Estimating the Message Delivery Probability Without Duplication in an Industrial Internet of Things Network System

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***Abstract*—The Industrial Internet of Things (IIoT) is actively used for remote monitoring and control of parameters affecting the efficiency of product release. The use of IIoT technologies allows to identify the equipment malfunctions before they significantly affect production processes. For this purpose, the sensors data are transmitted in real time to the production control center in the form of telemetry messages. Many modern IIoT systems operate based on the Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN) protocol. This protocol provides three levels of data transfer quality. The highest level is Quality of Service 2 (QoS 2). It allows messages to be delivered exactly once and guarantees the absence of duplication of delivered messages, but uses double acknowledgements that require the transmission of an excess number of service packets. Numerous studies of the MQTT-SN protocol are focused on security, performance, and delays reduction in data transmission. However, there is insufficient attention to the message delivery probability estimation when using this protocol. The paper proposes to fill this gap. A model is presented that was developed using the probability graph methodology. The model takes into account all possible states of the analyzed message transmission process when implementing QoS level 2. Using the model, it is possible to estimate the message delivery probability depending on the current bit error rate and the set retransmission counter. The results of calculations and experiments based on the model showed the possibility of using it to select the QoS level and the number of retransmissions that ensure the required reliability of data delivery, and minimize the packet traffic and energy consumption of network devices.**

***Keywords*—Industrial Internet of Things (IIoT), Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN) protocol, Quality of Service (QoS), telemetry message delivery, bit error rate, retransmissions, sensor device, probability graph**

I. INTRODUCTION

Wireless data transmission technologies are now being developed for remote monitoring and control in a variety of fields, including but not limited to the following: emergency services [1, 2], medicine [3], Geoecology [4], natural objects observation [5], construction [6] and many other areas [7]. In practice, technical solutions implemented within the framework of the Internet of Things (IoT) concept are in demand [8, 9]. IoT networks are used in smart healthcare systems [10, 11], agriculture [12], machine-to-machine interaction [13], as well as in manufacturing enterprises for preventive management of technological processes [14, 15]. Industrial Internet of Things (IIoT) systems are based on sensor technologies and are used to control production processes [16, 17]. Common standards regulating the operation of such systems include the Message Queuing Telemetry Transport (MQTT) application layer protocol [18, 19] and its modified version Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN), adapted for sensor networks [20, 21].

The specified protocols for telemetry data delivery regulate the use of the server as an intermediate device to which client devices are connected. Sensor devices are used as such clients in the IIoT system. They measure controlled parameters and send corresponding telemetry messages to the server, as well as IoT devices of the production process control center, to which these messages are transmitted from the server. To increase the message delivery probability, the MQTT system uses repeated transmissions of distorted or lost information packets, and also provides three levels of data transmission quality (QoS 0, QoS 1 and QoS 2).

Two primary considerations must be considered while selecting the Quality of Service (QoS) level. The primary aspect influencing the selection of data transmission quality in the IIoT system is the likelihood of telemetry message delivery from a sensor device to the control center IoT device. As the QoS level and the likelihood increase, the assurance of detecting any fault in the monitored equipment before its substantial impact on production operations also escalates. This enables the prompt implementation of steps to eradicate or mitigate adverse outcomes that may occur from the identified fault.

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The second consideration is associated with the fact that raising the QoS level does have certain detrimental effects. As a result, the IIoT system experiences a dramatic spike in both data transmission and service traffic. This causes sensor nodes to use a lot more power than necessary, causes message delivery delays to worsen, and overloads wireless channels.

The present research evaluates the probability of message delivery in an IIoT system while using the optimal data transmission quality as per the MQTT-SN protocol. This level has been designated as QoS 2 and is used to ensure the sent message is delivered precisely once, without any duplication of delivery.

