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OPTIMIZATION OF WIRELESS NETWORKS USING THE INET FRAMEWORK

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The article explores methods of modeling wireless networks in the OMNeT++ environment using the INET Framework. It examines the basic concepts related to the modeling of wireless networks, and also describes the basic requirements for models in this field. The OMNeT++ simulation environment, its characteristics and advantages compared to other simulation environments are analyzed in detail. The article examines the main components of wireless network models, including network layer models, physical layer models, and radio channel models. For each of these components, the article examines modeling methods and highlights possible nuances associated with the choice of various modeling parameters. The article can be a useful source of information for those interested in modeling wireless networks and using OMNeT++ with the INET Framework. The article details the structure of the wireless network model using the IEEE 802.11 network as an example. In addition, the article describes methods of modeling various types of network protocols, including the MAC protocol, the network layer protocol, and others. The article examines the issue of testing models of wireless networks and their analysis. It describes the methodology of testing and comparing different models, and also pays attention to the analysis of modeling results and their interpretation. In general, the article provides a detailed description of wireless network simulation methods in the OMNeT++ environment using the INET Framework. The article presents a methodology for developing wireless networks that uses ready-made components of the INET framework to create a device model that meets specific requirements. Various modes of interaction of nodes in wireless networks, both direct *and indirect through intermediate nodes, as well as an approach to modeling the physical level and the phenomenon of interference, are considered. The method of solving problem situations, in particular the analysis of time diagrams, in the context of the use of a simulation modeling environment for the analysis of project solutions in the process of creating wireless networks, was also investigated.*

Key words: *networks, Wi-Fi, simulation modeling, interference, OMNeT ++, Framework.*

Антоненко А. В., Твердохліб А. О., Востріков С. О., Бегліцов С. В., Гергель О. Г., Бобков Р. А. Оптимізація роботи бездротових мереж з використанням INET Framework

Стаття досліджує методи моделювання безпроводових мереж у середовищі OMNeT++ з використанням INET Framework. В ній розглядаються основні поняття, пов'язані з моделюванням безпроводових мереж, а також описані основні вимоги до моделей у цій галузі. Детально проаналізовано середовище моделювання OMNeT++, його характеристики та переваги порівняно з іншими середовищами моделювання. Стаття розглядає основні складові моделей безпроводових мереж, включаючи моделі мережевого рівня, моделі фізичного рівня та моделі радіоканалу. Для кожної з цих складових в статті досліджуються методи моделювання і висвітлюються можливі нюанси, пов'язані з вибором різних параметрів моделювання. Стаття може бути корисним джерелом інформації для тих, хто цікавиться моделюванням безпроводових мереж та використанням OMNeT++ разом з INET Framework. У статті детально вказано структуру моделі безпроводової мережі з використанням прикладу мережі стандарту IEEE 802.11. Крім того, у статті описані методи моделювання різних типів мережевих протоколів, зокрема протоколу MAC, протоколу рівня мережі та інших. В статті розглядаються питання тестування моделей безпроводових мереж та їх аналізу. Вона описує методику тестування та порівняння різних моделей, а також звертає увагу на аналіз результатів моделювання та їхню інтерпретацію. У цілому, стаття надає детальний опис методів моделювання безпроводових мереж у середовищі OMNeT++ з використанням INET Framework. Також в статті подано методику розробки безпроводових мереж, що використовує готові компоненти фреймворку INET для створення моделі пристрою, відповідної специфічним вимогам. Розглянуто різноманітні режими взаємодії вузлів у безпроводових мережах, як прямі, так і непрямі через проміжні вузли, а також підхід до моделювання фізичного рівня та явища інтерференції. Також досліджено методику вирішення проблемних ситуацій, зокрема аналіз тимчасових діаграм, в контексті використання середовища імітаційного моделювання для аналізу проектних рішень у процесі створення безпроводових мереж.

