# Exploring the Usability of Network Simulation Tools

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# Declaration

This work has not been previously accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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# Abstract

Current network simulation tools provide advanced simulation solutions that cut down on costs and provide a simpler way to test different scenarios and mitigate risks before actual deployment. However, many of these tools still possess several shortcomings that hinder their widespread adoption and usability. These limitations encompass their static nature, which lacks the capacity to accommodate dynamic scenarios. Additionally, these tools struggle to handle changing conditions like low bandwidth scenarios, a common occurrence in diverse contexts such as defence applications. Moreover, the current tools lack essential usability features and adaptability, resulting in suboptimal user experiences and interactions.

Our study explores professional's experiences of using network simulation tools, to better understand their current limitations and future potential. Research in the field details many of the technical limitations of existing network simulation tools that hinder their effectiveness in replicating real-world network scenarios. However, usability issues that pose a significant barrier, impacting user-friendliness and productivity, are not fully explored. In response to these challenges, our study employs a mixed-methods approach to collecting data. By analysing responses from a questionnaire and a design workshop, it uncovers the critical technical and usability features, needs, and challenges perceived by professionals in this field.

Our study provides a list of essential features for network simulation tool enhancement, underpinned by the feedback and experiences of participants. These features represent a way to refine these tools, streamline their user interfaces, and align their capabilities with the evolving landscape of network simulation tools. This study improves our understanding of the challenges faced by network simulation tools, particularly when applied within a day-to-day working experience with clients. It synthesises practical recommendations for tool enhancement and usability improvements, offering an initial blueprint for future developments.

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# Contents

# Chapter 1

# Introduction

## 1.1 Overview

A wide array of network simulation tools, including NS-2 [1], NS-3 [2], OPNET [3], QualNet [4], and OMNet++ [5] have enabled the modelling of various types of networks, ranging from local area networks (LANs) to wide area networks (WANs). These tools serve as invaluable tools for investigating the behaviour and performance of new protocol designs, reinforcing understandings of network concepts. They play a pivotal role in the development and evaluation of modern communication systems. These techniques allow researchers, network experts, and industry professionals to test and optimise wireless networks in controlled environments without the need for extensive physical setups. Real-time simulation is a particularly significant aspect of this field, as it replicates the timing behaviour of real-world targets, enabling cost-effective experimentation.

The continuous growth of networks, encompassing both wired and wireless systems, has underscored the significance of evaluating network performance and behaviour through simulation. Network simulation tools offer a cost-effective alternative to conducting experiments on production networks, making it a preferred method for evaluating networks and their performance. However, the increasing reliance on simulation tools could result in many correctness and validation issues. Many of these issues are purely technical but a thorough investigation into the usability and user-experience of using these tools has the potential of unveiling design issues affecting the users.

Our study was conducted with ITSUS Consulting, a technology solutions provider specialising in information and communication technology (ICT) solutions for critical communication systems. The company collaborates with leading aerospace, defence, and public sector organisations to drive digital transformation initiatives. This domain of operation, where the use of network simulation tools has a crucial role in making decisions and implementing projects, allowed us to uncover many of the technical and usability shortcomings of these tools. Our findings shed light on several technical and usability issues associated with these tools, emphasising the importance of considering the specific operational context when selecting them and placing the user at the centre of design when developing or upgrading these tools. Furthermore, our research highlights a recurring need for implementing multiple user profiles with varying functionalities and corresponding access rights within these tools to facilitate intuitive interactions between different teams.

### 1.1.1 Overview of Methods and Thesis Map

The investigated body of research examined papers from peer-reviewed journals and conference proceedings in networking, human-computer interaction (HCI), usability studies in network management tools, visualisation, usability of interfaces, and technical papers on simulation tools, encompassing new tools and comparative studies of current tools. To gather relevant literature, specific search terms were utilised, such as "network emulation," "wireless sensor network," "simulation," "simulator comparison," "network simulators," "Open Source," "network monitoring tools," "network management," "user-centred design," "graphical user interface," "usability," "verification," "real-time," "testbed," "wireless networks visualisation," and "visualisation". The search included studies published within the past 20 years, a broader range was considered due to the limited investigation of this topic in recent years. Additionally, a mixed-methods research design, comprising a questionnaire and a design workshop, was employed to gain insights into the technical and usability challenges faced by users and non-experts when utilising wireless network simulation tools.

