Enhancing Internet of Things conceptual, practical and programming learning skills

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Abstract. *The Internet of Things (IoT) is a computational paradigm that facilitates the interconnection of intelligent objects to the Internet, enabling interaction, operational efficiency, and communication. Moreover, it allows the collection of various environmental data, which can be processed to develop applications for diverse uses, such as e-health and smart agriculture. Therefore, due to the significant technological advancements and their continuous development and improvement, it is crucial to utilize alternative platforms for teaching and learning these technologies. These platforms should aim to enhance understanding and facilitate application development within these ecosystems. Utilizing tools for simulating or emulating IoT environments can facilitate practice, provide hands-on experience, reduce costs, and enhance agility in creating teaching proposals. This paper analyzes tools and platforms that aid in learning and developing IoT concepts and networks. Specifically, it discusses Internet of Things concepts and tools for simulating or emulating widely used environments.*

1. Introduction

The Internet of Things (IoT) has emerged as a transformative computational paradigm. It facilitates the seamless integration of a range of heterogeneous systems, fostering a ubiquitous network connecting data, people, objects, and applications through the power of the Internet [Atzori et al. 2010, Lin et al. 2017, Santos et al. 2018, Allioui and Mourdi 2023]. This paradigm unlocks the potential for developing intelligent and interconnected systems, enabling them to collect and exchange data across various environments. By leveraging sophisticated data analysis techniques and cutting-edge artificial intelligence (AI) technologies, the IoT paves the way for creating novel applications that enhance functionalities and drive advancements in various domains. The concept of IoT emerged in 1999 at the Massachusetts Institute of Technology (MIT) labs through RFID surveys sponsored by Kelvin Ashton, co-founder of Auto-ID [van Kranenburg and Dodson 2008].

The applications of IoT are highly diversified, with key and extensively debated areas including smart homes [Facchinetti et al. 2023], smart cities [Pandiyan et al. 2023], smart agriculture [Koshariya et al. 2023], and smart grids [Giannelos et al. 2023]. However, these applications also present several challenges for the community, including:

- **Scalability:** The number of devices can increase dramatically in a very short period, requiring systems to handle this growth seamlessly;
- **Big Data:** IoT entails massive data gathering, processing, and storage;
- **Network:** Most IoT applications require a constant Internet connection;
- **Software:** IoT demands diverse and intelligent applications;
- **Data Engineering:** Specialized professionals are needed to manage a large amount of data and leverage its potential effectively;
- **Analytics:** Performing real-time analytics with a high volume of data can be challenging.

Building large-scale network architectures, such as IoT ecosystems, poses a significant challenge for developers due to the complexity involved. Simulators and emulators play a crucial role in rapidly prototyping these infrastructures for real-time testing and task analysis. They also facilitate unit and integration testing to evaluate network performance.

A practical methodology for IoT teaching and learning involves using free simulators. One such example is the *Cisco Packet Tracer*, which, since its version 7, allows for IoT environment simulation and supports scenarios like *Smart City*, *Power Grid*, *Smart Industrial*, and *Smart Homes*. This enables the acquisition and improvement of skills required for programming and application development. Other tools available in the market for simulating IoT environments include Cooja Contiki, Ominet++, Netsim Pro, and Opnet. Cooja Contiki, in particular, provides a high-level abstraction simulation framework, allowing simulations at different hierarchies and integration between multiple layers in a single experiment [Zhang and Li 2014].

This paper focuses on presenting a perception of how a simulator may be used to facilitate the learning of IoT concepts and developments in a practical manner and without purchase costs, eliminating the need to purchase expensive hardware for prototyping, and shows their use in some simple tasks, demonstrating versatility, ease of use, and implementation cost. In addition, it presents a survey carried out in a laboratory that uses simulation tools to teach concepts of computer networks and IoT.

1. Present concepts of the Internet of Things;
2. Present some simulations using the Cisco Packet Tracer tool;
3. Present the applicability and demonstrate how the tools for simulation of IoT environments can be applied simply and practically for teaching complex contents;
4. Present results of an evaluation of the use of simulation tools in the teaching of computer networks and the Internet of Things in laboratories;
5. Present the results of a questionnaire in computer networks teaching associated with IoT.

