites-Repeaters (SRs) provide communication with IoT devices (see Figure 4). The Core Satellite Router provides the routing through the DS Internal Radio Network, between Inter-Satellite Links with other DS and terminals of the DS Internal Radio Network. The CS is an Internal Radio Network subscriber and is connected via a RS Router to a peer-to-peer ODCN.

As mentioned above, the adopted architecture for constructing the LEO IoT System Constellation involves the use of Inter-Satellite Links between DSs [7]. Each DS provides direct communication with four neighboring distributed satellites. Figure 5 shows the connectivity graph of the LEO IoT System Constellation. The symbol $DS_{n.m}$ defines the Distributed Satellite number m in the orbital plane number n.

As can be seen from the graph, each (HTML translation failed) $DS_{m.n}$ is directly connected to four neighboring $DS_{s.s0}$, the $DS_{3.3}$ is directly connected to the following satellites: $DS_{3.2}$ and $DS_{3.4}$ in the orbital plane 3, with the $DS_{2.3}$ in the orbital plane 2, and with the $DS_{4.3}$ in the orbital plane four.

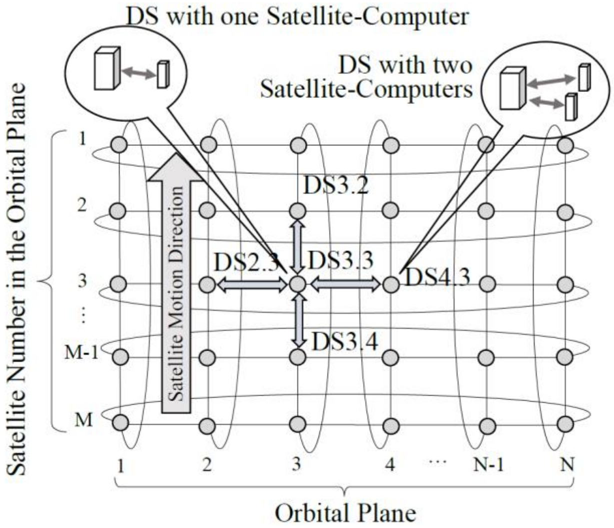

Figure 5 – Orbital peer-to-peer Computer Network connectivity

Based on the fact that all orbital planes contain the same number of DSs, connectivity in a peer-to-peer ODCN is described by a modified connectivity matrix – a rectangular matrix of dimension $M \times N$, where M is the number of DSs in the orbital plane, N is the number of orbital planes. Each of the matrix elements determines the number of retransmissions for the burst delivery from a specified distributed satellite. For the most distributed satellite, the element's value is 0. For $DS_{3.3}$ (see Figure 5), the modified connectivity matrix H looks like:

$$H_{3,3} = \begin{bmatrix} 4 & 3 & 2 & 3 & 4 & 5 & K & 5 \\ 3 & 2 & 1 & 2 & 3 & 4 & K & 4 \\ 2 & 1 & 0 & 1 & 2 & 3 & K & 3 \\ 3 & 2 & 1 & 2 & 3 & 4 & K & 4 \\ 4 & 3 & 2 & 3 & 4 & 5 & K & 5 \\ M & M & M & M & M & L & L & M \\ 5 & 4 & 3 & 4 & 5 & 6 & K & 6 \end{bmatrix}.$$

The value of each element $h_{m,n}$ is determined as follows

$$h_{m,n} = \Delta_m + \Delta_n,$$

where Δ_m and Δ_n are the difference in the DS number in the orbital plane and the difference in the numbers of the orbital planes, respectively. Considering the connectivity graph shown in Figure 5, these differences are calculated as follows:

$$\Delta_m = \begin{cases} |m_i - m_0| & \text{для } \Delta_m \le N/2; \\ |M + m_i - m_0| & \text{для } \Delta_m > N/2, \quad m_0 > m_i; \\ |M + m_0 - m_i| & \text{для } \Delta_m > N/2, \quad m_i > m_0. \end{cases}$$

The calculation of the Δ_n value is the same.

The connectivity parameters of a peer-to-peer orbital computer network are important in determining the processing time of an IoT device package during a redistribution of computing load, i.e. in the case of a code, for various reasons, part of the computational load is transferred to processing in computing satellites of other distributed satellites.

