The methods and approaches to computer networks simulation using virtual network infrastructure

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Abstract. The article is devoted to the problem of computer networks simulation in educational process. The article examines the current state of affairs in this area. The analysis of the existing software for computer networks simulation is performed. The practical example of Cisco Packet Tracer software using for computer network simulation as part of the Computer Networks training course is provided.

1. Introduction
Computer networks are the important topic in the process of training specialists in the field of information technologies. Out of the whole variety of network technologies, students should be able to configure, manage and diagnose network failures. Laboratory works carried out using real devices allows students to acquire skills in working with equipment that they will have to deal with in their professional activities. At the same time, carrying out network laboratory classes on specialized hardware for teachers in the field of computer networks is not always possible. For the organization and carry out of laboratory works, the full range of equipment is needed (network infrastructure, switches, hubs, routers, access points), specialized laboratories, maintenance engineers, etc. The full range of equipment for each student requires a large physical space. In addition, the high cost of network hardware for universities makes it necessary to use networks simulation software when working with large groups of students or working with complex network topologies [1]. The use of virtual educational tools in laboratories that provide a virtual network configuration as real, simplifies the learning of computer networks compared to traditional teaching methods. It is optimal to use real equipment in simple cases and virtual environments in more complex ones, maximizing the advantages of both approaches [2].

Additionally, it is worth noting the fact that the need for the physical presence in the laboratory at pre-planned hours of practical training limits the capabilities of many students who potentially want to take courses on computer networks. The need to develop alternatives that allow students to get online access to laboratory hardware commonly used offline is increasing every day. The work [3] describes the transfer of the traditionally full-time course on routing and switching to online training. The solution is based on remote access via VMware View to virtualized servers. Any student enrolled in the course who has access to the Internet can authenticate with a secure server. After gaining access, the student is assigned a random virtual server in the pool. At the end of the work, the virtual server is deleted and re-created from the snapshot so that the next student receives a clean copy of the server and does not have access to the data of the previous one. As soon as a student is granted access to a virtual server, he can carry out simulations in Boson NetSim software using virtual routers, switches, terminals, and various communication protocols. After completing training in a virtual environment,
students can also access real laboratory facilities that connect onsite in the laboratory for specific topics (switches, routers, VoIP phones) and perform laboratory exercises as if they were present in the laboratory. If necessary, assistants can provide help through remote access.

Another possible solution to such problem for universities in developing countries is remote access to network educational equipment in developed countries. This solution is potentially cost-effective if the universities are in different time zones. The variant of the educational platform for students with remote access is demonstrated in [4].

Many specialized courses or programs perfectly prepare students for the use of network devices. Special mention should be made of the academic programs of Cisco Networking Academy and Juniper Networks, which include basic and intermediate courses on setting up dial-up networks, routing protocols, and security. Passing the courses offered by these and other companies will perfectly prepare for certified exams and report students in detail about the selected technology manufacturers. At the same time, there are no courses or trainings that would prepare for real work as the administrator of a complex network with a large number of mixed hardware from different manufacturers.

2. The structure of the computer network simulation course

The question arises, what should be the content of a "Computer Networks" course at a university and what knowledge a student should have after learning this subject. It is necessary to highlight the issues of architecture and management of computer networks in the process of a “Computer Networks” course learning. The following structure of a "Computer Networks" course for a university is optimal in our opinion:

- The classification of computer networks.
- The topologies of computer networks.
- Network equipment.
- The addressing in computer networks.
- The routing in computer networks.
- The wireless networks.
- Web, DNS and DHCP servers.

