Energy efficient method of data transmission in a heterogeneous network of the Internet of things for remote areas

I. I. Lysogor, L. S. Voskov, A. Y. Rolich and S. G. Efremov

Abstract — **The paper reviewed and analyzed protocols, technologies for transferring and presenting IoT data, developed a model of a heterogeneous IoT network for hard-to-reach areas, proposed a method to improve the efficiency of data transfer in a heterogeneous IoT network.**

As a result of the work, a model of using the Internet of Things technology (LPWAN) in hard-to-reach areas was developed, information presentation methods were identified that allow solving the problem of collecting information from remote sensors located in the absence of traditional communication channels and a practical check of the results obtained. The paper uses simulation modeling to study the applicability of different methods of presenting information in the case of transmitting IoT data over low-speed satellite communications channels.

The method proposed in the paper allowed the use of the Internet of things technology in remote areas using the SBD satellite short message service. The proposed method allowed reducing the volume and number of SBD messages during data transmission via low-speed satellite communication channels, which made it possible to reduce the cost of communication data transmission by 4.82 times

Index Terms—**Internet of Things, Lora, Protobuf, Iridium, SBD, Remote areas, Internet of Remote Things, Energy-efficiency, Heterogeneous networks.**

I. Introduction

THE field of study is data transfer in a heterogeneous Internet of Things environment. The paper analyzes and develops an efficient data transfer method in a heterogeneous Internet of Things network implemented by a protocol at the representative level of the OSI model. The main features of data transmission in the Internet of Things are the requirements for energy efficiency of transmission, autonomy of device operation and minimization of the amount of transmitted data. The main criterion of the studied protocols and technologies for data transfer is the ratio between service and useful transmitted data, as well as an increase in the amount of useful transmitted data.

The number of physical objects of the Internet of Things is growing exponentially and, according to Cisco, will reach 50 billion devices by 2020. At the same time, the de facto standard for communication of the physical objects of the Internet of Things are the three main data transmission technologies - LoRa, LTE and satellite communication channels. The sharing of various communication channels for transferring IoT data (LoRa, LTE, low-speed satellite channels) makes it possible to expand the scope of IoT technologies.

For use in hard-to-reach areas, in areas such as mining, agricultural use and trucking [1], a heterogeneous network consisting of a LoRaWAN network and low-speed satellite channels is considered.

Development of protocols for interaction in a heterogeneous network is one of the main methods for improving the efficiency of data transfer. Thus, research and development of methods for improving the efficiency of interaction in the heterogeneous network of the Internet of things is relevant and allows you to expand the scope of use of the Internet of things.

The object of the study is to transfer data in heterogeneous networks of the Internet of Things.

The subject of research is the methods and protocols of data transmission in a heterogeneous Internet of Things. The protocol should provide more efficient data transfer compared to existing protocols and technologies. The amount of data transmitted is taken as the performance criterion.

The aim of the study is to develop an efficient method for transmitting data in a heterogeneous Internet of Things for hard-to-reach areas.

To achieve this goal it is necessary to solve the following tasks:

1. To review and analyze the protocols, technologies for transferring and presenting the Internet of Things data. Develop a model of a heterogeneous Internet of Things for hard-to-reach areas.
2. Develop a method for improving the efficiency of data transmission in a heterogeneous network of the Internet of things, implemented in the protocol of the representative layer of the OSI model.
3. Conduct experimental verification of the proposed method.

The main criteria for choosing a data transfer protocol in a heterogeneous Internet of Things are maximum efficiency, the ability to use the protocol in remote areas with a maximum coverage area of one base station, the possibility of using

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unlicensed radio frequency range.

Based on the proposed criteria and analysis, the most appropriate communication technology in a heterogeneous Internet of things is LoRaWAN.

We will consider a heterogeneous Internet of Things network consisting of LoraWAN network and low-speed satellite channels Iridium. Given the possibility of pre-determining the structure of the transmitted data, the format with the minimum amount of transmitted service information is the format of Protobuf.

Thus, to develop an effective interaction protocol in a heterogeneous IoT network using satellite communications, it is necessary to develop a method for presenting information at the representative level of the OSI model using the Protobuf format.

II. Heterogeneous network model

We consider a model to study the applicability of the proposed method. We will perform the task decomposition and define the main stages in the transfer of data from sensors to the data collection and analysis system.

