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Имитационная модель исследования параметров передачи трафика сенсорных сетей с использованием протокола LoRaWAN

Simulation model for studying the parameters of sensor network traffic transmission using the LoRaWAN protocol

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Аннотация. *В статье предложена имитационная модель передачи данных сети LoRaWAN на участке граничный шлюз - транспортная сеть – удаленный сервер. Реализованная модель основана на операционной системе Linux, процесс имитации транспортной сети осуществляется штатными инструментами, такими как «tc» (Traffic Control) с использованием утилиты «NetEm». Данная утилита позволяет эмулировать такие явления, как: потери, задержки при передаче, изменение порядка передачи, искажение пакетов, а также другие факторы, искажающие пакеты транспортного уровня.*

Ключевые слова: сенсорные сети, транспортные сети, LoRaWAN, сетевые задержки, потери пакетов, эмуляция сетевых условий

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Abstract. *The article proposes a simulation model of data transmission of the LoRaWAN network in the boundary gateway - transport network – remote server section. The implemented model is based on the Linux operating system, the process of simulating a transport network is carried out by standard tools such as "tc" (Traffic Control) using the "NetEm" utility. This utility allows you to emulate phenomena such as: loss, transmission delays, reordering, packet distortion, as well as other factors that distort transport layer packets.*

Keywords: sensor networks, transport networks, LoRaWAN, network delays, packet loss, emulation of network conditions

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Introduction. Today, sensor networks have become widespread in many areas of human activity [1], such as personnel monitoring, security systems, smart home, environmental control and many others. Existing solutions are based mainly on the use of LoRaWAN, ZigBee, Bluetooth, and Wi - Fi technologies.

At the same time, the development of existing communication networks places new and increases demands on existing network solutions. To indicate the main directions of development and meet increasing requirements, the International Telecommunication Union presented the results of the Network 2030 study carried out by the ITU-T FG NET-2030 focus group [2]. The result of their work is a series of recommendations Y .3000. Within the framework of these recommendations, many experts have identified this type of change as the transition to ultra-dense sensor networks [3] (up to 1 million sensor devices located in an area of 1 km ^{2} [4]), which places new demands on existing transport networks [5].

At the same time, for the Internet of things (IoT - Internet of things) in the Russian Federation, the national standard GOST R 71168-2023 has been developed and approved, which is based on LoRaWAN technology [6]. Despite the “voluntary” use of the standard, companies such as ER-Telecom Holding and Rostelecom are already working with the Russian version of this protocol. The advantage of using the standard is that it takes into account Russian legislation and, at the same time, is compatible with the global LoRaWAN protocol.

Considering the above, to meet the requirements of the Network 2030 concept and the use of the new domestic standard based on the LoRaWAN protocol, additional research is required, including modeling of various sections and elements of these networks. At the same time, the domestic standard provides a fairly detailed description of the “sensor-gateway” level, but for the section of the transport network it is only stated that: “The gateways connect to the network server via IP connections” [6], which is clearly not enough for the practical implementation of sensor networks. Note that a characteristic feature of using the LoRaWAN protocol is the presence of remote, including cloud, servers. When the number of sensor devices increases to the predicted ones, it is necessary to study the traffic load created by these devices when transmitted through transport networks, ensuring the required characteristics of information exchange quality indicators (Quality of Service, QoS).

For modeling networks based on the LoRaWAN protocol, several software packages of different levels are known, from simulation models independently developed by scientists [7-9], to libraries such as FLoRa (based on OmNet ++) or LoRaSim.

However, the OmNet ++ developer does not provide access to its products for citizens of the Russian Federation [10]. Support for the LoRaSim package, according to updates to the repository on the github resource, was discontinued in July 2017 [11]. At the same time, most of the implemented models involve studying only the radio section "sensor-gateway" of the LoRaWAN network.

Thus, the task of developing a simulation model for studying traffic generated by sensor networks using the LoRaWAN protocol in the gateway-server section is relevant.

The purpose of creating a simulation model is to study the characteristics of the packet flow created by sensor networks using the LoRaWAN protocol in the gateway-server section.