II. Literature Review

Consideration of IoT networks functioning aspects is of great research interest. Various protocols have been developed that regulate the operation of such networks. Much attention in publications is paid to IoT protocols of the application level. There are known protocols that are an alternative to the above-mentioned MQTT and MQTT-SN protocols. These include, for example, Constrained Application Protocol (CoAP) and Advanced Message Queuing Protocol (AMQP). When choosing the most suitable protocol for IIoT systems, it is necessary to take into account the data delivery features they have. IIoT networks typically use low-speed sensor nodes to transmit short telemetry messages under conditions of electromagnetic interference generated by production equipment. Such networks are unreliable and have low performance, so the MQTT protocol is a preferable choice for them over CoAP [22, 23]. Experimental results show that the MQTT protocol is more suitable for use in Internet of Things applications under conditions of limited available resources and network instability than the AMQP protocol [24]. However, the MQTT protocol is inferior to its modified version MQTT-SN in some aspects. A significant advantage of MQTT-SN is the ability to configure timers and retransmission counters [25]. This feature allows to limit the unjustified growth of network traffic. Overall, this protocol is a lightweight version, specifically adapted to the operating conditions of sensor nodes, so MQTT-SN is recommended for use in many IIoT applications.

There are works devoted to the analysis of energy consumption of IoT devices when using different QoS levels [26, 27]. A number of publications are devoted to the study of the influence of QoS level on the values of packet drop indicators and delivery delays when using the MQTT protocol [28, 29] and its SN modification [30, 31].

The influence of the selected class of service in MQTT-SN systems of the Internet of Things on the data delivery timeliness that ensures the operation of applications in real time was studied [32, 33].

A detailed study of the performance characteristics and IoT protocols depending on the implemented QoS levels was conducted [34, 35]. Much attention was paid to the consideration of issues related to potential cyber threats countering to ensure the security of data transmission when using the MQTT-SN protocol [36, 37]. The correctness of the MQTT logic was verified when implementing different QoS levels based on the use of formal modeling software tools [38]. Resilience to packet loss when using different levels of data transmission quality to service MQTT applications was studied [39].

In order to ensure the messages delivery carried out during the operation of IoT applications, a method for dynamic adaptation of QoS levels implemented in accordance with the MQTT-SN protocol has been developed [40]. This method is based on the analysis of network delay and allows to increase the system performance during data transmission. An approach to measuring the delay of data exchange implemented in accordance with the MQTT protocol [41] is proposed. In this case, an analyzer of packets transmitted during the Messages delivery with various QoS levels is used to analyze end-to-end delays.

Ali *et al.* [42] considered the issues of estimating the probability of message delivery taking into account possible failures to transmit MQTT packets due to the lack of free buffer space in channel queues. At the same time, as the results of the study showed, due to the short length of the transmitted MQTT packets, the probability of packet loss due to channel queues overflow is negligible and has virtually no effect on the message delivery probability in the IoT system. Most IIoT networks are provided with a sufficient number of multi-channel network gateways and operate mainly in underloaded mode. In such conditions, network performance increases significantly and message transmission delays are minimized. Based on this, the main reason for the decrease in the probability of message delivery is, first of all, the distortion of transmitted data, caused by high level of bit errors in wireless channels.

Based on the review results of scientific and technical publications on the topic of the study, it can be concluded that a significant number of works are devoted to the study of the specifics of application-level protocols used in IoT systems. The existing publications focus on issues of security, performance, resource use and delays reduction in data transmission. However, insufficient attention is paid in the literature to the issues of studying the MQTT-SN protocol for estimating the message delivery probability taking into account bit errors in IIoT channels, retransmission counters and the implemented QoS level. This determines the relevance of the scientific research, the results of which are presented in this paper.

III. Model Development

In order to estimate the message delivery probability in the IIoT system, it is proposed to use the mathematical apparatus of probability graphs [43, 44], which allows to take into account all possible states of the simulated process and transitions probabilities from one state to another [45, 46].