The delay value in the Inter-Satellite Link between the DSs in one orbital plane t_{IS} is almost constant and is estimated by the following expression:

$$t_{\mathrm{IS}} = \frac{2\left(R_{\mathrm{e}} + h\right)\sin\frac{\Delta\lambda}{2}}{c} = \frac{2\left(R_{\mathrm{e}} + h\right)\sin\frac{360^\circ}{2M}}{c}$$

where R_{e} is the radius of the Earth (6371 km); h is the orbit altitude; $\Delta\lambda$ is the space/angular separation between the DSs in the orbital plane; M is the number of DSs in the orbital plane; c is the speed of light, 3108 m/s.

The delay value in the Inter-Satellite Link between DCs in adjacent orbital planes t'_{IS} varies depending on the latitude of the sub-satellite point of both DSs. With regard to the DS phasing in the adjacent orbital planes, this delay value varies within the following limits:

$$t'_{\mathrm{IS}_{\min}} = \frac{1}{2} t_{\mathrm{IS}} = \frac{2\left(\mathrm{R_e} + h\right)\sin\frac{\Delta\lambda}{2}}{c}$$

$$t'_{lS_{\max}} = \frac{2\left(\mathrm{R_e} + h\right)}{c}\sin\left[\frac{1}{2}\arccos\left(\cos\frac{\Delta\lambda}{2}\cos\frac{L}{\mathrm{R_e}}\cdot\frac{180^\circ}{\pi}\right)\right]$$

where L is the width of the Orbital Plane Street.

Table 2 shows the magnitude of the delay depending on the width of the Orbital Plane Street [10].

Table 2 – Value of Delay in the Inter-Satellite Link Between the DS
for LEO IoT System (Orbit Height 850 km)

VSAT beam elevation β (degree)	Width of the Orbital Plane Street (km)	Number of DS in Orbital Plane	t_{IS} (ms)	$t'_{\mathrm{IS}_{\min}}$ (ms)	$t'_{lS_{\max}}$ (ms)
40°	1179	32	4.72	2.36	5.0
50°	855	48	3.15	1.57	3.59
60°	600	64	2.36	1.18	2.55

DISTRIBUTED LOCALIZED DATABASE

In the memory of the computing module of the satellite-calculator is stored a database containing the following information:

– data on IoT devices, including data for identifying devices (MAC and IP addresses, type and method of addressing), device types, coordinates of IoT devices (for stationary devices) and boundaries of service areas for mobile (mobile) IoT devices, constants, coefficients, other data supplied by the operator of the IoT system for processing information from specific IoT devices;

– IoT information processing software that provides calculations for the tasks and services of IoT systems and tools, performance characteristics of IoT devices;

– real-time IoT information processing results in relation to each device;

– other information.

The database and, accordingly, the memory of the computing module, is divided into two parts: the conservative part and the operational part. The conservative part contains information with a long shelf life, the relevance of which remains for a period that exceeds one orbital period (the period of revolution of the satellite in orbit). The operational part contains the results of IoT information processing in real time, taking into account the provision of database recovery points in the event of failure of one of the system elements and partial loss of information of the operational part.

Based on the constant movement of satellites relative to the Earth’s surface in low-orbit satellite systems, depending on the limitations of the elevation angle of the earth station’s terminal antenna and orbit altitude, the time of “visibility” for a satellite is from a few minutes to 15–20 minutes. After this time, the satellite “leaves” from the visibility zone of the earth station terminal and the next satellite “enters” the zone of visibility. To ensure the continuity of the provision of services to IoT devices and systems, the low-orbit satellite communications system should ensure the transfer of the results of previous information processing operations from the computing satellite from the “outgoing” satellite to the computing satellite of the “incoming” satellite.

The database stored in the memory of the computing modules of the orbital distributed computing network takes into account the location of IoT devices on the Earth's surface and consists of a collection of localized databases. The main part of the localized database is the operational part of the database, since this part is “attached” to IoT devices in this area. In order to localize the database, “distributed satellites” transmit and receive information on the results of processing current requests from IoT devices in relation to the place of their location on communication lines between satellites. Figure 6 shows the scheme of information transfer in one orbital plane to maintain a localized database. As can be seen from Figure 6, information is transmitted in the direction opposite to the direction of motion of the satellites in the orbital plane.