When developing a simulation model, the following requirements are imposed on it. The simulation model must be able to change the following traffic transmission parameters:

- limiting the queue and packet servicing discipline;
- packet delay, including jitter adjustments;
- use of various distribution laws to form the output stream of packets;
- packet loss percentage;
- changing the order of packet transmission;
- changing the fixed packet transmission rate.

As restrictions, we set the size of the payload coming from the packet gateway to 223 bytes, which corresponds to the maximum payload size with maximum filling of service information in the LoRaWAN frame [6].

Materials and research methods. Gateways can use various protocols to transmit data to the server, which are:

1) HTTP POST requests.
2) MQTT.
3) FTP.
4) WebSockets.

The advantages and disadvantages of the above protocols are presented in Table 1.

Table 1 – Advantages and disadvantages of IoT data transfer protocols

Protocol	Advantages	Flaws
HTTP POST	Wide support and ease of implementation	High network load due to the need to establish a new connection for each request
	Supports various data types and formats (e.g. JSON, XML)	Significant overhead when transferring small amounts of data
	Easy integration with existing web servers and applications	Does not support real (or near real) time without the use of additional mechanisms
MQTT	Low network load and efficient use of bandwidth	The need to configure and manage an MQTT broker
	Publish-subscribe support, which allows gateways to send data to the server without explicit addressing	Additional security required (such as encryption)
	Ability to work in low bandwidth and unstable connection conditions	Possibility of message loss due to unstable connection
FTP	Suitable for transferring large amounts of data or files	Heavy network load due to the need to establish a separate connection for each file transfer
	Possibility of organizing a structured file system for storing data on the server	Limited support for real-time data and streaming
	Ability to interrupt and resume file transfers	Additional security required (such as encryption)
WebSockets	Continuous two-way connection allowing real-time data transfer	Possible scalability issues with large numbers of simultaneous connections or when working in distributed environments
	Low network load and efficient use of bandwidth	Consumption of additional resources on the gateway and server to maintain a persistent connection and process WebSocket messages

	Support for feedback and notification mechanisms allowing the server to send data to the gateway on request or by events	The need to implement control and security mechanisms to protect the connection and transmitted data

Thus, the simulation model being developed must use one of the above protocols. Note the possibility of “combined” implementations of the MQTT protocol, for example, “MQTT over TCP" or "MQTT over WebSockets", which allows you to take advantage of the two selected protocols. Considering the limitation in data transfer speed in the sensor-gateway section of the LoRaWAN protocol, ranging from 0.3 to 50 kbit/s [6], there is no need to use a protocol such as FTP. The HTTP protocol does not allow for near real-time operation and has high overhead when transferring small amounts of data. Thus, it is most appropriate, in the developed simulation model, to use the MQTT protocol.

The general diagram of the developed simulation model is presented in Figure 1.

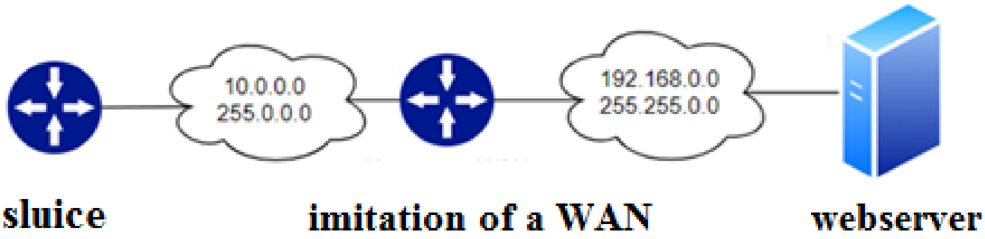

Figure 1 – General diagram of elements and connections of the simulation model

The Linux operating system is used as a gateway Ubuntu. An algorithm has been implemented in Python using the paho - mqtt 2.0.0 library that allows you to compose sensor network packets with a payload for further transmission through the transport network. The software operation algorithm is presented in Figure 2.