Fig. 1 shows the probability graph of the transmitting information packets process and confirmations from the sensor device to the server when implementing the QoS 2 data transmission quality level in accordance with the MQTT-SN protocol. The initial state of the simulated process is designated by node "B". In this state, network connections are established between the client devices and the server, and the transmission of the PUBLISH information packet from the sensor device to the server begins.

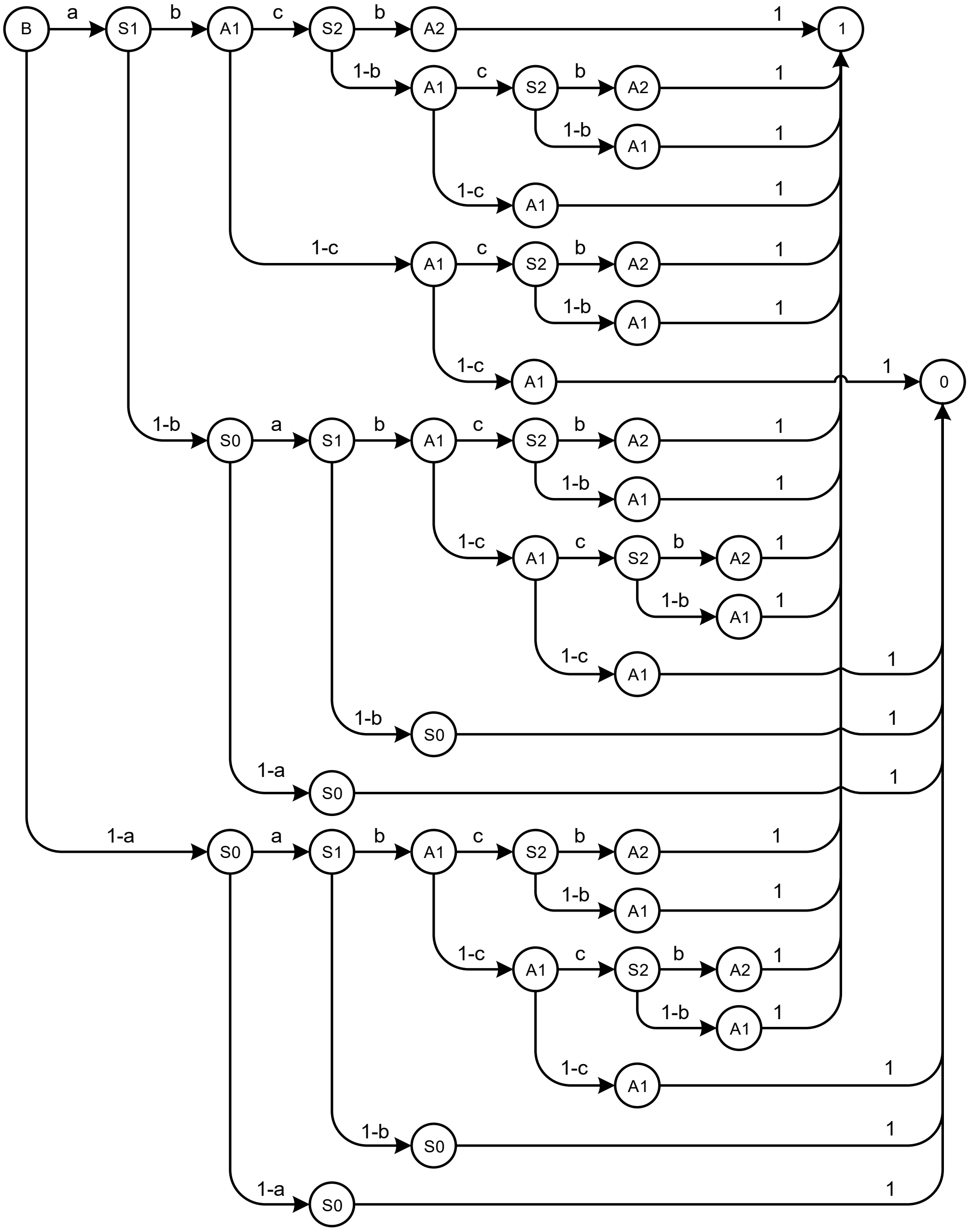

Fig. 1. Probability graph of information packets transition process and confirmations from a sensor device to a server when implementing the Quality of Service 2 (QoS 2) data transmission quality level in accordance with the Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN) protocol.