Ключові слова: *мережі, Wi-Fi, імітаційне моделювання, інтерференція, OMNeT++, Framework.*

Introduction. The design of any modern information system, which has a complex structure with a wide set of protocols, always begins with the construction and study of its simulation model [1]. The purpose of modeling is to determine the optimal topology, the adequate selection of network equipment, the determination of the operating characteristics of the network and possible development. One of the advantages of simulation modeling is the possibility of conducting a number of studies that allow determining the reliability of the system and its stability in the event of equipment failure [2, 3]. It is impossible to carry out such research on a working network, because it can negatively affect the stability of its work, besides, if the equipment used fails, there is a risk of suffering financial losses. Accurate modeling of the equipment under study allows you to obtain the same results as when using this equipment in real life, while allowing you to save money on its purchase.

Today, there are many simulation tools, which are subject to quite strict requirements, such as: detailed implementation of protocols at all levels, the ability to connect your own modules, the ability to change the parameters of the simulation model, platform independence, a developed graphical interface, as well as the availability of the product and its price . One such tool that meets the listed requirements is the simulation modeling environment OMNeT++ [4], which has a developed graphical interface both for building models and for analyzing the obtained results. Another important advantage is its availability, while the functionality of the environment is not inferior to other paid means of simulation modeling.

The aim of the study. The purpose of the article is to research and analyze one of the possible approaches to design and wireless networks in the OMNeT++ simulation environment using the INET framework.

The subject of the study is the process of modeling wireless networks, different modes of their operation, and the methodology of model operation analysis.

The object of the article is methods and tools that can be used for modeling and researching wireless networks.

Analysis of recent research and publications. At the moment, one of the most interesting articles on this topic is "Design and implementation of wireless sensor network simulation using the OMNeT++ simulator" by A. Al-Gburi and S. Ngan. In this article, the authors consider the design and implementation of wireless sensor networks using OMNeT++ and the INET Framework. The study was conducted by creating a network model that reflects the real network and its subsequent simulation. Another interesting article on this topic is "Comparative Analysis of Wireless Sensor Network Simulation Tools" by M. Shahbaz, S. Ullah, and S. S. Khan. This paper provides a comparative analysis of network modeling tools, including OMNeT++, NS2, NS3, QualNet, and OPNET. The study focused on analyzing various aspects such as network modeling capabilities, performance, accuracy of results, and scalability. Additionally, the article "OMNeT++ based Wireless Sensor Network Simulation" by P. Yadav and S. Singh describes the use of OMNeT++ and the INET Framework for wireless sensor network simulation. In the study, the authors focused on analyzing the performance and accuracy of the simulation results.

In general, these articles indicate a great interest in using OMNeT++ and the INET Framework for modeling wireless networks. However, there are a number of articles that compare different modeling tools to determine their advantages and disadvantages compared to each other. For example, in the article "Comparative study of simulation tools for wireless sensor network" by N. Kumar and M. Kumar, a comparative analysis of various simulation tools, including OMNeT++, NS2, NS3, and QualNet, was conducted. The authors compared these tools on several criteria, such as performance, accuracy of results, and extensibility, and concluded the advantages and disadvantages of each. Also, the article "Performance evaluation of wireless sensor network protocols using OMNeT++ simulation" by S. Singh and P. Yadav is devoted to the performance evaluation of wireless sensor network protocols using OMNeT++ and the INET Framework. In the study, a comparative analysis of different protocols was carried out, and the impact of various factors on network performance was also studied.

One of the most interesting Ukrainian articles is "Modeling and analysis of wireless networks based on the IEEE 802.15.4 standard using the OMNeT++ platform" by M. Kulchytska, E. Makarenko and Yu. Khrustalev. This article deals with the design and modeling of wireless networks based on the IEEE 802.15.4 standard using OMNeT++ and the INET Framework. The authors investigated various network parameters, such as network performance and efficiency, and compared simulation results with experimental data.

In addition, the article "Modeling and research of wireless networks based on the ZigBee protocol using the OMNeT++ platform" by I. Gryn and E. Drozdova is devoted to modeling and research of wireless networks based on the ZigBee protocol using OMNeT++. In the study, the authors studied the influence of various network parameters on its performance and efficiency.