However, a detailed learning of all of the above topics in practice is problematic due to the fact that with a large amount of educational literature in the form of electronic publications, including on the Internet, equipment for conducting laboratory classes is expensive and unavailable in sufficient amount. Due to the high cost of network hardware, it is often impossible to create network laboratories of full value at universities, which in turn makes it difficult for students to understand a theoretical material of the course. Moreover, laboratory works are crucial in the study of a "Computer network" course. It becomes more difficult for students to understand and master the abstract concepts of computer networks, protocols and process of data packet transmission during theoretical lectures, as a network environment is becoming more and more complex [5]. At the same time, there are free software for creating virtual training tools that provides the same configuration environment as real network equipment. Such training mode not only reduces dependence on a real environment, but also helps students master complex network concepts and improve their practical working skills. For greater clarity, as practical exercises, students can model, for example, the university campus network, as shown in [6]. In particular, to eliminate intentionally introduced failures in the network, while at the same time studying in practice such concepts as NAT, VLAN, TCP / UDP protocols, packet formats, such application services as DNS, DHCP, e-mail.

Studying the routing of data packets as one of the basic processes on the Internet is very important for students. The routing protocols define the methods of communication between routers used in interconnection of networks. There are a number of routing protocols used on the Internet, such as OSPF, RIP, EIGRP, OPNET, IGRP, etc. Each protocol has its own feature of packet routing. The
comparative study of the dynamic routing protocols RIP and OSPF in virtual network environments is presented in [7, 8].

Wireless networks, unlike wired networks, are not such an established area of information technology. In the case of wireless networks, software simulators are widely used in educational and research processes to develop and test new protocols and algorithms. Since results of such modelling should be as accurate as possible, high reliability of a simulation is necessary. Thus, before choosing a modelling tool for use in the educational process, it is necessary to carry out a qualitative comparison, as was done in [9, 10] (with emphasis on CPT, OPNET Modeler, and NS2).

Simulation tools for wireless sensor networks are now increasingly being used to study sensor networks and test new applications and protocols in this growing field of research. When using simulation, there always arises the problem of the adequacy of the modelling results to the real situation. The comprehensive comparison of popular sensor networks simulators is presented in [11] in order to help in choosing the best simulator available for the specific application environment.

Wireless networks, Internet of Things (IoT) and smart homes are also becoming widespread currently. Modern infrastructure is increasingly dependent on these communications and automation technologies. To study new technologies in the field of wireless networks and IoT devices in practice, it is necessary to use software simulators. One popular example of such class of software is Cisco Packet Tracer (CPT). The example of using CPT for designing the smart home based on wireless and IoT devices with the various network scenarios demonstration is described in [12].

Wireless LANs are becoming increasingly important in public transport systems, where they are used to reduce the cost of providing new services to passengers. However, implementation of wireless interfaces in security-critical applications implies a preliminary analysis of various communication protocols and their security settings. The comparison of the proposed wireless security architecture in the large public transport system based on the Host Identification Protocol (HIP) with IPSec, tested in the real environment and in the virtual scenario, is analysed in [13]. The comparison was carried out in real conditions using commercial Wi-Fi devices. At the same time, Common Open Research Emulator (CORE) software with the expandable Ad-hoc mobile emulator (EMANE) platform was used in the virtual test bench to evaluate the same scenario. The comparison results showed that the secure wireless communication integrated into the simulation tool works similarly to the on-board public transport network.

Along with teaching the fundamental and theoretical concepts of information security, the key factor for any educational course on information security in computer networks is practical training in a virtual laboratory environment. Such an environment offers a safer and more affordable solution with which students can experiment with attack and defence methods. This is especially important for universities with limited equipment budgets. The papers [14–16] discuss the possibilities of using virtual network environments (using the example of Common Open Research Emulator and Cisco Packet Tracer) for practical training in information security. They demonstrate in practice the software capabilities, for example, to develop the practical laboratory work on filtering network traffic. It is shown that using software allows students to gain a better understanding of the basic firewalls concepts using experiments in a virtual laboratory.

3. The comparison of software for computer networks simulation

The integration of practical laboratory exercises with traditional teaching methods allows IT lecturers to improve quality of their courses by applying theoretical knowledge to real professional scenarios. Three different laboratory models are possible: implementing a physical hardware infrastructure, a combination of physical hardware and software, and a fully virtualized simulation environment.