At the moment the PUBLISH packet is transmitted, a retransmission timer is activated on the sensor device, which counts down a certain timeout time. If the sensor device does not correctly receive the PUBREC confirmation packet before the timeout expires, the retransmission timer is triggered, after which the PUBLISH information packet is retransmitted. From state "B" the simulated process can move to the state of correct reception of the PUBLISH packet by the server. This state is designated by the node "S1". The probability of moving to state "S1" can be estimated by the equation:

$$a = 1 - (L1 \cdot BER1) \tag{1}$$

where $L1$ is the bit length of the physical layer information block in which the packet PUBLISH is encapsulated; *BER1* is bit error rate in the wireless channel connecting the sensor device to the server.

After the PUBLISH packet is correctly received, the server sends a PUBREC acknowledgement packet to the sensor device. If this acknowledgement is correctly and promptly received by the sensor device, then a transition from the S1 node to the A1 node will be performed. The probability of a transition from the S1 node to the A1 state can be estimated using the equation:

$$b = PRD \cdot [1 - (L2 \cdot BER1)] \tag{2}$$

where $L2$ is the bit length of the physical layer information block in which the packet PUBREC is encapsulated; PRD - the probability that the PUBREC acknowledgement packet will be received by the sensor device in a timely manner, i.e., before the retransmission timer is triggered.

After the correct reception of the PUBREC acknowledgement packet, the sensor device sends a PUBREL service packet to the server, which allows the transmission of the PUBLISH packet to the IoT device of the control center. At the moment the PUBREL packet is transmitted, the retransmission timer is activated on the sensor device, which counts down a certain timeout period. If the sensor device does not correctly receive the PUBCOMP acknowledgement packet before the timeout period expires, the retransmission timer is triggered, after which the PUBREL packet is retransmitted. If the PUBREL packet is correctly received by the server, then the transition from the "A1" node to the "S2" node is performed. The PUBREL packet, just like the PUBREC packet, does not have a payload, so the bit length of the physical layer information block in which the PUBREL packet is encapsulated is also equal to $L2$. Then the probability of transition to the "S2" state can be estimated by the equation:

$$c = 1 - (L2 \cdot BER1) \tag{3}$$

After the PUBREL packet is correctly received, the server sends a PUBCOMP acknowledgement packet to the sensor device. If this acknowledgement is correctly and timely received by the sensor device, then the transition from the S2 node to the A2 node will be performed. The PUBCOMP acknowledgement packet, just like the PUBREC acknowledgement packet, has no payload, so the bit length of the physical layer information block in which the PUBCOMP packet is encapsulated is also equal to $L2$. In this case, the probability of transition to the A2 state is equal to b, which can be estimated using Eq. (2).

If the PUBCOMP acknowledgement packet is not correctly received by the sensor device or is received after the retransmission timer has fired, then the simulated process will move from the node "S0" to the node "A1". The probability of such a transition is $(1 - b)$. In this case, if the number of completed retransmissions of the PUBREL packet does not exceed the specified value *Nretry*, then when the retransmission timer fires on the sensor device, a duplicate of the PUBREL packet will be sent to the server.

It is possible that the PUBREL packet will not be correctly received by the server, then the simulated process will move from the node "A1" to the node with the same designation. The probability of such a transition is $(1 - c)$.