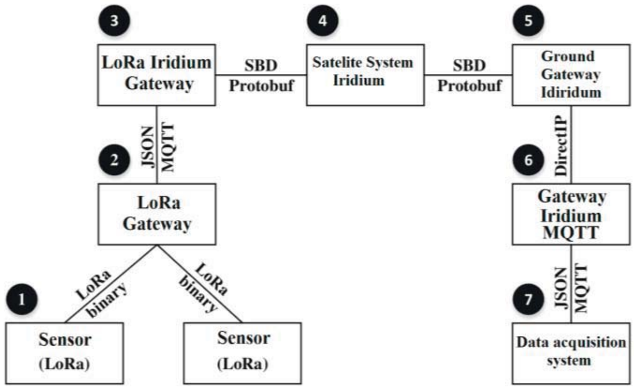


Fig. 1. Model of a heterogeneous network

The limitation that in our case can affect data transmission and should be taken into account when transferring information between nodes №1 and №2 is the maximum payload size of the LoRaWAN message, which is 222 bytes when sending messages through an intermediate device and 242 bytes when sending information directly between the sensor and the gateway [2]. It is also necessary to take into account that the delay in the transmission of messages can be from 60 to 1250 ms.

The generation of events by sensors is carried out independently of each other with a fixed average value of the probability of an event occurring, so we use the Poisson distribution to determine the number of messages from the sensors in one message from the sensor [3]. We assume that the values of the sensors will obey the normal distribution law.

LoRa gateway №2, when receiving information, forms a packet to which, in addition to the information that was transmitted by the sensor, the service information of the LoRa network is added, such as device MAC address, modulation type, signal-to-noise ratio, and channel number. This information is recoded into JSON format and published on the MQTT broker. LoRa Gateway does not perform additional data changes besides adding service information and generating a message in JSON format. The number of published messages corresponds to the number of received messages on the LoRa transmission channel.

The LoRa-Iridium gateway №3 receives messages from the LoRa gateway №2 through an MQTT broker. At the same time between the LoRa-Iridim gateway and the LoRa gateway there are no restrictions on the channel width and restrictions on the energy efficiency of transmission, since elements №2 and №3 are installed in places with stationary power supply and communicate with each other via a local computer network.

The main objective of the LoRa-Iridium №3 gateway is to transfer information from the data collect point to the centralized data collection and analysis system. It uses a low-speed communication channel with the widest possible territorial coverage. The limitation of the selected SBD technology is the maximum message size of 340 bytes [4] and the high cost of data transmission. Thus, one of the objectives of the LoRa-Iridium gateway is to reduce the amount of transmitted data and reduce the number of used S messages.

The solution to the problem of reducing the amount of transmitted data and reducing the number of messages used will be achieved by using the proposed method.

The SBD message is transmitted via satellite constellation №4 and the Iridium ground gateway №5 to the Iridium MQTT gateway №6. The message is transmitted using DirectIP [5], which uses TCP as the transport protocol and does not have a port number reserved by IANA. When transmitting traffic through the satellite constellation and the Iridium ground gateway, no changes are made to the data format and the number of messages. Thus, when modeling the transmission of a message by these nodes, it can be neglected.

The main task of the Iridium MQTT №6 gateway is to receive a message from the Iridium ground gateway №5, transcode it from the format used by the Lora-Iridium №3 gateway to optimize the size and number of transmitted messages to JSON format and publish the message to the MQTT broker in order to further transfer information to the data collection system №7.

III. The efficiency of the method

To test the hypothesis about the effectiveness of the proposed method of presenting the transmitted data, we will use the part of the model that includes the components №3, №4, №5 and №6 of the general model (Fig. 1) written in Python. Python allows you to use a large number of already developed modules for processing JSON and Protobuf formats, for processing SBD messages and using a mathematical tool to perform simulations, which makes it easier to perform this task.

The LoRa gateway publishes the following data in JSON format [6] on the MQTT server:

{
"phyPayload": "AAEBAQEBAQEBAgICAgICAgJpNbxrAh8 =",

```
    "rxInfo": {
        "channel": 1,
        "codeRate": "4/5",
        "crcStatus": 1,
        "dataRate": {
            "bandwidth": 125,
            "modulation": "LORA",
            "spreadFactor": 7
        },
        "frequency": 868300000,
        "loRaSNR": 7,
        "mac": "1dee08d0b691d149",
        "rfChain": 1,
        "rssi": -57,
        "size": 23,
        "time": "0001-01-01T00: 00: 00Z",
        "timestamp": 2074240683
    }
}
```


The sensor payload is transmitted in the "phyPayload" field, the MAC address of the sensor is indicated in the "mac" field. The remaining data contain the characteristics of the communication channel.