In recent years, many new software implementations of virtualized computer network environments have been developed. Although NS-2 has previously proved itself as the standard network modelling tool, today other network simulators are attracting more and more attention. However, these software tools are often difficult to configure and maintain, for example, in university lab settings. The issues of evaluating modern software tools for network emulation for use in computer
network simulation courses and in research projects are raised in [17]. Particular attention in the assessment process is paid to scalability for a large number of students, low administrative and financial costs, low downtime and compliance with educational requirements. One of the criteria when choosing the network simulation tool can be considered a performance comparison by implementing the same simulation settings in several simulators. The results show large differences both in performance at runtime and in memory use generally [18, 19].

In the process of choosing the virtualized environment, it is necessary to evaluate models of virtual laboratories and compare them in terms of functionality. The simulation variants for the same network configurations in GNS3 and CPT software are presented in [20-22]. In these studies, the software are compared according to various criteria, their advantages and disadvantages are determined. Depending on the goals facing the course lecturers, conclusions are drawn about the advantage of a particular software or the need for their combination in the learning process.

OMNeT ++, the discrete event simulation package designed to simulate computer networks and other distributed systems, was presented in [23]. OMNeT ++ has the modular structure and API. It was designed from the ground up to support the very large networks simulation. Much attention in its development process was paid to simulation models monitoring and debugging. These features make OMNeT ++ well suited for research and educational purposes. OMNeT ++ simulation engine can be easily integrated into other applications. OMNeT ++ source code is open and free for non-commercial use and has a fairly large user community.

The work [24] presents the capabilities of the EVE-NG environment for modelling of the large complex topology network, which can be used in the process of studying and gaining experience in setting up and maintaining large computer networks based on hardware from various manufacturers.

The issues of using Marionnet software for similar purposes are discussed in [25, 26]. The software package is quite actively used in the educational process at various universities around the world.

In order to choose the right software product for our laboratory works, we analysed computer networks simulators and emulators: Cisco Packet Tracer, EVE-NG, GNS 3, Boson NetSim, NS-3, OMNeT ++, Common Open Research Emulator, Psimulator 2, Marionnet. The choice of software for modelling computer networks was carried out on the basis of the following criteria:

1. The availability of a tool for creating patterns of network architecture that could be used to develop topics.
2. The ability to integrate with a real network.
3. The ability to simulate wireless networks.
4. The ability to simulate IoT.
5. The free distribution or availability of a free version.
6. The simultaneous support for Linux and Windows family operating systems.
7. The low software requirements for system resources.
8. The intuitive graphical interface.

As the result of the analysis (shown in table 1), it was decided that, taking into account our goals and application possibilities in university environment, Cisco Packet Tracer will be the most rational. In addition to meeting most of the criteria we have identified, the software for computer network simulation, in our opinion, has a much simpler interface with sufficient functionality than other alternative software.

As the results of the student surveys conducted at the end of the network simulation courses show [27], the use of the software helps them understand the key concepts of computer networks in practice, and not just as abstract terms.
4. Cisco Packet Tracer Software

The capabilities of Cisco Packet Tracer provide a practical learning of all the topics and directions described earlier. The software implements the ability to simulate both local and wide area networks. The opportunity of creating separate classrooms, buildings, cities, etc., with the possibility of moving from a small segment to the network as a whole, is used. This allows students to compactly place in the single work area a large number of network segments, which facilitates the work in the future. Consider the possibilities of using Cisco Packet Tracer to explore topics related to our networking course.

The topics “The classification of computer networks” and “The topologies of computer networks” imply the use of such hardware as laboratory equipment: a personal computer, a network cable, a switch (hub), server equipment. The use of real equipment, as mentioned above, is not always possible. Cisco Packet Tracer has all the necessary components for such purpose. A whole group of devices called «End Devices» can be used for simulation computer, laptop, printer, phone, TV, etc. The group of components for modelling connecting cables is “Connections”. It contains all the standard cables needed to connect all the necessary devices to a network. In separate groups, devices such as a hub – «Hubs» and devices like a switch – «Switches» are allocated.