Thus, it can be said that the article on the modeling of wireless networks in the OMNeT++ environment using the INET Framework is relevant and important, since this topic is quite extensive and requires further research. Recent studies indicate that OMNeT++ together with the INET Framework is a powerful tool for modeling and researching wireless networks, allowing the study of various aspects of network performance and efficiency.

Presentation of the main research material. Let's consider one of the possible approaches to the design and analysis of wireless local networks (Wireless Local Area Network – WLAN) using the OMNeT++ simulation environment. The task of a comprehensive study of the simulation model of the simplest mobile WLAN by successively complicating it to take into account the features of various modes of operation of the wireless network is set. As a basis for the development of models, it is proposed to use typical components of the INET framework, the configuration of which allows you to model devices that meet the necessary requirements.

The object of research is WLANs, which fully comply with the standard of wired networks such as Ethernet [5], but use a different data transmission medium: infrared radiation or microwave radio waves. These networks can be stationary, mobile and mobile roaming. Stationary nodes of the network are rigidly tied to a certain point in space. Mobile allows the movement of network nodes within the range of one access point or one network segment, and mobile roaming allows not only the movement of network nodes, but also ensures their roaming due to automatic switching from one access point to another. Depending on the nature of the connection, WLANs can support two main modes of operation:

– point-to-point (point-to-point), or Ad-Hoc mode [6, 7], in which communication between nodes is established directly without using special access points;

– point-to-multipoint (point-to-multipoint), or infrastructure mode, in which the network consists of at least one access point connected to the wired network and some set of wireless nodes.

In this article, the main attention is paid to the analysis of models of mobile Ad-Hoc networks, which work both with direct interaction of nodes, and with indirect interaction through intermediate nodes. This made it possible to investigate the operation of self-organizing WLANs with dynamic routing of messages to nodes that are outside the radio access zone of a particular low-power transceiver of the node, using intermediate nodes for this purpose and significantly expanding the area of operation of a particular WLAN segment [8, 9].

For simulation modeling of this kind of networks, it is suggested to use the INET framework included in the OMNeT++ delivery. It contains a large set of components for modeling both the network as a whole and its individual elements, namely: the physical environment and signal propagation modes in it, various types of antennas, receivers, transmitters and network cards with the possibility of accounting for their energy consumption [10] .

The first stage on the way to solving the task was the development of technology for the process of building and researching the simplest WLAN, which consists of only two nodes connected by a radio channel for the transmission of UDP datagrams. To design a simulation model of such a network, it is enough to use only three components of the INET framework, namely:

– WirelessHost component module,

– component module of IdealRadioMedium,

– simple IPv4NetworkConfigurator module.

The WirelessHost component module is a wireless network host model and is one of the extensions of the StandartHost module, which is the basis for other TCP/IP host models. The internal structure of this module (Fig. 1) consists of four levels: application, transport, network and channel, represented by the network interface.