In accordance with the given format, we will create a proto-file [7]:

```
syntax = "proto3";
import "google / protobuf / timestamp.proto";
message phypayload {
  repeated float data = 1;
}
message rate {
  int32 bandwidth = 1;
  enum mod {
    LORA = 0;
  }
  mod modulation = 2;
  int32 spreadFactor = 7;
}
message info {
  int32 channel = 1;
  string codeRate = 2;
  int32 crcStatus = 3;
  rate dataRate = 4;
  int64 frequency = 5;
  int32 loRaSNR = 6;
  string mac = 7;
  int32 rfChain = 8;
  sint32 rssi = 9;
  int32 size = 10;
  google.protobuf.Timestamp time = 11;
  google.protobuf.Timestamp timestamp = 12;
}
message iotj {
  phypayload phyPayload = 1;
  info rxinfo = 2;
}
```

This definition of Protobuf makes it possible to ensure the identity of the transmitted data in JSON format and the Protobuf format used. Generate 1000 LoRa messages from sensors with different amounts of sensor data - from 0 to 13 (the number of sensors is determined by the Poisson distribution) and compare the amount of transmitted data using the JSON format and using the proposed format. The results are shown in the table below.

Thus, using the proposed method reduces the size of transmitted messages by an average of 4.82 times. Taking into account the size limit of the SBD message of 320 bytes, it can be concluded that using the standard JSON format for data transmission over satellite communication channels is impossible, but the problem of the size of the transmitted data can be solved using the proposed format.

TABLE I
DATA TRANSFER WITH THE USED JSON FORMAT AND USING THE PROPOSED FORMAT.

Number of sensors	Total number of messages	Average message size in JSON format (bytes)	Average message size in the suggested format (bytes)	Message size ratio (3/4)
0	7	313	70	4,47
1	32	339,78	78	4,36
2	90	368,77	82	4,5
3	153	397,69	86	4,62
4	170	426,94	90	4,74
5	177	455,63	94	4,85
6	143	484,59	98	4,94
7	107	514,1	102	5,04
8	54	542,41	106	5,12
9	36	572,14	110	5,2
10	21	601,33	114	5,27
11	5	629,4	118	5,33
12	3	664	122	5,44
13	2	693,5	126	5,5
Total	1000	453,67	93,676	4,82

IV. SENSOR MESSAGE PACKING METHOD IN SBD MESSAGES

According to previous modeling data, when using the Google Protobuf data presentation format, the size of the Internet of Things message on the LoRaWAN network varies from 70 to 126 bytes depending on the number of sensors (from 1 to 13). The maximum size of the SBD transmission is 320 bytes, thus it becomes possible to pack several Internet of Things messages in one SBD transmission session. Upon receipt of the Internet of Things messages, the LoraWAN-Iridium gateway buffers the message and, when the buffer is larger than a specified size, packages the messages to perform transmission using the Iridium SBD communication channel.

The size of the transmitted messages in one packet must be less than or equal to the maximum volume of the short message:

$$\begin{pmatrix} v_1x_{11}+\cdots+v_nx_{1n}\leq S \\ v_1x_{21}+\cdots+v_nx_{2n}\leq S \\ \cdots \\ v_1x_{m1}+\cdots+v_nx_{mn}\leq S \end{pmatrix} \quad (1)$$

But since all messages of type bi must be transmitted:

$$\begin{pmatrix} x_{11}+x_{21}+\cdots+x_{m1}=b_1 \\ x_{12}+x_{22}+\cdots+x_{m2}=b_2 \\ \cdots \\ x_{1n}+x_{2n}+\cdots+x_{mn}=b_n \end{pmatrix} \quad (2)$$

V - the buffer capacity of messages for sending using a satellite communication channel (in bytes);

$b_1, b_2, ..., b_n$ - the number of messages of the i-th type;

$v_1, v_2, ..., v_n$ - the volume of messages of each type (in bytes);

x_{ij} - the number of messages of the i-th type in the j-th satellite message;

n - the number of types of sensor messages in the buffer;

S - the maximum amount of SBD messages (in bytes);

T - time between receiving messages (in seconds);

m - the number of packets with the help of which V is transmitted.