2. Related Work

Literature has explored the use of simulation tools for very specific teaching purposes [Yen 2014, De la Torre et al. 2021, Lei et al. 2022]. Some studies also analyze the intersection of IoT and education [Dantas et al. 2018]. Notable examples of educational uses of Cisco Packet Tracer are seen in [Vijayalakshmi et al. 2016, Gwangwava et al. 2021], where authors employed it as a pedagogical tool for teaching computer network concepts. However, these did not utilize some resources present in the latest version of the tool, that is at the forefront of computing development. Other studies [Dumitrache et al. 2017, Obelovska et al. 2022] focused on the Cisco Packet Tracer, presenting a comparative study of routing protocols but did not delve into IoT concepts.

In a different vein, [Stanley et al. 2012] utilized simulation tools for teaching computer architecture, focusing on logical simulations for computer design. They demonstrated the effectiveness of simulation tools in fostering a deeper understanding of intricate concepts within computer architecture, particularly the internal workings of instructions and data flow control paths. However, their work primarily focuses on the individual processor level, excluding the intricacies of computer networks that encompassing interconnected systems and communication protocols. In [Cristian et al. 2023], authors simulate several Internet of Everything (IoE) scenarios. The paper uses a variety of Cisco components to simulate some network components functions. Even though this paper considers IoE, the authors do not consider it in an educational scenario to evaluate the teaching concept to students.

Another example is found in [Korman and Johnston 2013], where the authors describe the development and implementation of a teaching tool called "Construction Industry Simulation" (COINS) at California Polytechnic State University. This tool aimed to prepare students for engineering or software architecture careers without a direct focus on computer networks. In [Moz et al. 2023], authors have highlighted the increasing digitization of communication and the importance of updating skills to keep pace with technology. Their research focuses on developing a secure and stable campus network, proposing a topology for multiple networks and VLANs using Cisco Packet Tracer.

Unlike the aforementioned works, our research takes an educational perspective, focusing on enabling students to learn computer network and IoT concepts through simulation tools. We analyze students' feedback regarding these simulation environments to assess their effectiveness as educational tools.

3. Use of Free Tools for IoT Simulation

This section presents some valuable tools that enable IoT simulations in a variety of environments, with a focus on the Cisco Packet Tracer.

3.1. Cisco Packet Tracer Analysis

Cisco Packet Tracer (PT) is utilized as a teaching and learning tool to present diverse concepts of computer networks, including networks with a high degree of complexity. It also complements Cisco equipment in laboratories. This academic software supports multi-user functionalities, enabling a community learning model that allows interaction in physical and logical environments.

The simulator's logical environment (see Fig. 1) allows the creation of network topologies by connecting devices in a virtual network. The physical environment (also in Fig. 1) provides a scalable view of the environment as a whole, creating a generic representation of the real world, including device location, distance, and positioning.

The physical environment feature in Cisco Packet Tracer offers a geographic view of the network implementation, resembling a blueprint that allows for several levels of hierarchy, such as city and office.

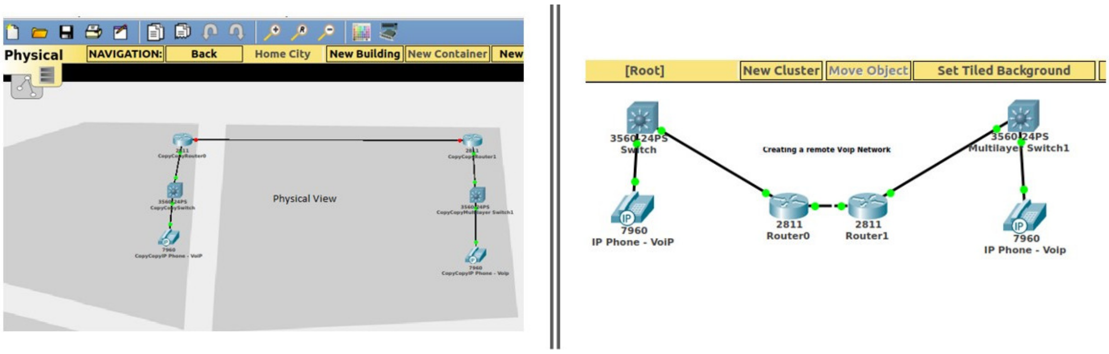

Figure 1. Simulator's Physical and Logical Environments - VoIP Example

3.2. Supported Protocols

The Packet Tracer enables interaction with many protocols, simulating real network scenarios. Table 1 shows the main protocols supported by the simulator and their respective layers.