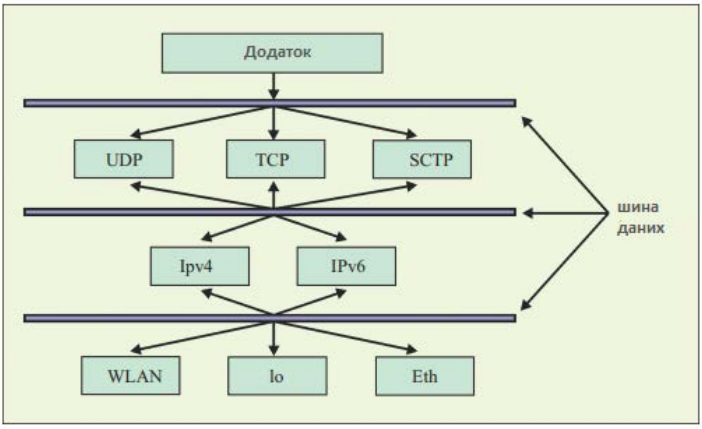


Fig. 1. The internal structure of the WirelessHost host

Each of the levels includes a set of predetermined components from the INET framework, the type of which can be changed through a configuration file. In particular, the application layer contains a dimensionless array of components of the "application" type, each of which simulates the operation of the application on the host model. This module can generate outgoing traffic, transmitting it to lower levels, and receive incoming traffic. The transport layer includes three components that model User Datagram Protocol (UDP), Transmission Control Protocol (TCP), and Stream Control Transmission Protocol (SCTP). The network layer consists of two components: Internet Protocol version 4 (Inernet Protocol version 4 – IPv4) and Internet Protocol version 6 (Inernet Protocol version 6). The channel layer contains components that implement network interfaces, such as wired Ethernet (Eth), wireless (wlan), internal loop interface (Loopback – lo), etc. Each of the levels is connected to each other through common data buses.

The IdealRadioMedium component module is used to simulate the physical environment in which wireless communication takes place. It is responsible for modeling signal propagation, its attenuation as it is removed, accounting for interference and other physical phenomena. The physical environment model determines when, where, and how transmission and extraneous noise arrive at receivers. The IdealRadioMedium module has a complex structure and includes other predetermined components that simulate the following physical phenomena and processes:

– propagation of a radio signal in space (propagation) – the component describes how a radio signal propagates through space in time;

– analog representation of a radio signal (analogModel) – models the process of how an analog representation of transmissions turns into an analog representation of receptions;

– background noise (backgroundNoise) – represents a model of background noise and describes thermal noise, cosmic background noise and other random fluctuations of the electromagnetic field that affect the quality of the communication channel;

– power reduction from distance (pathLoss) – describes the power reduction as the signal propagates through space;

– reduction of the radio signal when passing through obstacles (obstacleLoss) – is a loss model and describes the reduction of signal power when it passes through obstacles and physical objects.

In general, the physical environment models implemented in INET describe a physical device that is capable of transmitting and receiving signals. They include: antenna model, receiver and transmitter models, and energy consumption model. The antenna model is divided between the transmitter model and the receiver model. The separation of the transmitter model and the receiver model allows the use of asymmetric configurations.

Consider the model of interaction between two wireless nodes using the UDP protocol. The approach to building this model will be considered on the example of a wireless network consisting of two nodes interacting with each other using the UDP protocol. In this model, the nodes will be located at a distance of 400 m from each other, while the radius of action of the receiver of each node will be equal to 500 m. The use of UDP as a data transmission protocol means that the nodes must function not only at the transport level, but also at the user level applications. The INET framework contains two types of modules that work using the UDP protocol:

– UDPBasicApp – a module that provides generation of UDP packets of a given length to a given IP address at a given time interval;

– UDPSink – a module simulating a program that receives messages received from the UDP layer, counts their number and stops their further processing.

In the studied model, it is necessary that the node hostA generates a UDP message of length 1 KB and transmits it to the node hostB after a random time interval. The WirrelessHost wireless node model used from the INET framework already has an application interface module, therefore, to implement the task, it is only necessary to redefine the type of module used in the configuration file, which can have the following form:

```
*.hostB.numUdpApps = 1
*.hostB.udpApp[0].typename = “UDPSink”
*.hostB.udpApp[0].localPort = 5000
*.hostA.numUdpApps = 1
*.hostA.udpApp[0].typename = “UDPBasicApp”
*.hostA.udpApp[0].destAdresses = “hostB”
*.hostA.udpApp[0].destPort = 5000
*.hostA .udpApp[0].messageLength = 1000B
*.hostA.udpApp[0].sendInterval = exponential(10ms)
```

This setting tells hostA to use the UDPBasicApp module, which generates 1 KB UDP messages and sends them at a random time interval described by an exponential distribution with a mean of 10 ms. In order for the generated messages to reach the recipient, the configuration file specifies the name of the host to which the message is assigned, as well as the port number, for example, 5000. The hostB node uses the UDPSink module and also works on port 5000.