## 1.2 Motivations

The development and evaluation of wireless network systems require frameworks that are not only efficient but also user-friendly. However, the majority of reviewed research in this field predominantly focuses on building and introducing new tools [6, 7, 8] or comparing the performance of widely used tools [9, 10]. This research builds upon prior studies mainly focused on performance, while addressing an essential gap in the body of literature concerning the usability and interactivity of simulation tools for wireless network designs.

Our motivation for this research stems from the pressing need to comprehensively understand the most widely used network simulation tools and address their limitations. Through our study, we aim to shed light on both the technical and usability challenges faced by users of these tools. The motivation behind this research is to enhance the effectiveness and efficiency of network simulation tools by compiling a list of important updates to be incorporated in the next steps of design or updates for these tools. Ultimately contributing to the improvement of network infrastructure design and deployment processes.

## 1.3 Aims and Objectives

Our primary objectives for conducting this study are as follows:

- To provide an overview of current research on the usability of network simulation tools.
- To investigate the current user experience pains, pitfalls and barriers while using network simulation tools to carry out clients' commissioned projects.
- To investigate the common practices and workarounds employed by users to overcome shortcomings.
- To propose a list of recommended upgrades and customisation for tool enhancement and future development based on our findings.

## 1.4 Research Questions

Our research is guided by the following three research questions:

**[RQ1]** What network simulation tools are used by ITSUS specialists to accommodate clients' needs, and what are the key features of tools in use?

**[RQ2]** What are the strengths/weaknesses of the above tools/features in the light of client's requests and needs, and concerning their ease of use and technical ability?

**[RQ3]** How would end users of these tools including clients and employees like to see these tools evolving in the future both from a technical and user experience perspective?

First, we will begin by discussing definitions and key concepts in Chapter 2 and present related work in the field in Chapter 3. Chapter 4 will detail the methodology employed for the research. The results of the study will be presented and discussed in Chapter 5 and Chapter 6. Finally, Chapter 7 will offer our concluding remarks and recommendations.

# Chapter 2

# Background

This background chapter introduces the fundamental concepts of network simulation and its associated tools. It begins by providing an overview of network simulation, defining key terms, and exploring various techniques. The sections highlight the advantages of using network simulation and compare the currently employed techniques. It concludes by introducing some widely utilised simulation tools prevalent in both industry and academic research. It is important to note that the list of tools provided is not exhaustive. The choice of the presented tools was made considering their frequent appearance in the majority of reviewed research and their popularity in the industry. The list comprises a combination of open-source and commercial tools, ensuring a comprehensive understanding of both types of tools.

## 2.1 Wireless Network Simulation

Real-time simulation is a process where a system or an application is simulated in a manner that replicates the timing behaviour of the real-world targets or entities being simulated [11]. In other words, the simulation runs in sync with real-time, mimicking the timing characteristics of the actual system. The process runs on simulator objects which are the components within the simulation that emulate, or represent, various elements of the real-world system or application. They are responsible for reproducing the timing behaviour of the simulated targets. The target of this process is to simulate targets or entities which are the elements or components of the system, or application, that are being simulated. The simulator objects aim to replicate their timing behaviour.

The simulated application or system interacts with its virtual environment in the same way it would interact with a real environment [12]. This means that the simulated system responds and behaves as if it were operating within a real-world setting. By using real-time simulation, developers can test their application or system in various environments while avoiding real-world challenges. This means they can evaluate its performance, behaviour, and functionality in different scenarios without the need for extensive physical setups.

The majority of network simulators fall into the category of discrete event simulators [11, 13], which enable the modelling of network behaviour at different levels of granularity. Operating with a virtual simulation clock, they execute the network model independently of real-time constraints. Conversely, certain simulation tools can be seamlessly integrated into operational networks, necessitating real-time operation and the use of actual network data. These tools are commonly referred to as network emulators to differentiate them from event-based simulators [13].

The evolution of wireless network simulation tools has been marked by continuous advancements driven by the need for accurate performance evaluation, cost-effective experimentation, and advancements in wireless technologies, from early modelling and simulation techniques to the emergence of network emulation and the integration of physical and virtual components [14]. As wireless networks continue to evolve, simulation tools development will undoubtedly play a critical role in driving innovation, improving performance, and shaping the future of wireless communication systems. Therefore, understanding the different types of simulation tools and their purposes is crucial before developing or choosing the best tool for the task.