If the PUBREC acknowledgement packet is not correctly received by the sensor device or is received after the retransmission timer has fired, then the simulated process will move to the node "S0". The probability of such transition is $(1 - b)$. In this case, if the number of completed retransmissions of the PUBLISH packet does not exceed the specified value *Nretry*, then when the retransmission timer fires on the sensor device, a duplicate of the PUBLISH packet will be sent to the server.

It is also possible that the PUBLISH packet will not be correctly received by the server, then the simulated process will move from the initial node "B" to the node "S0". The probability of such a transition is $(1 - a)$.

Finally, the simulated process ends with a transition to one of two terminal states. One of them is designated by node "1". The transition to this node corresponds to the telemetry message delivery from the sensor device to the server. The transition to the second terminal node, designated "0", is carried out in cases where, after all permitted retransmissions, the message could not be delivered from the sensor device to the server.

The probability of message delivery from a sensor device to a server is equal to the simulated process transition probability from node "B" to node "1" and can be calculated using the expression:

$$PDELIV1 = 1 - P0 \tag{4}$$

where $P0$ is the probability that after all allowed retransmissions the message will not be delivered from the sensor device to the server.

To estimate the probability that after all allowed retransmissions the message will fail to be delivered from the sensor device to the server, use the expression:

$$P0 = (1 - a \cdot b)^{Nretry+1} \cdot a \cdot b \cdot (1 - c)^{Nretry+1} \times \times \sum_{i=0}^{Nretry} (1 - a \cdot b)^{i} \tag{5}$$

Then the equation for estimating the message delivery probability from a sensor device to a server will be as following:

$$PDELIV1 = 1 - [(1 - a \cdot b)^{Nretry+1} \times \times a \cdot b \cdot (1 - c)^{Nretry+1} \cdot \sum_{i=0}^{Nretry} (1 - a \cdot b)^{i}] \tag{6}$$

Similarly, to estimate the probability of message delivery from the server to the IoT device control center, we can use the expression:

$$PDELIV2 = 1 - [(1 - x \cdot y)^{Nretry+1} \times \times x \cdot y \cdot (1 - z)^{Nretry+1} \cdot \sum_{i=0}^{Nretry} (1 - x \cdot y)^{i}] \tag{7}$$

where x is probability of correct reception of the PUBLISH packet by the IoT device of the control center; y is the probability of correct and timely reception of the PUBREC confirmation packet by the server, as well as the probability of correct and timely reception of the PUBCOMP confirmation packet by the server; z is the probability of correct reception of the PUBREC packet by the server, or the probability of correct reception of the PUBREL packet by the control center IoT device, or the probability of correct reception of the PUBCOMP packet by the server. Value x can be calculated using the equation:

$$x = 1 - (L1 \cdot BER2) \tag{8}$$

where $BER2$ is the bit error rate in wireless channels connecting the server to the IoT device of the control center.

Value y can be calculated using the equation:

$$y = PRS \cdot [1 - (L2 \cdot BER2)] \tag{9}$$

where PRS is the probability that the server retransmission timer will fire correctly, i.e., the probability that it will not fire before receiving confirmation.

Value z can be calculated using the equation:

$$z = 1 - (L2 \cdot BER2) \quad (10)$$

Then the equation for estimating the message delivery probability in the IIoT system, i.e., the probability of message delivery from a sensor device to the IoT device of the control center, will be as follows:

$$PDELIV = PDELIV1 \cdot PDELIV2 \quad (11)$$

The proposed model takes into account dynamic network conditions. The quantities $BER1$ and $BER2$ are need to take into account the conditions of messages receiving in wireless environment, in particular, the current level of interference. The presence of network congestion and the use of adaptive retransmission mechanisms are taken into account using the values PRD and PRS. Changes in the number of network devices and the volume of transmitted traffic affect the packet reception delays. An increase in these delays causes premature triggering of retransmission timers, which leads to a decrease in the PRD and PRS values. Values $BER1$, $BER2$, PRD and PRS take into account the influence of network topology and environmental factors on the bit error rate and the probability of correct operation of retransmission timers.