Table 1. Packet Tracer supported Protocols.

LAYERS	Main Protocols
APPLICATION	FTP, SMTP, POP3, HTTP, TFTP, Telnet, SSH.
TRANSPORT	TCP e UDP, TCP Nagle Algorithm, RTP.
NETWORK	BGP, IPv4, ICMP, ARP, IPv6, ICMPv6, IPSec.
LINK	Ethernet (802.3), 802.11, HDLC, Frame Relay.

The protocol stack presented in the table allows for the development and teaching of various concepts associated with computer networks. These protocols enable students to design and develop complex computer topologies in a variety of ways.

Since version 7, the most recent versions of PT enable programming for IoT prototyping using components such as those listed in Table 2. These components facilitate the development of various environments that play an essential role in IoT usage.

Table 2. Components of the simulator

Components	Caracteristics
MCU board	Microcontroler Board
SBC Board	Single Board Computers
Things	Connectable physical objects
Actuators	Components to manipulate the Environment
Sensors	Components for perception of the Environment
IoT registers	Gateway or Register Server

An implementation example is shown in Figure 2, where two actuators connected to the microcontroller (MCU-PT) are present and connected to the Home Gateway. The smartphone allows for the visualization of the devices' status on the Internet, either using a browser or the IoE Monitor (Internet of Everything Monitor - available in the tool).

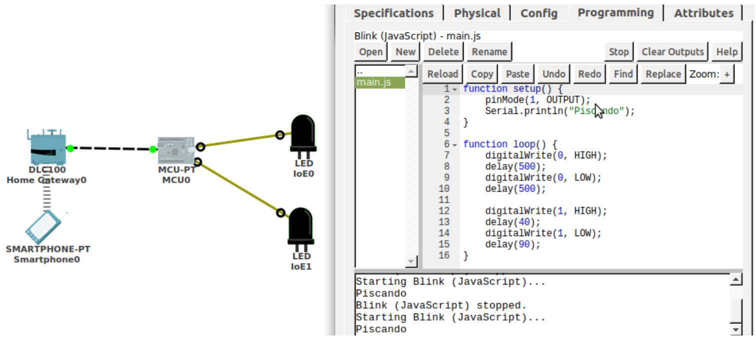

Figure 2. Javascript usage example in Packet Tracer

The ability to simulate IoT environments in Cisco Packet Tracer enables users to initiate or enhance their device programming skills by developing various applications. Furthermore, users can develop simulations using Python and JavaScript, as well as utilize HTML for creating web pages. This provides a wide range of possibilities for developing applications for diverse purposes.

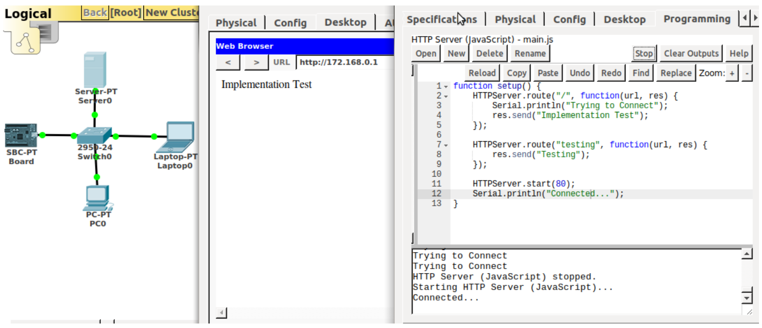

Figure 3. Programming Example

Figure 3 illustrates an example of an implemented function that initializes the server (port 80) and displays the phrase “Implementation test” upon connection. This figure demonstrates integration with the browser through direct implementation on the SBC Board. In Figure 4, two LEDs are connected to two Single-Board Computers (SBCs). After activating the simulation, users can verify that the devices are active and accessible on the Internet via the address 125.125.125.2. This allows users to interact with and visualize the status of the LEDs remotely.