## 2.2 A Comparison between Network Simulation Tools

Network simulators, emulators, and testbeds are three distinct tools and approaches used in network evaluation and experimentation [15]. Each approach offers unique advantages and limitations. The word simulation is used in general to refer to the use of any of the tools in this research, specific mention of the tool category is used when necessary. The choice between simulators, emulators, and testbeds depends on the specific research objectives, available resources, and the desired level of accuracy and realism required for the network evaluation, a comparison between the three tools is shown in Table 2.1. Simulators are cost-effective and scalable but may lack accuracy and realism [16]. Emulators provide real implementations and real-time interaction but have limitations in scalability and cost

[17, 16]. Testbeds offer the highest level of accuracy and real-world conditions but come with increased cost and complexity [18]. Researchers must consider these factors when selecting the appropriate approach for their network evaluation and experimentation.

Network simulators are software-based tools that create virtual models of networks using mathematical formulas and algorithms [15]. They are cost-effective, scalable, and provide rapid results. Simulators are particularly useful for research and educational purposes, as they offer a lower cost and ease of implementation. However, simulators operate at a higher level of abstraction [19, 18], which may limit their accuracy in representing real-world network behaviour. Simulators, such as NS-3 [2], QualNet [4], and OMNeT++ [5], provide predefined modules and configuration tools, facilitating customised simulation experiments. They often rely on abstract models of protocols and applications, which may not accurately represent the behaviour of actual implementations. Additionally, simulated network conditions may not fully reflect real-world scenarios, such as fixed communication ranges or random mobility models [18].

On the other hand, network emulators combine software and hardware to execute real network protocol implementations in a controlled environment [17]. Emulators allow the examination of the performance of actual protocol and application implementations, offering real-time interaction and reproducibility [20]. By using firmware and actual devices, emulators offer greater accuracy and fidelity compared to simulators. Emulators, such as CORE [21] and Seawind [17], enable the testing and evaluation of protocols and applications in a more realistic setting. They provide a valuable test environment for protocol development and performance evaluation. However, emulators may have limitations in terms of scalability, cost, and interference issues [20]. Emulators that employ real wireless equipment can be expensive and challenging to manage. Interference from external factors can also impact experimental results.

Testbeds involve the deployment of physical network setups for evaluation and experimentation [15]. They provide the most accurate representation of network behaviour and allow for examination under real-world conditions, including interference and other external factors [15]. Testbeds offer high accuracy and reliability compared to software-based tools. Prominent testbeds, such as GENI [22] and PlanetLab [23], provide real-world testing environments. However, testbeds can be costly to set up and maintain due to the requirement for physical network equipment. They also have limitations in terms of scalability, as the availability of resources and hardware can restrict their size and complexity. Moreover, testbeds may have constraints on reconfigurability and the reproducibility of experiments.

In terms of accuracy, emulators and testbeds offer more realistic scenarios as they interact with actual network implementations, while simulators lack the fidelity of emulators and testbeds due to their abstract nature [24]. When it comes to scalability, simulators and testbeds can handle large-scale networks and traffic volumes [25, 26], whereas emulators may have limitations due to their hardware-based nature [17]. Flexibility-wise, simulators and emulators can be easily customised and adapted to different scenarios [19], while testbeds may have limitations in changing the physical layout but offer flexibility through software modules [18]. Development time and effort differ, with simulators providing faster development due to their reliance on mathematical models, emulators requiring more effort due to their hardware-based nature, and testbeds demanding significant time for infrastructure setup and management. Simulators; however, can still lack some protocols resulting in an increase in developing time, in addition to modelling problems of different environments and power consumptions [19]. Cost considerations favour simulators [27], which are cost-effective as they don't require dedicated hardware, while emulators and testbeds may involve infrastructure costs and resource allocation.