When considering traffic routing in low-orbit satellite systems, the rotation of the Earth must be taken into account. The effect of the Earth's rotation increases with an increase in the inclination of the orbit of the satellite system. The effect of the Earth's rotation, in particular, is manifested in the fact that subscribers located on the border of service areas of two distributed satellites belonging to neighboring orbital planes gradually move from the service band of one orbital plane to the service band of another orbital the plane [11]. For IoT systems, this can lead to a situation where the IoT device that sent the parcel cannot receive the command, because it will go into the coverage area of the adjacent orbital plane, and the computing satellites in this orbital plane will not receive the updated operational part of the localized base data. The likelihood of such an event increases as the breadth of IoT devices decreases.

In order to avoid loss of control of IoT devices and ensure continuity of service provision throughout the service area, an orbital distributed computing network should ensure that part of the traffic of the operational part of the localized database is routed to neighboring orbital planes in the direction of Earth rotation to take into account the movement of IoT devices between the service bands of orbital planes. In Figure 7 shows the principle of traffic distribution of the operational part of a localized database in an orbital distributed computer network.

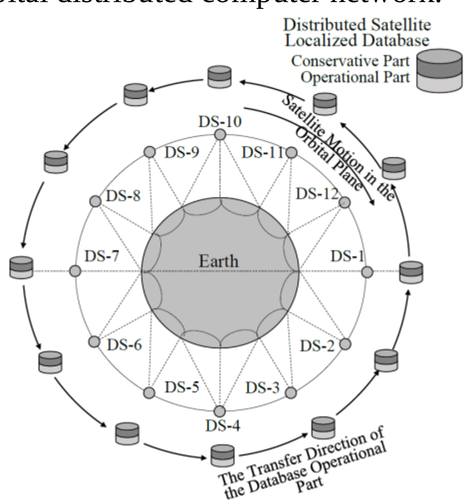

Figure 6 – Distributed database of one LEO Satellite IoT System orbital plane

The operational part of the localized database is transmitted from the $PC_{2.2}$ computing satellite to the $PC_{2.3}$ computing satellite. A $PC_{2.3}$ computing satellite analyzes the listing of IoT devices that fall into the $PC_{2.3}$ service area and transmits to the computing satellite from $PC_{3.3}$ in the adjacent orbital plane that part of the database that relates to IoT devices that have switched to the band serving the adjacent orbital plane. The rest of the operational part of the localized database continues to circulate in the orbital plane 2, taking into account its actualization according to the results of processing the current packages of IoT devices. Similarly, a $PC_{3.3}$ computing satellite after processing current packages of IoT devices from the $PC_{3.3}$ service area transmits the operational part of the localized database to a $PC_{3.4}$ computing satellite. A $PC_{3.4}$ satellite computer performs a similar procedure for distributing the operational part of a localized database.

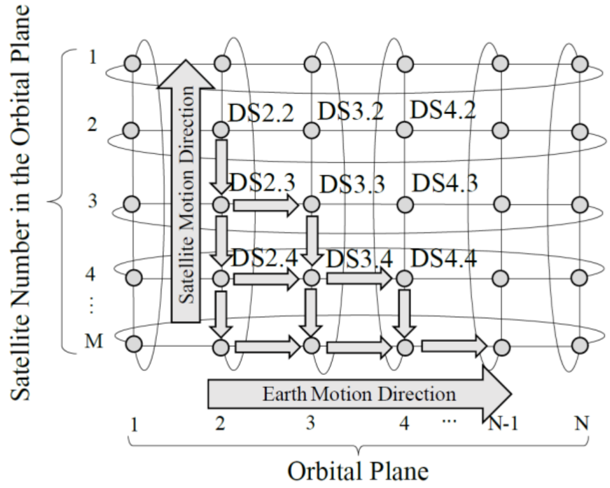

Figure 7 – IoT Information Traffic Routing in direction of the Earth rotation

Overload distribution and overflow to the circumpolar and oceanic regions

Based on the nature of IoT, the basic requirement for an IoT system is to minimize the likelihood of a denial of service for an IoT device (processing an IoT device package). The implementation of the concept of “foggy” and “boundary” computations significantly reduces the risk associated with the transmission of information through composite data transmission channels of large lengths. The desire to minimize the likelihood of denial of service in the IoT system leads to the need to significantly increase the computing power of the space segment. A compromise between the cost of the orbital segment and the probability of denial of service of the system can be found on the basis of an analysis of the traffic features of IoT devices.