3.3. OMNeT++

OMNeT++ is an open-source, modular discrete event simulator developed primarily in C++ with robust graphical user interface (GUI) support. It caters to various application domains, including Vehicular Ad-hoc Networks (VANETs), Mobile Ad-hoc Networks (MANETs), mesh networks, internetworking, queuing systems, and performance evaluation. OMNeT++ provides features such as extensions for real-time simulation, use of alternative languages (Java, for example), and database communication OMNeT++ offers valuable features such as:

- **Real-time simulation extensions**: Enables the simulation to run in lockstep with real-time systems, allowing for real-time protocols and systems validation.

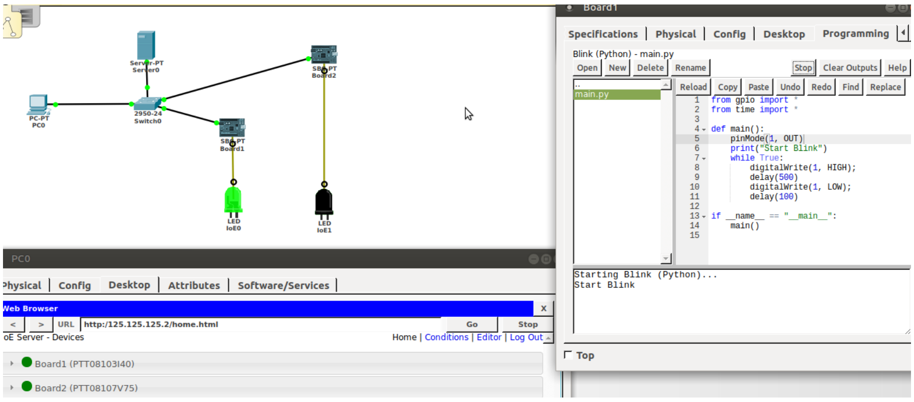

Figure 4. Programming usage example

- **Alternative language support**: Provides the capability to integrate components written in languages like Java, extending the tool's functionality and leveraging the strengths of different programming paradigms.
- **Database communication**: Facilitates interaction with various database systems, enabling the storage and retrieval of simulation data for further analysis.

A fundamental feature of this simulator is that it was developed based on Eclipse, a well-known IDE that is widely used in academic and professional settings. This allows easy creation of new packages to extend the tool's functionalities. The main parts of OMNeT++ simulation models can be summarized in:

- **INET Framework:** Comprised of the standard protocols of the simulator, such as TCP, UDP, IPv4, IPv6, and BGP protocol stacks. It has support for mobility, DiffServ, MPLS, and data link protocols (e.g., IEEE 802.11);
- **Castalia:** Simulator focusing WSN (Wireless Sensor Networks), BAN (Body Area Network), and low power components - IoT devices, for instance -which allows the development of parametric simulations for radio communication, promoting realistic processing, data loss analysis, and data visualization.

3.4. Cooja Contiki

Developed at the Swedish Institute of Computer Science (SICS), Cooja Contiki is a free and open-source simulation platform designed explicitly for Wireless Sensor Networks (WSNs). It leverages the Contiki Operating System (OS), written in C, which focuses on resource-constrained devices and accurately replicates memory limitations typically encountered in IoT scenarios.

Cooja Contiki is a two-layered system:

- **uIP layer**: This layer implements basic networking protocols like TCP/IP and UDP/IP, tailored for resource-constrained devices.
- **Rime layer**: This layer handles low-level communication tasks like media access control (MAC) and network access layer (NAL) protocols, providing efficient communication over wireless channels.

Cooja, the simulation environment, is developed in Java but enables integrated development alongside the C-based Contiki OS. This integration fosters a seamless user experience and allows developers to combine the strengths of both languages in their simulations. Due to its focus on WSNs and its tight coupling with the Contiki OS, Cooja Contiki is particularly well-suited for simulating resource-constrained IoT networks and is available online for download. While it can technically function independently, using Cooja Contiki in conjunction with VMware Player can offer additional benefits, such as facilitating the simulation of various network environments and operating systems.

4. Architecture and Simulation

In IoT, a broad range of applications can be developed. Among them are residential monitoring, advanced security systems, energy network operation, and road traffic analysis.