In addition to the application layer, the configuration file must contain the definition of the physical layer, which is represented in the WirelessHost host model as a network adapter, which includes an antenna and a radio transceiver. In the INET environment, there is a wide variety of radio modules supporting different physical layer protocols, but this example will use an idealized model of the physical environment whose hosts contain the IdealRadio module as part of IdealWirelessNic. Based on the above, the configuration of the physical layer will look like this:

```
*.host*.wlan[*].typename = “IdealWirelessNic”
*.host*.wlan[*].radio.transmitter.CommunicationRange = 500m
*.host*.wlan[*].radio.receiver.ignoreInterference = true
* *.bitrate = 1Mbps
```

After starting the created simulation model for execution, a graphical window of the execution environment will open, where the entire network and the modules included in it will be presented. The environment allows you to display the internal structure of the assembled module at any time by double-clicking on its icon. It should be noted that the structure of the displayed module will differ from the one presented in fig. 1. This is due to the fact that after running the execution model, the simulation environment processed the configuration file and configured the parameters of the WirelessHost components.

Each host has only one network adapter, but with two network interfaces each. At the same time, one of them is an internal loop (lo), and the second is external (wlan) and connected to a wireless network through an internal transceiver. Both nodes have the same structure both at the physical level and at the channel, network and transport levels. The difference is observed only at the level of applications, namely, in the type of application used.

After running the model, you can observe how the UDPBasicApp program running on the hostA node generates UDP packets with a random time slot. After that, these packets, having passed through the UDP and IPv4 layers, arrive at the wlan network interface, which puts the incoming packets in a queue and transmits them as soon as such an opportunity arises. The use of a stack implementation in the network interface allows you to match the speed of incoming packets from the upper level with the bandwidth of the channel, as well as the speed of the environment. This means that as long as there are packets in the stack queue, they will be transmitted one after the other without spaces between them.

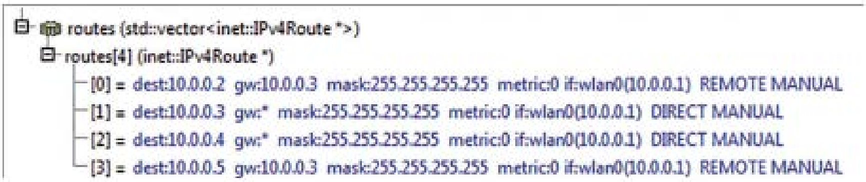
According to the simulation results, it can be seen that the UDP application on the hostA node generated 2427 packets in 25 minutes. At the same time, 2426 packets were processed at the UDP transport level. Of these, 2422 packets were transmitted over the radio channel and arrived at the hostB node. Here, they passed through the link, network, and transport layers of this node and arrived at the UDP application of host hostB. Thus, the packet counter indicates that 2422 packets of length 1028B (1000B message + 8B UDP + 20B IP) each were received in 25 s, which means that the transfer rate was about 800 kbit/s.

Consider the model of static routing for the interaction of remote nodes. The possibilities of using the OMNet++ simulation environment are not limited to the process of designing and researching only simple models. It also allows you to investigate more complex models and situations, such as in [11], where the effectiveness of the use of transmission reservation was analyzed on the example of the created simulation model of a wired computer network. Another example, which will be discussed below, demonstrates an approach to the design and research of a more complex structure, but already a wireless network [12, 13]. Let's assume that there is a need to provide wireless communication and transfer UDP messages from node hostA to node hostB with a radius of action of their receivers of only 250 m. At the same time, the distance between these nodes is 400 m, which excludes the possibility of their direct interaction. In addition, there are three more nodes hostR1, hostR2 and hostR3 located between the nodes, which in the process of their work can interfere with the work of neighboring nodes. The peculiarity of the studied model is that the receivers of network adapters, having low power, limit the radius of their action, which leads to the impossibility of direct communication between two nodes. However, a connection can be established if there are other nodes between these nodes that can broadcast and transmit network packets. For this, all or part of the intermediate nodes must support routing.