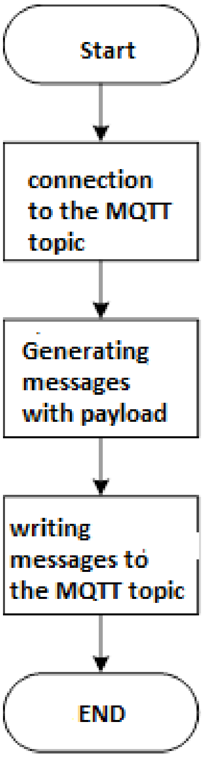

Figure 2 – The algorithm of the gateway operation

The Linux operating system is used as an element simulating a transport network Ubuntu. This computer is equipped with two network cards, one of which is connected to the 10.0.0.0/8 network, and the second to the 192.168.0.0/16 network. To simulate distortions of transport layer packets, the “NetEm” utility is used, which receives a stream of packets from network 10.0.0.0/8, carries out the specified transformations and redirects the outgoing stream of packets to network 192.168.0.0/16. Note that the limitation of the utility is that it can only monitor outgoing traffic. The advantage of this utility is the ability to create your own distribution laws that describe traffic distortions (delay, change in the order of packet transmission, etc.) as well as the fact that this software is included in the Linux kernel, starting with version 2.6. A detailed description of the capabilities and command structure is presented in [12].

As an example, we give the procedure for generating packet delay, the command of which is as follows:

tc qdisc add dev eth0 root netem delay 500ms.

This command adds a delay of 500 ms for each outgoing packet. It is also possible to use jitter, in which case the packet delay will be *delay* ± *jitter*, the value from the range of which is selected randomly. Then the command is represented as:

#tc qdisc add dev eth 0 root netem delay 500 ms 100 ms,

in this case, the packet flow delay will be 500 ± 100 ms.

NetEm utility used provides the ability to use the laws of distribution of random variables. Initially, it supports the following distribution laws: normal, lognormal, Pareto, Pareto-normal and uniform. It is possible to use independently developed distribution tables with the required law. An example of using the normal distribution law is presented below:

#tc qdisc change dev eth 0 root netem delay 500 ms 100 ms distribution normal.

the Linux operating system is used as a server. Ubuntu using an MQTT broker that receives information from the gateway. When updating a topic, the server transfers the received message to a database controlled by the PostgreSQL DBMS. To measure end-to-end delay, it is necessary to synchronize the server and gateway in time, after which information about the departure time is added to the sensor network payload. Thus, given the time a packet was sent, it is possible to calculate its end-to-end delay.

Research results and their discussion. For the developed simulation model, 5000 sensor network packets with a payload in the form of temperature readings were generated. Also, information about the time of packet formation has been added to the payload. The packet is sent immediately after it is formed. The transport network load used a Pareto-normal distribution with a delay of 1200 ms, jitter of 400 ms and loss of up to 6% of packets. To generate the specified conditions, the “NetEm” command looked like this:

#tc qdisc change dev eth 0 root netem delay 1200 ms 400 ms distribution paretonormal loss 6%.

A histogram of the end-to-end delay of received packets is shown in Figure 3.

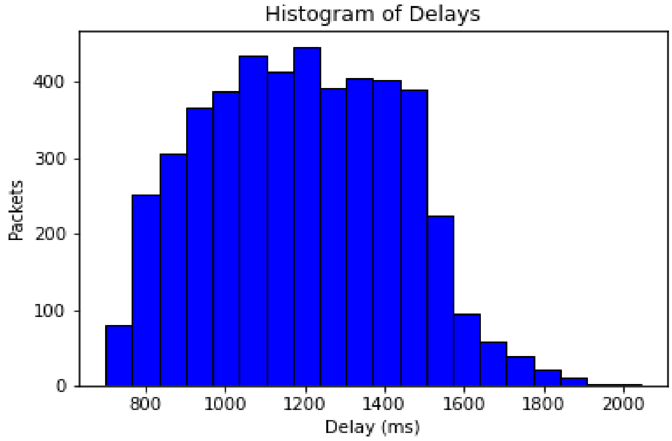

Figure 3 – Histogram of the end-to-end delay of received packets

Research results: 269 packets out of 5000 were lost, which is 5.38%, which corresponds to the values specified in the simulation. At the same time, the shape of the distribution corresponds to the Pareto-normal distribution, which has a "heavy tail" in the range of 1700-2000 ms; respectively, the maximum and minimum end-to-end delays were 2041.61 ms and 699.24 ms.