The topic "Network equipment" is very extensive in terms of equipment use. These include end devices, patch cables, switching equipment, and server hardware. Cisco Packet Tracer software has all the necessary equipment for learning this topic.

The topic “The addressing in computer networks” does not imply the use of any specific equipment in the laboratory works. The work here is more focused on performing various calculations related to the network address, host address, and subnet mask. In this regard, the laboratory work on this topic can be carried out, in fact, in any unequipped laboratory. But for a more accurate understanding of addressing, it is necessary not only to learn how to perform certain calculations, but also to understand how to apply the data in practice. For this purpose, Cisco Packet Tracer can build a network using a different number of segments interconnected by switches. You can also configure static and dynamic packet routing between network segments.

When teaching the topic “The routing in computer networks”, lecturers are faced with the problem of demonstrating how to move a packet from network to network. To view the path, students can use a special software to determine the route. In the Microsoft Windows operating system, such software is called “tracert”. But using such software students see only the addresses of routers that the data packet pass through in sequence. However, they cannot get information about where these routers are located.

### Table 1. The comparison of the network simulation software.

| The criterion | Cisco Packet Tracer | Common Open Research Emulator | EVE-NG | GNS 3 | Marionnet | Boson NetSim | NS-3 | OMNET++ | Psimulator 2 |
|---------------|---------------------|-------------------------------|--------|-------|-----------|--------------|------|---------|--------------|
| 1             | +                   | +                             | +      | +     | –         | +            | +    | +       | +            |
| 2             | +                   | –                             | +      | –     | –         | –            | –    | +       | +            |
| 3             | +                   | –                             | –      | –     | –         | –            | –    | –       | –            |
| 4             | +                   | –                             | –      | –     | –         | –            | –    | –       | –            |
| 5             | +                   | +                             | +      | –     | –         | +            | +    | +       | +            |
| 6             | +                   | –                             | +      | +     | –         | +            | +    | +       | +            |
| 7             | –                   | +                             | +      | +     | –         | –            | –    | –       | –            |
| 8             | +                   | +                             | –      | –     | +         | +            | +    | +       | +            |
and how they are interconnected. Therefore, such method does not allow to understand the full picture of the network structure.

In Cisco Packet Tracer, the special “Simulation” mode is implemented to view the packet route. If students switch to this mode and send a data packet from one network device to another, the software in real time will visually display the movement of the packet between routers and network devices. If at some step the data packet cannot be sent further, the software will show it visually.

In connection with the distribution of portable computer technology the learning of the topic "The wireless networks" requires a lot of attention. A full study of the topic without the special equipment use is impossible. Although at present almost every student has a smartphone with the ability to wireless connection that is not enough to fully understand the principle of wireless networks operation. Cisco Packet Tracer contains special components for modelling wireless network devices connection, and it is also possible to visually see the packet transmission order within the wireless network, which is an undoubted plus.

Learning the topic “Web, DNS and DHCP servers” requires the presence of all these servers. This is necessary due to the fact that it is not possible to show the principle of operation and configuration of a server on one stationary computer. Cisco Packet Tracer has created a special “Server-PT” component for this purpose. The ability to use one component to create multiple devices is implemented using roles. By enabling or disabling the corresponding roles, students can activate or deactivate the corresponding server.

5. The network simulation examples using Cisco Packet Tracer
Here is the example of Cisco Packet Tracer using to solve the specific task from the training course - modelling a network using given input data.

The university has 2 laboratories, let us call them conditionally Laboratory 1 and Laboratory 2. Each laboratory has its own separate subnet with its own router (conditionally, Router 1 and Router 2) and the DHCP server. Researchers of each of the laboratories should be able to wirelessly access the network using Wi-Fi technology, while devices connected via the wireless connection must be on the same subnet as devices connected via the wired connection. The university also has the separate router (conditionally Router 3), which provides access to the Internet. The routers of each laboratory are connected to Router 3 through different subnets with static addressing. In the separate subnet connected to Router 3, there is the DNS server that stores the record about the test.edu resource located on the network accessible to Router 3. Also, when designing the network, all server equipment must have static addressing.