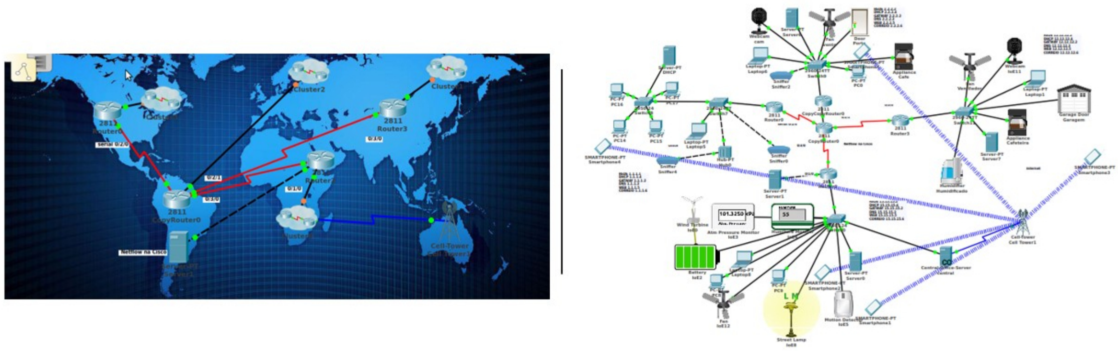

Figure 5. IoT Simulation on Cisco Packet Tracer

This simulation (see Fig. 5) shows the device registration through the server. The programming was performed directly on the inserted devices (things). The figure is a superficial demonstration without the advanced components of a *Smart City*, in which several interactions occur, in addition to the components communicating via 4G cellular, local Wireless, and local wired networks. Also, this simulation includes the presence of the *Smart Home*, *Smart City*, and *Smart Energy* components of the simulator, all communicating and enabling interaction through the Internet. Additionally, Cisco Packet Tracer 7 simulations allow the user to implement the behavior in two ways, either through the device or through the boards (MCU or SBC).

If the presented environment is overloaded with objects, as in Figure 5, separate *Clusters* can be created. These enable the user to relocate selected devices from a particular network into a separate environment, making the visualization more enjoyable and less visually overloaded. An example of using clusters is also performed and presented in Fig. 5.

5. Methodology and Evaluation

This section presents the evaluation and results regarding the use of computer network simulation tools focused on teaching IoT concepts and their programming. The evaluation was performed through an electronic form filled out by students and professors in STEM (Science, Technology, Engineering, and Mathematics).

5.1. Evaluated Tools and Questionnaire Used

An electronic form was developed to evaluate the capacities of IoT network simulation and emulation tools for knowledge acquisition and programming. The form was sent to students and faculty in STEM courses, either those who use such tools frequently or not. At the end of the application of the form, which lasted a week, relevant information about the experiences developed was gathered. The questions used in the form are synthesized in Table 3.

Table 3. Synthesis of the questionnaire used for information gathering

Page	Topic	Gathered data
1	User	Education, contacts and additional data
2	IoT	Fundamentals, applications and prototiping
3	Cisco Packet Tracer	General usage and IoT usage
4	Netsim	General usage and IoT usage
5	Omnet++	General usage and IoT usage
6	Cooja Contiki	General usage and IoT usage

The participants answered questions about users, network fundamentals, IoT, and some general-purpose simulation/emulation tools, covering a 6-page form. The group of participants was formed by students and faculty from various educational institutions - both public and private - from Portugal and Brazil.

5.2. Evaluation and Results

The participants in the evaluation primarily consisted of students and faculty from Computer Science courses. Figure 6 illustrates the distribution of the 32 participants (1 professor, 21 students, and 10 former students) according to their education level: High School, Incomplete Superior Academic (undergraduate student), Higher Education Complete (bachelor), Master in progress (graduate student), and Master's degree holders. It also shows the distribution of participants according to their disciplines, with Computer Science being the most mentioned course. At the same time, Digital Media and Systems and Analysis and Systems Development had fewer mentions.