Table 2.1: A Comparison Between Network Simulation Tools.

| Criteria | Simulators | Emulators | Testbeds |
|---|---|---|---|
| Cost | Generally low or free | Moderate to high | High (equipment and maintenance costs) |
| Accuracy | High, but may have some abstraction | High (emulates real hardware) | Highest (real-world environment) |
| Scalability | Limited by computational resources | Limited by hardware capacity | Can be large-scale depending on setup |

A comparison between network simulation tools (continued)

| Criteria | Simulators | Emulators | Testbeds |
|---|---|---|---|
| Flexibility | Highly flexible, easy to modify and simulate various scenarios | Limited by hardware and firmware | Limited, setup may be fixed |
| Fidelity | Medium to high, depending on level of abstraction | High (emulates real-world behavior) | Highest (actual network devices and conditions) |
| Development Time | Shorter development time, easy to implement changes | Moderate, requires specific hardware and setup | Longer setup and configuration time |

## 2.3 Advantages of Simulation Tools

Simulation tools use in wireless networks provide research with adaptability. These tools can be easily customised to simulate various network configurations, protocols, and scenarios, allowing researchers to investigate specific research questions or test the performance of new protocols and algorithms in a controlled and repeatable manner [11]. They also offer the advantage of scalability. Giving users the ability to simulate large-scale wireless networks with thousands of nodes, accurately replicating the complexities and challenges that arise in real-world deployments. The ability to simulate networks of varying sizes, from small-scale deployments to large-scale infrastructures, allows researchers to study the impact of network growth, resource allocation, and issues [20]. These tools allow flexibility in modifying network parameters, traffic patterns, and application scenarios to cater to specific research or business objectives.

The use of simulation tools brings cost-effectiveness and efficiency to wireless network testing and evaluation [17]. Building and deploying real-world wireless networks for experimentation can be costly, time-consuming, and logistically challenging. The tools provide a cost-effective alternative by creating virtual network environments that mimic real-world conditions. This significantly reduces the time, effort, and resources required for network testing and evaluation [17].

Simulation tools also contribute to performance optimisation in wireless networks. Researchers can analyse various network parameters, such as throughput, latency, packet loss, and network capacity, to identify bottlenecks and optimise network configurations. They allow the recreation of specific network scenarios, including rare or extreme events, which are difficult to replicate in real-world deployments. This enables the study of network behaviour under various conditions, such as network congestion, interference, mobility patterns, and environmental factors, providing a deeper understanding of network dynamics and performance. Additionally, simulation tools provide a safe and controlled environment for testing and experimenting with network protocols, algorithms, and configurations [20, 16]. Researchers can assess the impact of changes or updates without risking disruption to operational networks, ensuring the stability and reliability of network systems.

Lastly, the development of these tools has been flexible and extendable to many changes in technologies over time. Although many of these tools were originally designed for ad-hoc networks, they were, for example, later developed to accommodate advances in networks and are now suitable to scale and use with wireless networks. Some of these tools include NS-2 [1], Opnet [3], COOJA [28], and TOSSIM [29].

## 2.4 Examples of Network Simulation Tools

The selection of a suitable wireless network simulation tool depends on the specific research requirements or business needs, expertise, and resources available. NS-2, NS-3, OPNET, OMNeT++, QualNet, CORE, and GNS3 are a few of the prominent tools available, each with its strengths and limitations. When attempting to choose a tool, researchers and users should consider factors such as scalability, accuracy, flexibility, ease of use, and cost. In this section, we provide an overview of several wireless network simulation tools discussed in the literature. We describe their features, functionalities, and capabilities, and compare them based on criteria such as scalability, accuracy, flexibility, and ease of use as discussed in the literature reviewed. Additionally, we will highlight their strengths and limitations, Fig. 2.1 shows the interfaces of several of these tools.