The networks settings
Laboratory 1
Network Address: 172.16.7.0/24
Router IP Address: 172.16.7.1
DHCP Server IP: 172.16.7.2
All user computers on the network receive automatic network settings from the DHCP server. The entire subnet is used.

Laboratory 2
Network Address: 172.16.8.0/24
Router IP Address: 172.16.8.1
DHCP Server IP: 172.16.8.2
All user computers on the network receive automatic network settings from the DHCP server. The entire subnet is used.

The network “Router 1, Router 2, Router 3”
Network Address: 172.16.10.0/24
Router 1: 172.16.10.1
Router 2: 172.16.10.2
Router 3: 172.16.10.3
The network “Router 3 - DNS Server”
Network Address: 172.16.11.0/24
Router 3: 172.16.11.1
DNS server: 172.16.11.2

The network “Router 3 - Web Server of test.edu”
Network Address: 81.1.253.0/24
Router 3: 81.1.253.1
Resource test.edu: 81.1.253.2

When building a network, students should ensure the availability of devices between both laboratories. All devices also need access to the test.edu resource.

For modeling laboratories and demonstrating network functioning, in addition to the main equipment, one or two devices with wired connection and one device with wireless connection are enough. In this example, for each laboratory we will use 2 additional wired devices and one wireless.

Based on the task’s conditions for the implementation of Laboratory 1 model, we need one router, one switch, 2 personal computers, one access point for wireless network and one laptop with wireless Wi-Fi interface. We make all equipment settings according to the task requirement. The general view of the implementation in Cisco Packet Tracer program is as follows.

The network parameters for the main devices are written in the figure for a better understanding. Personal computers receive all network settings from DHCP server.

In the same way, we model the Laboratory 2 network.
Then it remains to simulate the remaining network with the devices specified in the task.

Figure 2. The Laboratory 2 Subnet

After connecting the devices, students need to make all the settings in the model. The software implements the ability to perform settings using both the visual interface and the command line. A
regular user uses the visual interface to configure parameters while working at a computer, and a system administrator often resorts to command line interface (CLI) when working with a router. In this regard, such feature of the software is a big deal.

After completing all the settings, it remains to check the network performance. As mentioned above, to check the network’s operability, the software has visual interface that allows sending packets from one device to another, which makes the process of implementing a computer network model even more visual.

The result indicating the operability of this network model is the fulfilment of two criteria. The first criterion is the availability of computers in the second laboratory from the subnet of the first and vice versa. The second criterion is the availability of the site test.edu by domain name from the networks of both laboratories.

To verify the possibility of transferring data between networks, students can use the visualization of sending a packet from device to device. For each shipment, students should get the “Successful” result.

![Figure 4. The confirm of the device availability](image)

This indicates that the devices are available.

To check the availability of the site test.edu, students should run the command “ping test.edu” from the command line of each device. We give the result of one check. All the rest are similar.

![Figure 5. The confirmation of the site availability](image)

It is shown that in Cisco Packet Tracer software, students can create a clear network model.

6. Conclusion
The practice of carrying out laboratory classes on computer network modelling using Cisco Packet Tracer software showed that its capabilities are sufficient to fully cover the needs for using specialized laboratories and equipment. It is proved that for practical training it is enough to have a laboratory equipped with computers running the Microsoft Windows operating system. Thus, the use of Cisco Packet Tracer program makes it possible for students to perform laboratory work not only in the classroom, but also at home, which is an indisputable advantage in organizing students' independent work.

One of the options for further development of the computer network modelling course is a combination of Cisco Packet Tracer software capabilities with Moodle e-learning platform. The API of this e-learning system is open and third-party developers can expand its functionality by writing additional modules. In particular, the PTActivity module that integrates Cisco Packet Tracer with the Moodle platform is described in [28].
Acknowledgments
The overview of the state of the art and network modelling software tools was carried out under state contract with ICMMG SB RAS 0315-2019-0006.

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