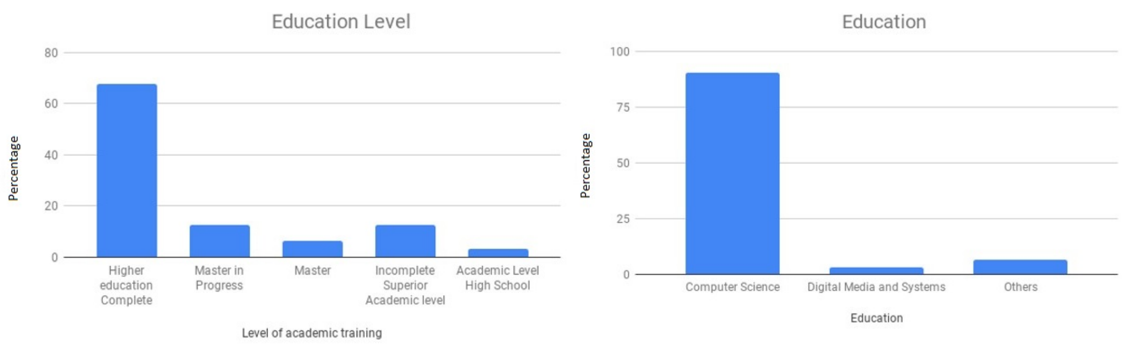

Figure 6. Participants' Education

The analysis of Figure 7 reveals that 81.2% of the participants believe IoT should be integrated into their curriculum as a primary discipline course. Regarding the use of the Cisco Packet Tracer tool for simulating IoT, 43.8% of the respondents reported previous use, while 46.9% had not. Interestingly, only 37.5% of those used Cisco Packet Tracer version 7 or newer to simulate IoT devices with device programming. Among these participants, 96.9% considered themselves to have adequate technical knowledge of IoT.

The results indicate a significant improvement in students' learning of IoT concepts and simulation of smart environments through the use of the Cisco Packet Tracer tool. The implemented practices resulted in substantial knowledge acquisition among participants.

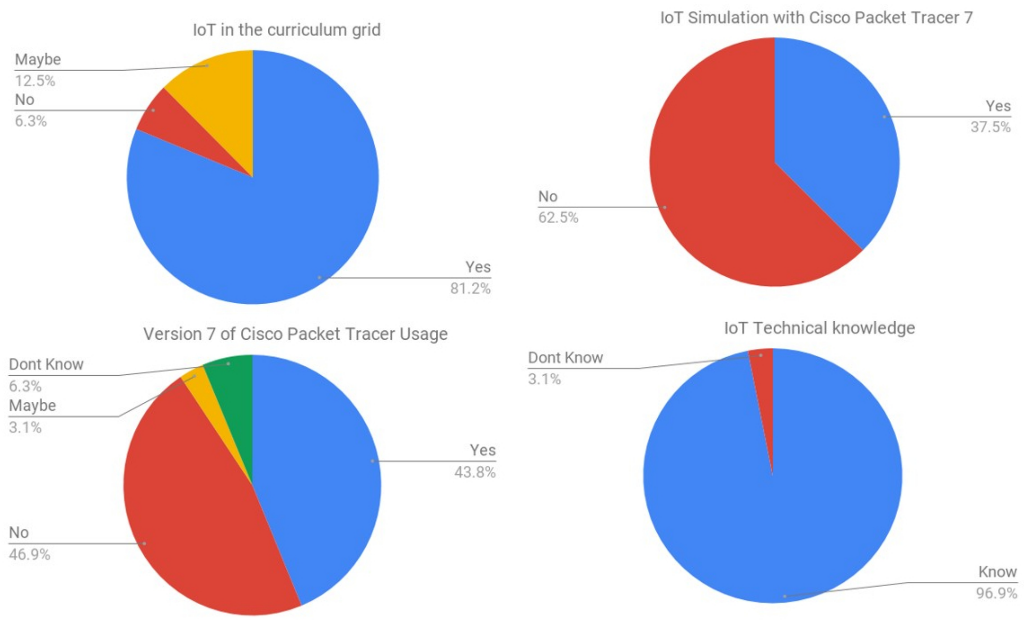

Figure 7. Participants answers synthesis

Participants were also asked about their previous knowledge or use of other popular tools for learning computer networks and IoT, such as Netsim, OMNeT++, and Cooja Contiki. As shown in Figure 8, few participants were familiar with these tools, while most participants knew Cisco Packet Tracer, and some had never used any of the tools. Participants who had used the tools for IoT were asked to rate the tool (on a range from 0 to 10, with 10 being the highest score) regarding its suitability for learning IoT concepts and programming. 75% of the respondents rated the tool 8 or higher.