A lot of publications have been devoted to the research of IoT traffic of systems and devices [14, 15, 16, 17, 18]. Despite the increased attention to research on IoT traffic of systems and devices, the vast majority of research is focused on the operation of LTE, 5G generation communication networks for the transmission of IoT traffic, on the analysis of traffic generated by IoT devices in a city or campus, on the analysis of traffic on IoT devices generated running various management software. Common in all studies is the application of traffic theory and queuing systems to the IoT systems and devices estimation methods and mathematical apparatus [14, 15, 18].

Integral estimates of the volume of data transfer traffic in mobile networks and the density of IoT devices are also of interest. According to forecasts, 5G generation networks should ensure the functioning of IoT systems with the density of IoT devices up to 1 million devices per 1 km² [13]. Ericsson notes that in the 4th quarter of 2018, the global volume of data traffic amounted to 25.4 eB, or 2.54– 019 bytes [19].

A feature of the traffic of IoT devices and systems is its unevenness and dependence on the region (region), time of day and year. You can predict a significant increase in traffic in the event of emergencies of natural or man-made origin. Thus, the low-orbit satellite communications system for IoT should provide mechanisms for handling peak loads with a sharp increase in the traffic of packages of IoT devices.

An important advantage of distributed computing networks is the ability to increase computing power quickly when peak loads occur due to the redistribution of computing load on idle/unloaded computing modules (computers, processors) using communication lines between distributed satellites. Figure 8 shows the principle of redistribution of computing load in the system.

An orbiting distributed computing network uses this feature of a distributed network to provide IoT services in areas with a high density of IoT devices and in conditions of a sharp increase in traffic. When the load on the computing satellite approaches or exceeds the maximum performance of the computing module, part of the load is transferred to the computing satellites of other "distributed satellites" along the communication lines between the satellites.

When redistributing the computing load, it is necessary to take into account the peculiarity of the functioning of IoT devices and their requirements for the efficiency of information processing/generation of control commands for executive IoT devices. As was shown in Section 3, the main component of the transmission delay time of an IoT device is the propagation delay of the signal in the Earth-to-space line. The maximum value of this delay depends on the height of the orbit and the minimum angle of elevation of the beam of the antenna of the VSAT terminal adopted in the system. This delay can reach 5.3 ms (see Table 1). Thus, in a two-way channel, the delay can be up to 10.5 ms. This value determines the minimum possible guaranteed processing time for sending an IoT device and receiving a control command.

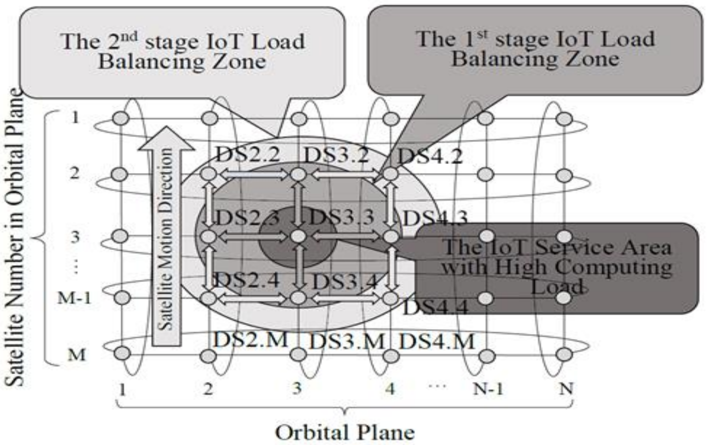

Figure 8 – Illustration of the principle of redistribution of computing load
in an orbital computing network

Under conditions of high load/intensive traffic growth, the satellite-calculator forms a queue for processing packages of IoT devices. The queue is formed taking into account the priority of service.

The highest priority is given to packages of IoT devices with minimal latency. The permissible waiting time for such devices cannot exceed the time of two-way exchange between the IoT device and the neighboring distributed satellite, taking into account the propagation delay in the communication line between the distributed satellites (see Table 2). So for a system with an orbit height of approximately 800–850 km, this delay cannot exceed 17.72 ms. Parcels of IoT devices with an acceptable response time of no more than 17.72 ms are processed directly by the computing satellite of the distributed satellite, in the service area of which there is an IoT device (in Figure 8 this is $PC_{3.3}$).