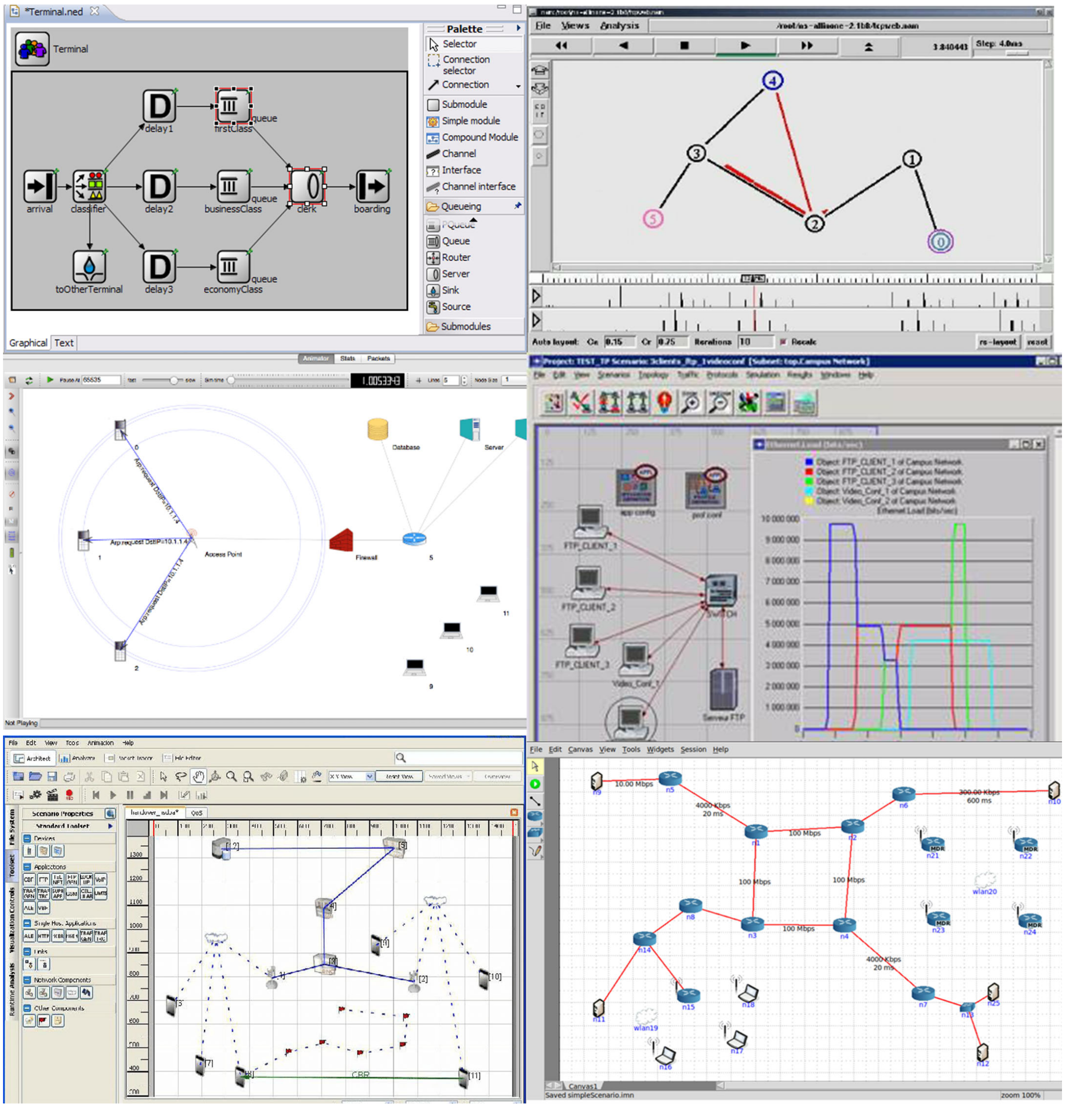



Figure 2.1: Examples of Network Simulation Tools Interfaces

### 2.4.1 NS-2 (Network Simulator 2):

NS-2 is an open-source discrete event simulator widely used for network research and development [1, 30, 31, 11, 19, 18, 27]. It is one of the most well-known and extensively used simulators in the academic community. NS-2 was developed at the VINT (Virtual

InterNetwork Testbed) project at UC Berkeley and USC/ISI (University of Southern California/Information Sciences Institute) in the late 1990s as a variant of the REAL simulator. It provides a wide range of network protocols, models, and traffic patterns, making it a versatile tool for simulating various types of networks, including wired and wireless networks.

NS-2 is built in C++ and provides a simulation interface through OTcl, an object-oriented dialect of Tcl. Users describe network topologies using OTcl scripts, and the main NS program simulates these topologies with specified parameters. It supports arbitrary network topologies composed of routers, links, and shared media, and processes network activities and queues them as events, creating a virtual simulation environment. It also provides a visualisation tool called Network AniMator (NAM) for visualising network behaviour and plotting statistics.

The tool's extensibility is one of its significant strengths, allowing researchers to create and use new protocols easily. It offers features tailored for wireless networks, such as sensor channels, battery models, lightweight protocol stacks, hybrid simulation support, and scenario generation tools. It also has a large user community and extensive documentation, which makes it easier for researchers to get started and find support.