It is necessary to minimize the number of packets transmitted via satellite communication channel, i.e. $L = \min(m)$

We define the lower limit of the number of messages m - the number of transmitted packets, for which buffer messages from the buffer with the volume V can be transmitted with the volume of the short message S subject to the restrictions (1) and (2):

$$m = \frac{V}{S} \quad (3)$$

An additional limitation is the lifetime of a single Internet of things thing (t_i), the rate at which new messages arrive (T) and, as a result, the number of simultaneously open containers (SBD messages) is M.

This task is the task of packing with limited access to containers. The problem is solved under the following condition:

$$\sum_{i=1}^{K} V_i^k < \sum_{j=1}^{M} V_j^o \quad (4)$$

V_k, V_o - the volume of Internet of Things and SBD messages, respectively.

The transmission time of the message from the sensors to the system for collecting and analyzing information should not exceed the threshold value - T_p. The main task will be to choose the most suitable algorithm that uses the smallest number of containers and introduces a delay in the process of sending messages no more than T_p.

Since the packing problem is NP-complete [8], the minimum number of required containers can be determined only by the exhaustive search method. Consider several approximate faster packaging algorithms that have proven asymptotic guaranteed accuracy estimates:

Algorithm 1. "First suitable" with one open container. Objects are selected sequentially from the buffer and placed in the first container. If the free volume of the container to place the object is not enough, then a new container is opened. The filled container is closed and shipped.

Algorithm 2. Objects are selected sequentially from the buffer and placed in the first container. If the free volume of the container for placing the object is not enough, then the object is placed in the next container. At the same time, all containers remain open and close only after all objects are placed from the buffer.

Algorithm 3. The objects in the buffer are sorted in descending order of size. After that, objects are selected sequentially from the buffer and placed in the first container. If the free volume of the container for placing the object is not enough, then the object is placed in the next container. At the same time, all containers remain open and close only after all objects are placed from the buffer.

TABLE II
COMPARISON OF PACKAGING ALGORITHMS

	Alg.1	Alg.2	Alg.3
Number of sent messages	334	333	330
Number of used containers	2,99	3	3,03
Average number of messages per container	280,99	281,83	284,4
Average container size in bytes	87,8 %	88 %	88,8 %
Container usage	1 000	167 347	667 518
Number of iterations for packing messages into containers	3T	1000T	1000T
The delay associated with the process of packing messages into containers	334	333	330

Let us check the work of the above algorithms using the model of a heterogeneous network (Fig. 1). Generate 1000 LoRa messages from nodes with different amounts of sensor data - from 0 to 13 (the number of sensors is determined by the Poisson distribution) and pack the messages using the three algorithms under consideration. The results are presented in table 2.

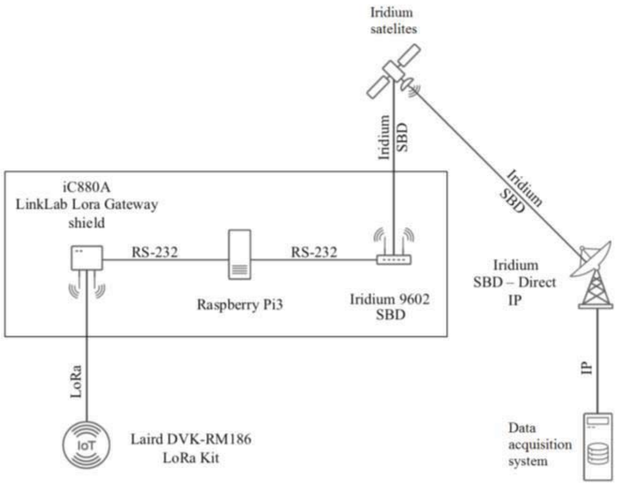
Thus, it can be concluded that algorithm 1 (“first suitable with one open container”) is no more than 2% worse than algorithm 3 “first suitable with open containers and message sorting”. The use of the container in the case of Algorithm 1 is 87.8%, which is 1% more than Algorithm 3. Given the limitations on the delay in sending messages and the resource-intensiveness of the algorithm, it can be concluded that Algorithm 1 is “first suitable”.