If we add three more nodes to the original model (Fig. 3), limit the power of all receivers to 250 m and run the model for execution, we can see that the hostA node sends UDP packets to neighboring nodes, but the latter do not receive them, because these packages are not intended for them. In order for the neighboring nodes not to discard the received packets, but to transfer them to another node, it is necessary that the routing table be configured on the intermediate nodes [14]. In this simplest case, an example of static routing is considered, which is configured through a simple IPv4NetworkConfiguration module in a configuration file that looks like this:

```
# Automatic configuration of static routes
*.configurator.config = xml("<config>
<interface host='**' address='10.0.0.x' netmask='255.255.255.0' />
< autoroute metric='errorRate' />
</config>")
#Disabling optimization of routing table entries
*.configurator.optimizeRoutes = false
#Disable routing table entries created from netmask
**.RoutingTable.netmaskRoutes = ""
```

This setup is done using an XML string whose parameters tell the configurator to assign IP addresses in the 10.0.0.x range and use the estimated peer-to-peer error rate to configure static routes. In this way, the routes will be formed in such a way as to minimize the total errors, resulting in the creation of a correctly configured IPv4 network without any additional manual settings. The generated routing tables are stored in the routingTable parameter of each of the hosts, which is available for viewing in the graphical execution environment (Fig. 2).



```
⊟ routes (std::vector<inet::IPv4Route *>)
  ⊟ routes[4] (inet::IPv4Route *)
     ├[0] = dest:10.0.0.2  gw:10.0.0.3  mask:255.255.255.255  metric:0 if:wlan0(10.0.0.1)  REMOTE MANUAL
     ├[1] = dest:10.0.0.3  gw:*  mask:255.255.255.255  metric:0 if:wlan0(10.0.0.1)  DIRECT MANUAL
     ├[2] = dest:10.0.0.4  gw:*  mask:255.255.255.255  metric:0 if:wlan0(10.0.0.1)  DIRECT MANUAL
     └[3] = dest:10.0.0.5  gw:10.0.0.3  mask:255.255.255.255  metric:0 if:wlan0(10.0.0.1)  REMOTE MANUAL
```

Fig. 2. Routing of node hostA: dest – destination address, gw – gateway; mask – subnet mask; metric – network metric, REMOTE MANUAL – remote access; DIRECT MANUAL – direct access

From the given table it can be seen that the node hostA (10.0.0.1) has a direct communication interface with the nodes hostR1(10.0.0.3) and hostR2 (10.0.0.4). Also in the table is a route that informs that hostB (10.0.0.2) can be reached through hostR1 using the latter as a gateway, and hostR3 (10.0.0.5) can be reached through hostR2's gateway. After completing the configuration of the network model and running it for execution, you can see in the dynamics how the UDP packet generated by the hostA node arrives at the input of the hostR1 node, but now it does not discard this packet, but accepts it and forwards it to another node.

This process occurs according to static routing settings, in which the intermediate nodes of a given WLAN segment play the role of gateways, almost doubling the range of possible wireless interaction between hostA and hostB nodes. The main difference of this model is that it simulates the process in which the packet (UDPBasicAppData-0) generated by the hostA node arrives in the radio channel not directly to the hostB node, but passing through the network and channel levels of the hostA node, is now addressed to the hostR1 node. This process is performed on the basis stored in the memory of the hostA node, the routing table, based on which all packets intended for delivery to the hostB node are addressed for transmission to the input of the hostR1 node. Packets received at its input will rise to the network level and immediately be sent back to the network according to the routing table stored in the memory of the hostR1 node. Since the hostR1 node has a direct access route to the hostB node, the UDP packet received at its input will be directly broadcast to the hostB node.

Let's consider the model of accounting for mutual interference. In the previous WLAN model, idealized network operating conditions were implemented, which did not take into account such a physical phenomenon as radio wave interference, which occurs when two or more radio signals enter the input of a radio receiver, due to which they collide, distort and disrupt the normal operation of the radio signal receiver [1] . Until this moment, this effect was not taken into account, and in fact devices with full duplex communication were simulated [15]. At the same time, the OMNeT++ environment implements four basic methods of describing and presenting signals.