NS-2 has been used in numerous research studies and has contributed significantly to the advancement of network protocols and technologies. However, it operates in discrete event mode, which can impact simulation performance for large-scale scenarios. Moreover, due to its age, some newer network technologies and protocols may not be fully supported or may require additional effort to integrate into the simulator. It is also considered hard to learn despite having extensive documentation. Finally, as of 2010, the tool is no longer developed nor maintained.

### 2.4.2 NS-3 (Network Simulator 3):

NS-3 is an open-source, event-driven simulator widely used in academia and industry [2, 32, 15, 33, 9, 27, 30, 34, 35, 12, 36, 34, 37, 32, 38]. It offers a comprehensive set of models and protocols for simulating wireless networks. NS-3 provides a flexible and extensible architecture, allowing researchers to develop custom network models and algorithms. Its accuracy and scalability make it suitable for a wide range of research applications.

It is an open-source network simulation tool that is widely used in the academic and research community. It is the successor to NS-2 and was developed to address some of the limitations of its predecessor as a replacement, not an extension. It does not have an OTcl API, and it is written in C++ language and Python. One of the key advantages is its flexibility and extensibility. It provides a modular architecture, allowing researchers to develop and incorporate custom models, protocols, and algorithms easily. This flexibility makes NS-3 suitable for a wide range of research applications, from general networking protocols to specific application scenarios.

The tool supports various network technologies and standards, including WiFi, LTE, WiMAX, and even vehicular communication (VANETs). This breadth of support makes it a powerful tool for studying and evaluating the performance of diverse communication systems. Another significant advantage is its focus on accuracy and realism. It provides detailed models for wireless channel characteristics, packet propagation, and network protocols, making it suitable for simulating real-world network behaviours accurately.

However, NS-3's power and flexibility come at the cost of complexity. It requires users to have a strong understanding of programming and simulation concepts, which can be challenging for newcomers. The learning curve for it can be steeper compared to other simulators that offer more user-friendly interfaces. The tool is active and under constant development. The community and extensive documentation provide valuable support to users, making it a prominent choice for cutting-edge network research and development.

### 2.4.3 OPNET(Riverbed Modeler):

OPNET is a well-established commercial discrete event network simulator initially proposed by MIT in 1986 in C++ [39, 40, 15, 41, 42, 34, 31]. It was acquired by Riverbed Technology in 2012. While it is primarily commercial software, it can also be used free of charge by researchers applying to university programs for the product. It has gained popularity due to its fast simulation engine and a wide variety of niche simulators for both wired and wireless networks. It supports various network hardware components like antennas and transceivers and allows users to develop models and graphs through a graphical interface. The tool offers a rich set of modules for different protocol stacks, including IEEE 802.11 and IEEE 802.15.4, as well as various routing protocols like AODV and DSR.

It offers the ability to monitor and execute multiple scenarios simultaneously, making it a suitable choice for complex network simulations. It employs a hierarchical modelling environment, allowing users to define models at the network, node, and process domains/levels. The simulator operates at the packet level and supports a large library of existing network hardware and software protocols.

However, Scalability is a concern due to its object-oriented design. Also, the number of available protocols is relatively limited compared to other simulators. Despite its popularity, the high cost of commercial licenses and lack of customisation options for forming new networks or protocols are considered drawbacks. Despite its strengths when compared to other tools, the simulation environment may not provide presentable graphs or curves directly, necessitating the use of external simulators to plot modulation curves and accurately simulate physical layer behaviour.

### 2.4.4 OMNeT++:

OMNeT++ is a modular, discrete event-based simulation library and framework primarily used for designing wired and wireless networks [43, 39, 15, 44, 44, 27, 31, 30, 34]. It is implemented using C++ and provides an architecture for models that can be combined to create larger models with higher-level language support through Network Description (NED). It is a component-based architecture where simulation components, or modules, are programmed in C++. The simulation kernel library consists of the simulation kernel and utility classes used to create simulation components and assemble simulations from these components. The framework also provides runtime user interfaces and tools for simulation execution, debugging, and visualisation.

The tool has a powerful graphical user interface (GUI) environment, which makes tracing and debugging simulations much easier compared to other simulators. The software accurately models hardware and includes the modelling of physical phenomena, making it suitable for a wide range of network simulation tasks. However, it does not offer a wide variety of protocols, and users may need to implement many protocols themselves, which can be time-consuming. Additionally, the analysis and management of typical performance may not be as comprehensive as in other simulators.