To check the adequacy of the results of the developed simulation model, the degree of proximity of the output packet stream was checked using the Kolmogorov-Smirnov and Shapiro-Wilk agreement criteria.

For this purpose, using a simulation model, 500 packets with a uniform distribution law were generated, followed by its transformation into a normal law. The command used for this is shown below:

#tc qdisc add dev eth 0 root netem delay 90 ms distribution normal.

End-to-end delay was used as the parameter to be evaluated. The histogram of the received stream of packets of the normal distribution law is presented in Figure 4.

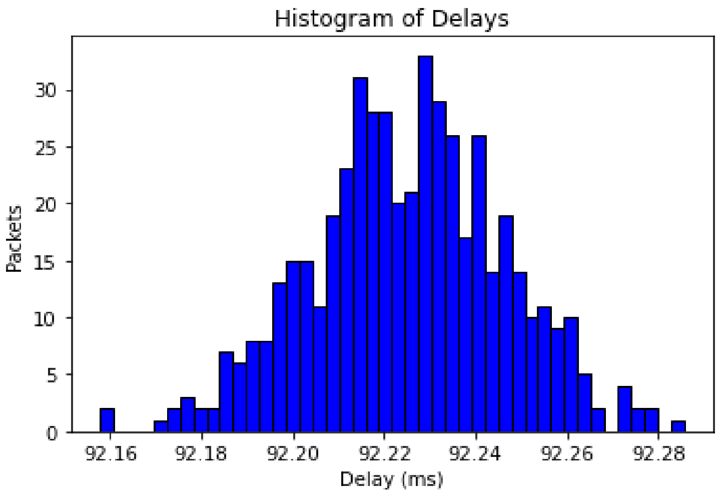

Figure 4 – The result of converting a uniform packet flow into a normal distribution law with 90 ms delay

In the Shapiro-Wilk test, to accept the hypothesis that the sample under study corresponds to a normal distribution (hypothesis H0), it is necessary that $\alpha>0.05$ (the alpha level is greater than 0.05) [13]. As a result of this test, the value of α was 0.9595, which allows us to accept the hypothesis that the sample under study corresponds to the normal distribution law.

To confirm the results obtained, a comparison was also made using the Kolmogorov-Smirnov test (one-sample test) [14]. As a result of this test, the value of α was 0.9818, which allows us to accept the hypothesis that the estimated sample corresponds to the normal distribution law. The results obtained indicate the adequacy of the developed model and the correspondence of the given distribution law to the actual sample obtained.

Thus, the developed simulation model makes it possible to study LoRaWAN protocol traffic in the "gateway-server" section when passing through a transport network with the required characteristics of information exchange quality indicators.

ЛИТЕРАТУРА

1. Дядюнов А. Н., Кузнецов К. Н. Моделирование беспроводных сенсорных сетей // Научный вестник МГТУ ГА. 2009. № 139. [Электронный ресурс]. URL: https://cyberleninka.ru/article/n/modelirovanie-besprovodnyh-sensornyh-setey (дата обращения: 11.04.2024).
2. Network 2030 A Blueprint of Technology, Applications and Market Drivers Towards the Year 2030 and Beyond Written by FG-NET-2030. [Electronic resource]. URL: https://www.itu.int/en/ITU-T/focusgroups/net2030/Documents/White_Paper.pdf (accessed: 11.04.2024).