5.3. Satisfaction and Perceived Relevance

The survey delved into the participants' satisfaction with using the tool for IoT simulation. Nearly all users with experience with it recommended its application in laboratory settings, emphasizing its practicality and user-friendliness.

Furthermore, participants discussed the tool's perceived relevance in teaching computer network concepts. They noted that the Cisco Packet Tracer enhances absorption and understanding of these concepts through hands-on practice.

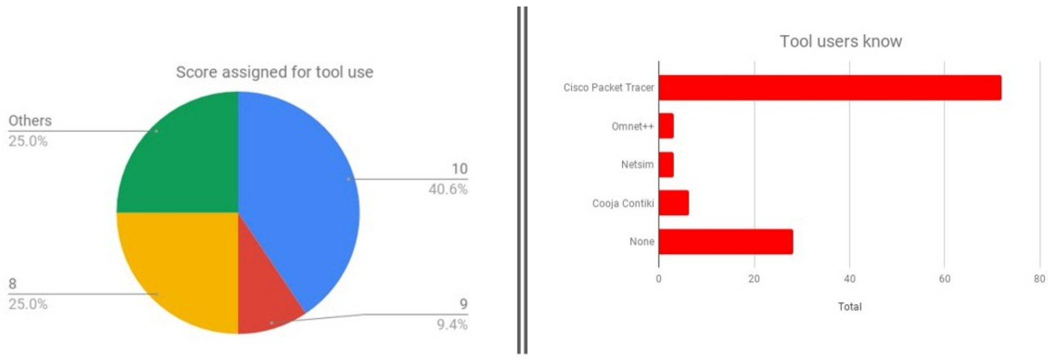

Figure 8. Evaluation of other tools used

5.4. Integration in Learning Process

Simulation tools offer various advantages in the learning process, especially when acquiring new hardware is cost-prohibitive. Some instructors purposefully integrate simulation tools as supplementary resources in their teaching. This approach aligns with the course's original objectives and often involves designing and implementing automated evaluations of learning.

Given participants' recognition of Cisco Packet Tracer's pivotal role in developing skills and understanding IoT environments, it is essential to integrate this tool and its methodologies into the classroom environment for enhanced engagement and learning.

6. Lessons Learned

This study underscores the widespread use of simulation tools for teaching computer network concepts, particularly in the context of IoT education. The increasing importance of IoT in academia is evident. This study's participants, including students and faculty, expressed a growing need for IoT-focused classes in network-related courses, given the prevalence of this computational paradigm in modern life. The results demonstrate the effectiveness of using simulation tools for learning IoT concepts, which are much cheaper for institutions that already have computer laboratories.

An interesting future work would be a specific evaluation of the opinion and experience of computer network professors (only one such professor participated in this survey), which can give more insights into implementing IoT-related practices. Another future work would be the evaluation of IoT learning among IT professionals who work with IoT (design and development), which could give further insight into which teaching approaches could be more effective for future professionals in the field.

References

Allioui, H. and Mourdi, Y. (2023). Exploring the full potentials of iot for better financial growth and stability: A comprehensive survey. *Sensors*, 23(19):8015.

Atzori, L., Iera, A., and Morabito, G. (2010). The internet of things: A survey. *Computer Networks*, 54(15):2787 – 2805.

Cristian, S., Georgian, A. F., Gabriel, P., Denisa, C. L., Nicoleta, A., and Constantin, P. D. (2023). Ioe simulation with cisco packet tracer. In *2023 15th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, pages 01–06.

Dantas, Á. M. C., Viana, H., Abijaude, J., and Sobreira, P. (2018). Internet das coisas e aprendizagem colaborativa: Revisão sistemática da literatura. In *Brazilian Symposium on Computers in Education (Simpósio Brasileiro de Informática na Educação-SBIE)*, volume 29, page 278.

De la Torre, R., Onggo, B. S., Corlu, C. G., Nogal, M., and Juan, A. A. (2021). The role of simulation and serious games in teaching concepts on circular economy and sustainable energy. *Energies*, 14(4):1138.