IV. Result and Discussion

Well-presented Sensor nodes use autonomous power sources, such as batteries, so energy consumption assessment is important in IIoT systems. It is logical to assume that the energy consumption of a transmitting network device depends on the packet sending rate, which is affected by the retransmissions number. A study was conducted to investigate the influence of retransmissions on these values. A previously published methodology was used to assess energy consumption [12]. The BER value was 0.0002, the output power of the transmitting module was 3.162 mW, and the packet transmission duration was 313 ms. Table I presents the results of overhead cost assessment.

TABLE I. Overheads

Values	*Nretry*	
	1	2
Average number of packets transmitted to deliver a message	8.312	8.371
Power consumption during message transmission (microwatt hour)	2.285	2.302

Analysis of Table I shows that increasing the retransmissions number leads to undesirable increase in packet traffic and energy consumption of network nodes. To minimize overhead costs, it is recommended to select the smallest number of retransmissions that ensures the required reliability of message delivery.

The developed mathematical model was used in the computational experiments. Experiments were conducted with the deployment of a real IoT network. The purpose of these experiments is to study the dependence of the telemetry message delivery probability on the values of data transmission parameters in the IIoT system when implementing the quality level QoS 2 in accordance with the MQTT-SN protocol.

A. Calculation Results

Let's assume that, based on the specifics of the production facility where the IIoT system is deployed, the probability of delivering a telemetry message from a sensor device to the IoT device of the control center should be no lower than 0.98. The following initial data were used in the process of conducting computational experiments: $L1$ = 256 bits; $L2$ = 128 bits; PRD = PRS = 1. The values of $BER1$ and $BER2$ varied within the range from 0.0002 to 0.001. The number of retransmissions varied from 1 to 5. Such parameters values were observed as a result of measuring the characteristics in real IIoT networks operating at 4 Russian machine-building enterprises.

As a result of calculations using Eqs. (1)–(11), the dependence diagrams of delivery probability of telemetry message on the bit errors intensity in wireless channels of the IIoT system were obtained for different values *Nretry*. Fig. 2 shows the diagram of the dependence of the value *PDELIV* on the values *Nretry* at $BER1$ = $BER2$ = 0.0002. Analysis of the diagram shows that under conditions of a given bit error rate, the probability of message delivery to the IIoT system exceeds the specified level *PDELIV* = 0.98 for any value *Nretry* >0. In this case, to reduce the packet traffic and the node power consumption, it is recommended to use no more than 1 retransmission.

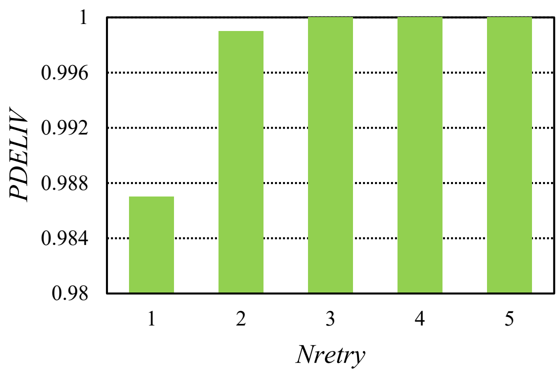

Fig. 2. Diagram of the dependence of the value *PDELIV* on the values *Nretry* at $BER1$ = $BER2$ = 0.0002.

Fig. 3 shows the diagram of the dependence of the value *PDELIV* on the values *Nretry* at $BER1$ = $BER2$ = 0.0004. Analysis of the diagram shows that under conditions of a given bit error rate, the probability of message delivery to the IIoT system exceeds the specified level *PDELIV* = 0.98 in those cases in which *Nretry* >0. Such results are marked in green. At *Nretry* = 1 value *PDELIV* is below level 0.98. Such result is marked in red. To reduce packet traffic and node power consumption, it is recommended to use *Nretry* = 1.