3. Волков А. Н., Мутханна А. С. А., Кучерявый А. Е. Сети связи пятого поколения: на пути к сетям 2030 // Информационные технологии и телекоммуникации. 2020. Том 8. № 2. С. 32–43. https://doi.org/10.31854/2307-1303-2020-8-2-32-43
4. Отчет "Концепция Сети 2030". [Электронный ресурс]. URL: https://www.itu.int/en/ITU-D/Regional-Presence/CIS/Documents/RI-WTDC17/RI%20CIS%205%20-%20Network%202030.pdf (дата обращения: 11.04.2024).
5. Кучерявый А. Е., Маколкина М. А., Киричек Р. В. Тактильный Интернет. Сети связи со сверхмалыми задержками // Электросвязь. 2016. № 1. С. 44–46. EDN VLPHZZ
6. ГОСТ Р 71168-2023 Информационные технологии. Интернет вещей. Спецификация LoRaWAN. Введ. 2004-07-01. М. [Электронный ресурс]. URL: https://www.gost.ru/portal/gost/home/standarts/catalognational?portal:componentId=3503536e-2ac1-4753-8ed1-09a92fee02de&portal:isSecure=false&portal:portletMode=view&navigationalstate=JBPNS_rO0ABXdIAAZhY3Rpb24AAAABABBjb25jcmV0ZURvY3VtZW50AARmcm9tAAAAAQACNDAABmRvY19pZAAAAAEABTQ4MTAyAAdfX0VPRl9f (дата обращения: 11.04.2024).
7. Ясир Я. М. Д., Польщиков К. А., Маматов Е. М. Имитационная модель функционирования беспроводной сети с низким энергопотреблением // Экономика. Информатика. 2023. № 3. [Электронный ресурс]. URL: https://cyberleninka.ru/article/n/imitatsionnaya-model-funktsionirovaniya-besprovodnoy-seti-s-nizkim-energopotrebleniem (дата обращения: 11.04.2024).
8. Ясир Я. М. Д., Польщиков К. А. Оценивание энергопотребления узлов беспроводной сети датчиков // Инженерный вестник Дона. 2023. № 9 (105). [Электронный ресурс]. URL: https://cyberleninka.ru/article/n/otsenivanie-energopotrebleniya-uzlov-besprovodnoy-seti-datchikov (дата обращения: 11.04.2024).
9. Ясир Я. М. Д., Польщиков К. А., Федоров В. И. Модель доставки сообщения в сенсорной сети с низким энергопотреблением // Экономика. Информатика. 2023. № 2. [Электронный ресурс]. URL: https://cyberleninka.ru/article/n/model-dostavki-soobscheniya-v-sensornoy-seti-s-nizkim-energopotrebleniem (дата обращения: 11.04.2024).
10. Official website OmNet++. [Electronic resource]. URL: https://omnetpp.org/ (accessed 11.04.2024).
11. Official website LoRaSim. [Electronic resource]. URL: https://mcbor.github.io/lorasim/ (accessed 11.04.2024).
12. tc-netem(8) — Linux manual page. [Electronic resource]. URL: https://man7.org/linux/man-pages/man8/tc-netem.8.html (accessed 11.04.2024).
13. Боровков А. А. Математическая статистика. Оценка параметров. Проверка гипотез. – М.: ФИЗМАТЛИТ, 2007. 704 с.
14. Орлов А. И. Непараметрические критерии согласия Колмогорова, Смирнова, омега-квадрат и ошибки при их применении // Научный журнал КубГАУ. 2014. № 97. [Электронный ресурс]. URL: https://cyberleninka.ru/article/n/neparametricheskie-kriterii-soglasiya-kolmogorova-smirnova-omega-kvadrat-i-oshibki-pri-ih-primenenii (дата обращения: 11.04.2024).