Dumitrache, C. G., Predusca, G., Circiumarescu, L. D., Angelescu, N., and Puchianu, D. C. (2017). Comparative study of rip, ospf and eigrp protocols using cisco packet tracer. In *2017 5th International Symposium on Electrical and Electronics Engineering (ISEEE)*, pages 1–6.

Facchinetti, G., Petrucci, G., Albanesi, B., De Marinis, M. G., and Piredda, M. (2023). Can smart home technologies help older adults manage their chronic condition? a systematic literature review. *International Journal of Environmental Research and Public Health*, 20(2):1205.

Giannelos, S., Borozan, S., Aunedi, M., Zhang, X., Ameli, H., Pudjianto, D., Konstantelos, I., and Strbac, G. (2023). Modelling smart grid technologies in optimisation problems for electricity grids. *Energies*, 16(13):5088.

Gwangwava, N., Mubvirwi, T. B., et al. (2021). Design and simulation of iot systems using the cisco packet tracer. *Advances in Internet of Things*, 11(02):59.

Korman, T. M. and Johnston, H. (2013). Using game-based learning and simulations to enhance engineering and management education. In *2013 IEEE Frontiers in Education Conference (FIE)*, pages 701–703.

Koshariya, A. K., Kalaiyarasi, D., Jovith, A. A., Sivakami, T., Hasan, D. S., and Boopathi, S. (2023). Ai-enabled iot and wsn-integrated smart agriculture system. In *Artificial Intelligence Tools and Technologies for Smart Farming and Agriculture Practices*, pages 200–218. IGI Global.

Lei, Y.-Y., Zhu, L., Sa, Y. T. R., and Cui, X.-S. (2022). Effects of high-fidelity simulation teaching on nursing students' knowledge, professional skills and clinical ability: A meta-analysis and systematic review. *Nurse education in practice*, 60:103306.

Lin, J., Yu, W., Zhang, N., Yang, X., Zhang, H., and Zhao, W. (2017). A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications. *IEEE Internet of Things Journal*, 4(5):1125–1142.

Moz, S. H., Hosen, M. A., and Tanny, N. F. I. (2023). Campus network configuration, monitoring and data flow simulation using cisco packet tracer. In *2023 International Conference on Inventive Computation Technologies (ICICT)*, pages 793–798. IEEE.

Obelovska, K., Kozak, I., and Snaichuk, Y. (2022). Analysis and comparison of routing and switching processes in campus area networks using cisco packet tracer. In *The International Symposium on Computer Science, Digital Economy and Intelligent Systems*, pages 100–110. Springer.

Pandiyan, P., Saravanan, S., Usha, K., Kannadasan, R., Alsharif, M. H., and Kim, M.-K. (2023). Technological advancements toward smart energy management in smart cities. *Energy Reports*, 10:648–677.

Santos, M. R. P., Andrade, R. M. C., Gomes, D. G., and Callado, A. C. (2018). An efficient approach for device identification and traffic classification in iot ecosystems. In *2018 IEEE Symposium on Computers and Communications (ISCC)*, pages 00304–00309.

Stanley, T., Chetty, V., Styles, M., Jung, S.-Y., Duarte, F., Lee, T.-W. J., Gunter, M., and Fife, L. (2012). Teaching computer architecture through simulation: (a brief evaluation of cpu simulators). *J. Comput. Sci. Coll.*, 27(4):37–44.

van Kranenburg, R. and Dodson, S. (2008). *The Internet of Things: A Critique of Ambient Technology and the All-seeing Network of RFID*. Network notebooks. Institute of Network Cultures.

Vijayalakshmi, M., Desai, P., and Raikar, M. M. (2016). Packet tracer simulation tool as pedagogy to enhance learning of computer network concepts. In *2016 IEEE 4th International Conference on MOOCs, Innovation and Technology in Education (MITE)*, pages 71–76.

Yen, Y. R. (2014). Simulation-based training improves catering apprentices' mise-en-place knowledge and procedure skills. In *2014 IEEE 14th International Conference on Advanced Learning Technologies*, pages 240–241.

Zhang, T. and Li, X. (2014). Evaluating and analyzing the performance of rpl in contiki. *Proceedings of the International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, 2014.