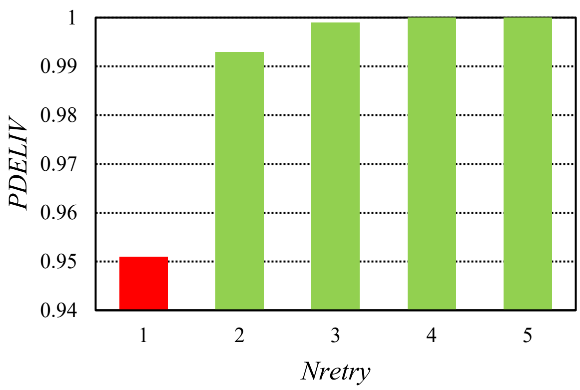

Fig. 3. Diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.0004.

Fig. 4 shows the diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.0006. Analysis of the diagram shows that under the given bit error rate, the probability of message delivery to the IIoT system exceeds the level *PDELIV* = 0.98 in those cases in which *Nretry* >2. Such results are marked in green. At *Nretry* ⩽2 value *PDELIV* is below 0.98. Such results are marked in red. Based on the obtained calculation results, it can be stated that in order to reduce packet traffic and nodes energy consumption, it is recommended to use *Nretry* = 3.

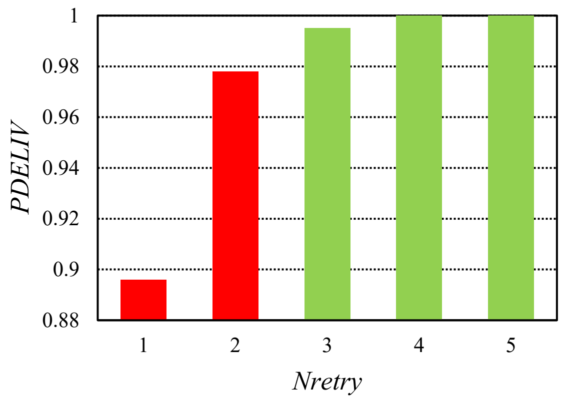

Fig. 4. Diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.0006.

Fig. 5 shows the diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.0008. Analysis of the diagram shows that under the given bit error rate, the probability of message delivery to the IIoT system exceeds the level *PDELIV* = 0.98 in those cases in which *Nretry* >2. Such results are marked in green. At *Nretry* ≤2 value *PDELIV* is below 0.98. Such results are marked in red. As in the previous case, to reduce packet traffic and nodes power consumption, it is recommended to use *Nretry* = 3.

Fig. 6 shows the diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.001. Analysis of the diagram shows that under the given bit error rate, the probability of message delivery to the IIoT system exceeds the level *PDELIV* = 0.98 in those cases in which *Nretry* >3. Such results are marked in green. At *Nretry* ⩽3 value *PDELIV* is below 0.98. Such results are marked in red. Based on the obtained calculation results, it can be stated that in order to reduce packet traffic and nodes energy consumption, it is recommended to use *Nretry* = 4.

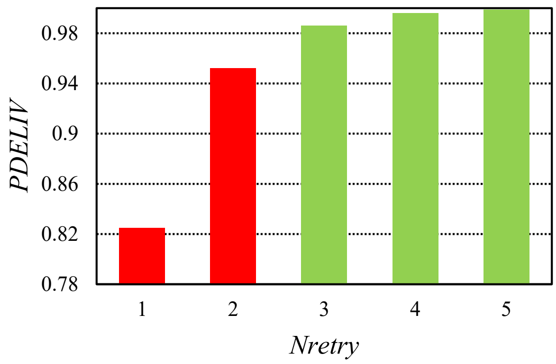

Fig. 5. Diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.0008.