REFERENCES

1. Dyadyunov AN, Kuznetsov KN. Modeling of wireless sensor networks. Civil Aviation High Technologies (Nauchnyi Vestnik MGTU GA). 2009;(139). [Electronic resource]. Available from: https://cyberleninka.ru/article/n/modelirovanie-besprovodnyh-sensornyh-setey [Accessed 11 April 2024]. (In Russ.).
2. Network 2030 A Blueprint of Technology, Applications and Market Drivers Towards the Year 2030 and Beyond Written by FG-NET-2030. [Electronic resource]. Available from: https://www.itu.int/en/ITU-T/focusgroups/net2030/Documents/White_Paper.pdf [Accessed 11 April 2024].
3. Volkov AN, Mutkhanna ASA, Kucheryavyi AE. Fifth generation communication networks: on the way to 2030 networks. Informatsionnye tekhnologii i telekommunikatsii = Information

technology and telecommunications. 2020;8(2):32-43. (In Russ.). https://doi.org/10.31854/2307-1303-2020-8-2-32-43
4. OTCHET “KONTSEPTSIYA SETI 2030”. [Electronic resource]. Available from: https://www.itu.int/en/ITU-D/Regional-Presence/CIS/Documents/RI-WTDC17/RI%20CIS%205%20-%20Network%202030.pdf [Accessed 11 April 2024]. (In Russ.).
5. Kucheryavyi AE, Makolkina MA, Kirichek RV. Tactile Internet: Ultra-low-latency communication networks. Ehlektrosvyaz = Telecommunications. 2016;(1):44-46. EDN VLPHZZ (In Russ.).
6. GOST R 71168-2023 Information Technology. Internet of Things. Specification LoRaWAN. Introduction 2004-07-01. M. [Electronic resource]. Available from: https://www.gost.ru/portal/gost/home/standarts/catalognational?portal:componentId=3503536e-2ac1-4753-8ed1-09a92fee02de&portal:isSecure=false&portal:portletMode=view&navigationalstate=JBPNS_rO0ABXdIAAZhY3Rpb24AAAABABBjb25jcmV0ZURvY3VtZW50AARmcm9tAAAAAQACNDAABmRvY19pZAAAAAEABTQ4MTAyAAdfX0VPRl9f [Accessed 11 April 2024]. (In Russ.).
7. Yasir YaMD, Pol'shchikov KA, Mamatov EM. Simulation model of functioning of a low-power wireless network. Economics. Information technologies. 2023;(3). Electronic resource]. Available from: https://cyberleninka.ru/article/n/imitatsionnaya-model-funktsionirovaniya-besprovodnoy-seti-s-nizkim-energopotrebleniem [Accessed 11 April 2024]. (In Russ.).
8. Yasir YaMD, Polshchikov KA. Estimating the energy consumption of wireless sensor network nodes. Inzhenernyi vestnik Dona = Engineering Bulletin of the Don. 2023;9(105). [Electronic resource]. Available from: https://cyberleninka.ru/article/n/otsenivanie-energopotrebleniya-uzlov-besprovodnoy-seti-datchikov [Accessed 11 April 2024]. (In Russ.).
9. Yasir YaMD, Polshchikov KA, Fedorov VI. Message delivery model in a low-power sensor network. Economics. Information technologies. 2023;(2). [Electronic resource]. Available from: https://cyberleninka.ru/article/n/model-dostavki-soobscheniya-v-sensornoy-seti-s-nizkim-energopotrebleniem [Accessed 11 April 2024]. (In Russ.).
10. Official website OmNet++. [Electronic resource]. Available from: https://omnetpp.org/ [Accessed 11 April 2024].
11. Official website LoRaSim. [Electronic resource]. Available from: https://mcbor.github.io/lorasim/ [Accessed 11 April 2024].
12. tc-netem(8) — Linux manual page. [Electronic resource]. Available from: https://man7.org/linux/man-pages/man8/tc-netem.8.html [Accessed 11 April 2024].
13. Borovkov AA. Matematicheskaya statistika. Otsenka parametrov. Proverka gipotez. Moscow: FIZMATLIT, 2007. 704 p. (In Russ.).
14. Orlov AI. Nonparametric tests of goodness of fit of Kolmogorov, Smirnov, omega-square and errors in their application. Nauchnyi zhurnal KuBGAU = Scientific Journal of Kuban State Agrarian University. 2014;(97). [Electronic resource]. Available from: https://cyberleninka.ru/article/n/neparametricheskie-kriterii-soglasiya-kolmogorova-smirnova-omega-kvadrat-i-oshibki-pri-ih-primenenii [Accessed 11 April 2024]. (In Russ.).

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