The first representation is called range-based. It is implemented in the IdealRadioMedium component. The advantage of this structure is compactness, predictability and high productivity. However, its drawback is that it does not accurately reflect the real behavior of the physical environment.

The second structure is a narrowband signal with a scalar signal power carrying frequency and bandwidth. Its advantage is that it allows you to calculate the signal-to-noise ratio, and in most cases it is sufficient for modeling IEEE 802.11 networks.

The third data structure defines a signal whose power is changed later. In this case, the signal power is represented by a one-dimensional clock value that precisely follows the transmitted pulses. This representation is used when modeling radio waves of the IEEE 802.15.4a UWB standard.

A fourth representation uses multivariate values to describe the power of a signal that varies with both time and frequency. This representation can be used when modeling radio waves of the IEEE 802.11b standard.

All the considered examples used the simplest physical environment model based on the IdealRadioMedium module, which uses a range representation, where the degree of signal influence on neighboring nodes depends on the distance at which they are located. When working with this module and its configuration, only three main ranges stand out.

1. Communication range – the range of reliable radio signal reception and transmission.

2. Interference Range – a range in which normal communication is no longer possible, but it still significantly affects the receivers of other devices.

3. Detection range – a range where there is no influence of the node on the receivers of other devices, but it is possible to detect the presence and operation of this device.

In order to investigate the degree of mutual influence of radio waves in the configuration file, the IdealRadioMedium component was set to an interference range with a distance of 500 m. The assigned parameters describe the fact that radio signals become weaker with distance, but there is a range in which they can no longer be correctly received, but they are still strong enough to affect other signals, resulting in reception failure.

#We allow accounting of interference in the radio receiver from the operation of neighboring nodes *.host*.wlan[*].radio.receiver.ignoreInterference = false

We make an interference range equal to the double range of communication *.host*.wlan[*].radio. transmitter.maxInterferenceRange = 500m

#Display on the scheme of the interference range of the node hostA*.hostA.wlan[0]. radio.displayInterferenceRange=true

To study this mode, the configuration file was included in the mode of registration and recording of events that occur in the model during an hour of its run. After the model was finished, report files were generated, according to which during the model's operation:

– node hostA generated 92 UDP messages of 1 KB size each;

– the UDP level of the hostA node passed 91 datagrams with a size of 1008 B;

– 89 packets with a size of 1028 B were sent to the network after passing through the MAC level;

– however, hostB received only 1 packet per 1 model time.

If we now analyze the time diagram of the registered network simulation process, we can find that only at 800 ms of the model time, one of the first messages, which was generated by the hostA node and relayed by the hostR1 node, arrived at the wlanB. hostB.udpApp(0) input. The high intensity (average hourly 10 ms) of the random generation of UDP packets by the hostA node, the presence of interference and the struggle for access to the wireless data transmission medium led to the fact that the message was sent from the hostA node to the hostB node only at the moment of a significant pause on hostA nodes. At the same time, the struggle for access to the wireless data transmission medium was conducted between hostA and hostR1 nodes, which wanted to transmit both direct and relayed UDP packets to hostB node. But if the hostB node received one of the first messages sent from the hostA node, this means that it was not lost in the network and was able to be saved somewhere. This question is answered by the graph of the dependence of time (T) on the length of the queue (L), which is formed in the buffer of the network gateway adapter hostR1, which relays packets between nodes hostA and hostB. From the figure shown in Figure 3 shows that in 1 s of model time, almost 80 packets sent by the hostA node, which the hostR1 node did not have time to relay to hostB, were stored in this buffer. Currently, the value of the maximum adapter buffer queue length is defined by default in the corresponding INET framework module. In a real wireless network, the length or size of the buffer is very important to the performance of the network, especially if this adapter is used in a device such as a gateway.