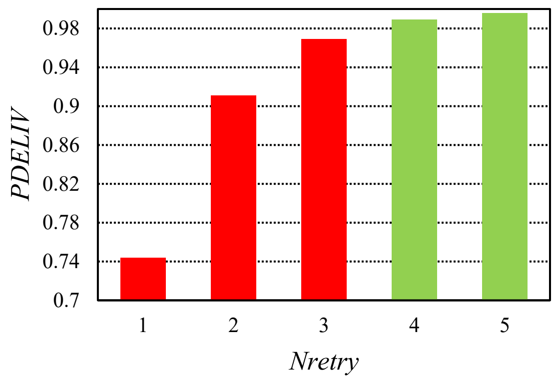

Fig. 6. Diagram of the dependence of the value *PDELIV* on the values *Nretry* at *BER*1 = *BER*2 = 0.001.

The results of the computational experiments showed that the use of the developed model makes it possible to select a value *Nretry* at which the value *PDELIV* does not exceed the specified permissible values at the current level of bit errors.

B. Experimental Results

Using the above initial data, experiments were conducted in a real IoT network. 20 network LoRaWAN devices with LW002-TH temperature and humidity sensors were connected to the eight-channel MKGW2-LW gateway. The MQTT-SN protocol in QoS 2 mode was used to control data transmission at the application layer. To change the *BER* level, the distance between the sensor network devices and the gateway was increased or decreased. The GW C-1200 protocol analyzer for wireless LoRa networks was used to measure the bit error rate. The message sending period for each sensor device was 1800 s.

Message delivery probability for different *Nretry* values was calculated as the ratio of the number of correctly received messages to the total number of messages sent.

As a result of the experiments, the data presented in Table II were obtained. Each row of the table indicates the *PDELIV* values and the recommended number of retransmissions obtained at the current level of bit errors based on the use of the developed model and on the basis of experiments.

A comparative analysis of these results shows that the relative error of calculations results and experiments does not exceed 0.6%. This confirms the adequacy of the developed model and the possibility of its use in practice.

TABLE II. RESULTS OF CALCULATIONS AND EXPERIMENTS

***BER*1 and *BER*2**	**Calculations results based on the model**		**Experiments results on real IoT-сети**	
	PDELIV	***Nretry***	***PDELIV***	***Nretry***
0.0002	0.987	1	0.982	1
0.0004	0.993	2	0.988	2
0.0006	0.995	3	0.989	3
0.0008	0.986	3	0.990	3
0.001	0.989	4	0.992	4

V. CONCLUSION

Thus, the developed model can fill the gap in the research of IIoT systems operating on the basis of the MQTT-SN protocol. A literature review has shown that existing studies of the applied protocols of the Internet of Things focus on the issues of improving security, performance, resource utilization, and delays reduction in data transmission. In comparison with them, the proposed model adequately reflects the dependence of the message delivery probability in IIoT system on the bit error rate in wireless channels and the limitation of the retransmissions set number on network nodes. Calculations and experiments have shown the practical usefulness of the model. Using the developed model makes it possible to justify the choice of such number of retransmissions used, at which the message delivery probability value takes values not lower than 0.98 at the current level of bit errors. At the same time, a reduction in packet traffic in the network is ensured and the energy consumption of sensor devices is reduced. The limitation of the model is that it allows to evaluate the characteristics of message delivery only at QoS level 2 of the protocol under study.

Further research within the considered topic is planned to be devoted to the development of models of message delivery probability assessment in the IIoT system when implementing QoS 0 and QoS 1 levels in accordance with the MQTT-SN protocol. Then, using the models that will be obtained and the model proposed in this paper, an algorithm will be developed for the best QoS level and number of retransmissions selection under current conditions. The application of such algorithm will be aimed at meeting the requirements for the message delivery probability and restrictions on the volume of transmitted traffic, taking into account the specifics of the IIoT systems operation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

MJY planned the study, conducted the research and formulated the initial manuscript; DA analyzed the data; KAP review the article, proposed different experiments; MSB wrote the paper; all authors had approved the final version.

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