The delay associated with the process of packing in containers depends on the number of open containers and is equal to the number of messages in one container multiplied by the number of open containers. Thus, to reduce the delay, you can use only algorithms with a minimum number of open containers.

V. EXPERIMENT

To verify the results obtained, a stand was created consisting of the Laird DVK-RM186 developer kit, the base station of the Internet of Things which was built on the basis of the computer Raspberry Pi3, radio module iC880A and LinkLab Lora Gateway shield, Iridium 9602 SBD modem, which was connected to the base station of the Internet of things, DirectIP (SBD) and MQTT servers that were installed on a virtual server in a cloud service.

The information was transmitted as follows: the data from the DVK-RM186 sensors arrived at the Raspberry Pi3 base station (LoRa base station). Further, the data were published on the local MQTT server (installed on the Raspberry Pi3). After that, the data of the MQTT server was processed by the process that converted them in accordance with the proposed method and sent them using the Iridium 9602 SBD modem to the Iridium satellite communication system. A DirectIP



service was installed on the virtual server, which received data from the Iridium server, converted it back to JSON format and published it on the MQTT server of the central system for collecting and analyzing information.

A. Sending messages from Lora sensors without packaging to SBD containers

The experiment was conducted as follows:

1. The module of the developer Laird DVK-RM186 generated LoRA messages with a frequency of one message in two seconds and a size of useful information from 18 to 20 bytes. Messages consisted of a pseudo-random sequence of characters;
2. Messages were received by the Internet of Things base station and placed in a processing queue;
3. Messages were successively retrieved from the processing queue, messages were encoded from JSON format to Protobuf format;
4. After transcoding, the message was placed in the SBD modem's buffer and the message was sent;
5. If the sending of the message was unsuccessful, then the sending attempt is repeated. If the number of attempts to send messages exceeds the maximum number of attempts (10), then sending a message is considered unsuccessful;
6. After sending the message, the status of sending the message (success), the size of the message in JSON format, the size of the message in Protobuf format and the time required to send the message;
7. The next message is retrieved from the message queue and the send cycle is repeated.

Sending messages was carried out in an open area and was carried out within 12 minutes. In 12 minutes, attempts were made to send 40 messages, of which 38 messages were successfully sent.

The effectiveness of sending messages was 95%. The average time of sending a message (excluding messages that were not delivered) is 12.52 seconds.

B. Sending messages from Lora sensors with packaging in SBD containers

Add in the previous experiment the stage of packaging messages so that the maximum number of Internet of things messages could be placed in each SBD message.

The experiment was conducted as experiment without packaging to SBD containers with changes in item №3. Messages were successively retrieved from the processing queue. In the course of processing, each message of the Internet of Things was recoded from JSON format to Protobuf format and placed in the SBD package. Then the size of the SBD packet was checked - if it was 316 bytes or less, then the packing cycle was repeated with the next IoT message. If the SBD packet size was more than 316 bytes, then the last message of the Internet of Things was removed from the SBD packet and returned to the queue, and the SBD packet was sent for sending;

Sending messages was carried out in an open area and was carried out within 12 minutes. In 12 minutes, attempts were made to send 41st SBD messages from which 40 messages were successfully sent.