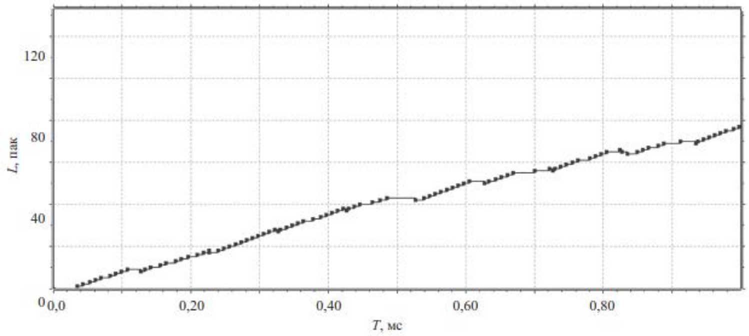


Fig. 3. Graph of the queue length in the network gateway buffer of the hostR1 node

The reasons that prevented the model of the simulated UDP packet from the hostR1 gateway buffer to reach the hostB node earlier? The answer to this question is provided by the analysis of the events registered in the network that occurred during its operation [16-19]. The time diagram of the operation of all elements for all nodes of the wireless network was considered, from which it can be seen that:

– the first packet (UDPData-0) enters the network (event #22) and after some time interval reaches nodes hostR1 (#23) and hostB (#26). Moreover, the second event occurs later, since the hostB node is located further;

– node hostB receives radio signals from node hostA (#26 – #45), but does not recognize them due to a significant distance from the transmission source;

– node hostR1 starts successfully receiving a packet from node hostA (# 23 – # 32);

– in the process of transmitting the first packet, the application wlanB.hostA.udpApp(0) (#27) generates the second UDPBasicAppData-1 message, which cannot be sent to the network. It is placed in the buffer of the network adapter and will be there until the end of the operation of the network adapter with the first packet. This moment describes event #36 and a green dashed arrow connecting it to event #27;

– node hostR1, having successfully finished receiving the first packet (#32), consults its routing table (#35). Based on it, it forwards the received packet to the hostB node and sends it to the network (#39);

– however, a little earlier (#32) node hostA started transmitting the second packet, which was previously stored in the buffer of its network adapter;

– two radio signals (#48 and #51) are received simultaneously at the receiver input of the node, which interfere with each other, preventing the hostB node from recognizing the UDP packet coming from the gateway.

Summarizing the study of the WLAN model taking into account interference from neighboring devices, it should be noted that there is a significant decrease in performance. Most of the time, the transmitting node and the gateway work at the same time, which causes two signals to arrive at the transceiver of the receiving node at once and their "collision" with each other.

This approach to the organization of wireless networks is unacceptable, and in order to reduce interference to a minimum, some access protocol to the multimedia environment is needed, which will allow determining which host has the right to transmit data and when [17, 18]. One of these protocols can be a CSMA/CA-based protocol operating at the MAC level with additional confirmations and a repetition mechanism, which in the OMNeT++ environment is implemented by the CsmaCaMac module, which, with appropriate settings, can successfully approximate the basic 802.11b Ad-Hoc mode [20–22].

Conclusions. The above studies demonstrate how simulation modeling is used in designing and studying the operation of real wireless networks. It is shown the possibility of creating simulation models of wireless networks using ready-made components from the INET framework, which help to describe various elements of the network, as well as perform their flexible configuration to simulate the required behavior.

The approach of modeling different modes of operation of wireless networks is demonstrated on the example of the implementation of direct interaction during the design of the Ad-Hoc mode, as well as the indirect one, in which the process of routing through intermediate nodes is implemented. The research in the article of such a physical phenomenon as interference made it possible to reveal the fact of the negative influence of the nodes located on each other, which worsen the quality of radio communication and can lead to a decrease in the speed of data transmission or their complete loss.

The article also demonstrates the approach of researching the operation of a wireless network by analyzing a time diagram file, the study of which allowed to explain the reason for significant delays in the relaying of network packets.

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