Parcels of IoT devices for which a permissible delay time for receiving a control command allows sending a parcel for processing to a computing satellite of a neighboring distributed satellite receive the first priority in service. The delay for such IoT devices can range from 17.72 ms to 27.72 ms for the same conditions. In this case, the parcels are sent for processing from $PC_{3.3}$ to $PC_{2.3}$, $PC_{4.3}$, $PC_{3.4}$, $PC_{3.2}$ as shown in Figure 8. These computing satellites are included in the computational load distribution zone of the first stage.

Similarly, the 2nd zone of distribution of the computational load is formed.

When choosing the direction of routing of excess computational load/routing of excess traffic, the propagation delay along the communication line between the distributed satellites plays. As can be seen from Table 2 in the direction along the orbital plane, the delay is almost unchanged. In communication lines between adjacent orbital planes, the delay varies from the maximum value that is observed for equatorial regions (part of the orbit) and exceeds the delay for the communication line in one orbital plane, to the minimum value in the subpolar region of the orbit, which is half the delay for one orbital plane.

There is another pattern in the distribution of IoT devices by region, which is directly related to the distribution of IoT device traffic and the computational load for an orbital distributed computing network. An analysis of the data on the rate of growth of the park/penetration depth of IoT devices and the growth rate of mobile traffic [19] suggests that for a low-orbit communication system for IoT there will be areas/regions with increased computing load. It can be assumed that the density of IoT devices in each region is directly related to population density. Consequently, the areas with the highest population density will approximately correspond to the areas with the highest computational load.

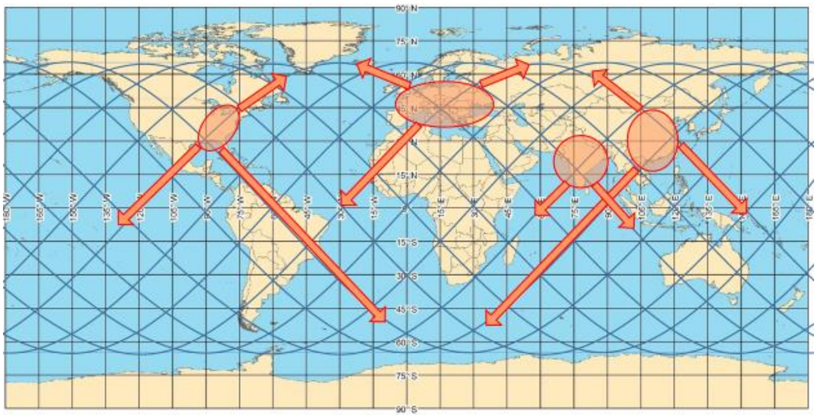

Figure 9 – Computational load flow to the polar and oceanic areas

The regions with the highest population density are conventionally shown in Figure 9, to which the eastern coast of the USA, Central and Western Europe, India, and Southeastern regions of China are assigned. The computing load generated by IoT devices in these areas will exceed the computing capabilities of satellite computers.

At the same time, there are areas with minimal computational load, or districts where there is no computational load at all. These areas include circumpolar regions and oceanic regions. Locally, the computational load will also be minimal for desert areas and high mountain ranges. To increase the computing power of a low-orbit distributed computing system in areas with high computing load, part of the load that allows processing delays is transferred to the circumpolar and oceanic regions, as shown in Figure 9. Transferring the computational load is carried out taking into account the priority of packages of IoT devices, which is determined on the basis of the allowable/acceptable time for processing information and the formation of control commands for IoT devices - executive bodies.

CONCLUSION

1 The concept of “distributed satellite” in a centralized architecture allows you to build a low-orbit communication system of the Internet of Things, which is adapted to the features of the functioning of the Internet of Things and implements the concept of “foggy” and “boundary” computing.

2 The satellite orbiting distributed computing network is an integral part of the low-orbit satellite communication system for the provision of IoT services, reflecting the features of IoT and implementing the concepts of “fog computing” and “boundary computing”.

3 The architecture of the “distributed satellite” allows you to quickly increase the computing capabilities of the space segment of the system and provide redistribution of computing load, which allows the use of computing tools with limited computing performance, and thereby reduce the cost of such devices.

4 The use of communication lines between distributed satellites makes it possible to realize the advantages of a peer-to-peer computer network for redistributing the computing load caused by the high density of IoT devices in certain regions, as well as emergency situations of natural or man-made origin.

5 A criterion has been proposed for the priority of servicing parcels/requests of IoT devices, based on taking into account the features of the orbital construction of the space segment of the system and focused on minimizing the probability of denial of service.

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