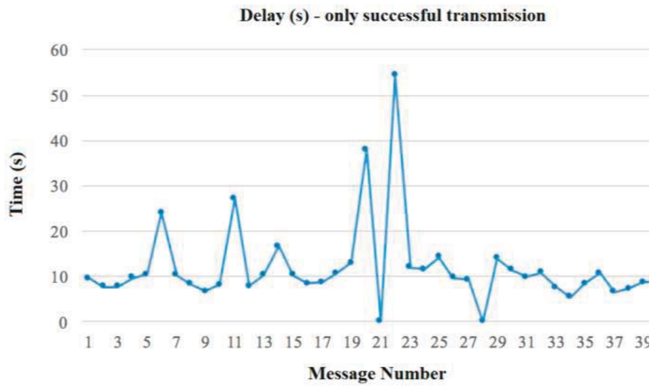


Fig. 3. Delay in sending SBD messages without packaging

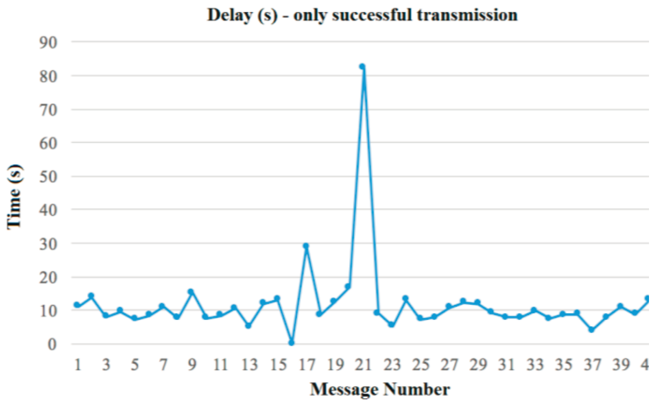


Fig. 4. Delay in sending SBD messages with packaging

The field experiment established that the conclusions of the simulation corresponded to the result obtained during the experiment. Thus it can be argued about the reliability of the data obtained as a result of modeling and the applicability of the results obtained in practice.

VI. Conclusion

As a result of the work, a model of using the Internet of Things technology was developed in hard-to-reach areas of the Arctic region, information presentation methods were identified that allow solving the problem of collecting information from remote sensors located in the absence of traditional communication channels and practical verification of received results. The paper uses simulation modeling to study the applicability of different methods of presenting information in the case of transmitting IoT data over low-speed satellite communications channels.

Scientific novelty and main results of the research:

1. A new model of a heterogeneous data collection network has been developed in remote regions of the Arctic region [5], which differs from the well-known ones in that it includes energy-efficient technologies of the Internet of Things at the data collection level and low-speed satellite communication channels at the level of integration with the global network.
2. A new method of encoding information in the representative layer protocol in heterogeneous networks of the Internet of Things has been developed, which differs from the well-known ones in that the session layer protocol of the OSI model uses the Protobuf format and the packaging of messages from sensors into containers, which allows increasing the efficiency of data transmission by reducing The volume of transmitted messages is 4.82 times.
3. The results of an experimental study of the proposed method on a simulation model and experimental equipment were obtained, which allowed to make a conclusion about its effectiveness in data transmission.

The method proposed in the paper allowed the use of the Internet of things technology in remote regions of the Arctic region using the SBD satellite short message service. The proposed method allowed reducing the volume and number of SBD messages during data transmission via low-speed satellite communication channels, which made it possible to reduce the cost of data transmission by 4.82 times. Reducing the cost of data transmission leads to an increase in the economic efficiency of the use of satellite communication channels for organizing data transmission networks in remote areas of the Arctic region, which do not have a telecommunication infrastructure. The further steps of the study are the study of methods for reducing the amount of transmitted data without reducing the information value of the transmitted messages.

The considered approach to building heterogeneous networks of the Internet of Things has recently received its own name in the scientific literature - the Internet of Remote Things (Internet of Remote Things, IoRT). For the Internet of remote things, the use of traditional models and methods for evaluating energy efficiency, balancing traffic, can lead to inefficient use of resources, so the urgent task is to develop new models, methods and algorithms. In an effort to determine the future of the field of research, we identify a number of tasks that need to be addressed within the framework of the Internet paradigm of remote things:

1. Development of the theoretical foundations of energy-efficient interaction of the Internet of remote things and cyber-physical systems in the context of underdeveloped network infrastructure.
2. Study of the scenarios of the absence or underdevelopment of the network infrastructure, due to various factors - the complexity of network deployment, the geographical distance of areas, etc.
3. Research and development of models for assessing the energy efficiency of the primary data collection systems in the framework of the concept of the Internet of remote things.
4. Research and development of the method of interaction of the Internet of remote things and cyber-physical systems based on the use of mobile data collection sinks.
5. Development of an energy efficiency assessment model and methods for its improvement for remote Internet of Things devices that interact with the global information infrastructure through satellite communication channels and intermediary data platforms.
6. Evaluation of the developed models and methods on the examples of systems for the collection and transmission of conventional and multimedia data, on intermediary platforms that interact within the global Internet network of remote things and cyber-physical systems through satellite communication channels and intermediary data platforms.
7. Formation of a unified approach to the definition of indicators of energy-efficient interaction of the Internet of remote things and cyber-physical systems with an undeveloped network infrastructure, to develop methods for assessing and improving these indicators.

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