The mobility extension in OMNeT++ is relatively incomplete, which can be a drawback when simulating mobile networks. Despite that, OMNeT++ is popular in academia and industry for its extensibility, open-source nature, and vast online documentation resources. It is widely used for network simulations, and several open-source simulation models have been developed for various network areas. OMNeT++ continues to grow and evolve, with a strong user community contributing to its development and expansion.

### 2.4.5 QualNet:

QualNet is a commercial network simulator developed by Scalable Network Technologies, Inc [4, 40, 42, 31, 34]. It was first released in 2000-2001 and is designed to predict the performance of wireless, wired, and mixed-platform networks and networking devices. The simulator is known for its ultra-high fidelity and is suitable for simulating large, heterogeneous networks and distributed applications. It is written in Parsec, a C-based language, as it is built on top of the GloMoSim protocol and supports both discrete event simulation and real-time emulation. It is equipped with several key features, including the ability to simulate large and heterogeneous networks.

QualNet is specifically targeted at ad-hoc network simulation and is based on the GloMoSim protocol. It offers an environment for users to design new protocol models, enhance existing ones, and design both wired and wireless networks using existing models. The simulator allows developers to work with the source code of the models to build new functions or modify existing ones, enhancing its extensibility. It is recognised for its speed, scalability, and ease of use, making it a preferred choice for simulating large and complex networks.

However, it still has a limited user-friendly code due to the availability of many built-in functions. The tool comes with a user-friendly graphical interface that simplifies the process of designing and configuring network topologies, defining traffic patterns, and visualising simulation results. It also offers scripting capabilities for more advanced users who prefer to use custom scripts for simulation setup and automation.

### 2.4.6 CORE(Common Open Research Emulator):

CORE (Common Open Research Emulator) is an open-source network emulator designed for emulating networks on multiple machines, connected to live networks [7, 9, 45, 21]. It provides a graphical interface for managing network topologies and Python bindings for scripting network emulation. CORE uses antennas to represent wireless connections and visualises device connectivity with green lines, making it an effective way to show the wireless network's layout.

The tool allows users to adjust the range of wireless signals, providing a visual representation of the transmission range of devices. It can emulate a wide range of network technologies, including wired and wireless networks, virtual machines, and software-defined networks (SDNs). This versatility makes it suitable for studying different types of networks and their interactions.

CORE offers a user-friendly graphical interface that allows users to create, configure, and connect virtual network nodes and devices easily; however, it falls short in executing detailed events accurately. It provides drag-and-drop functionality, making it accessible to users with various levels of technical expertise. The tool supports custom scripting using Python, enabling users to automate various simulation tasks, customise network behaviour, and define specific test scenarios. It also supports integration with other simulation tools, such as NS-3.

One major drawback is the lack of support for capturing wireless packets, including 2-way (Data/ACK) or 4-way (RTS/CTS/Data/ACK) exchanges. As a result, wireless communication is purely simulated, limiting its usefulness for studying real-world wireless networking scenarios. Additionally, CORE lacks built-in support for wireless security protocols, which is a critical aspect when using a simulator for teaching purposes, where security topics are essential. CORE's focus on wireless emulation at the physical and data link layers is limiting, and it lacks an integrated mechanism to deploy fully functional systems without configuring each component separately.

The tool supports real-time emulation, allowing users to observe the behaviour of network protocols and applications in a time-accurate manner. This is particularly useful for studying real-time applications and assessing their performance under different network conditions. It also includes a wide range of pre-built network templates and models, which can be easily modified and extended to create complex network topologies. This reduces the effort required to set up simulations and accelerates the research process.

However, it lacks configuration and deployment automation, requiring complex configuration scripts and making the validation process susceptible to errors. Additionally, running large-scale network scenarios in CORE can be resource-intensive, requiring significant computing resources and making it inaccessible to many researchers. Moreover, CORE's lack of support for fully integrated solutions with high-level configurations adds complexity for inexperienced users, increasing the learning curve and time required to validate network designs.

### 2.4.7 GNS3 (Graphical Network Simulator 3):

GNS3 (Graphical Network Simulation) is an open-source tool that utilises Cisco IOS images to emulate routers [46, 47, 48, 39]. It runs over Dynamips, which is the core program responsible for Cisco IOS emulation. GNS3 serves as the graphical front end for Dynagen, providing a user-friendly graphical environment similar to Packet Tracer. One of its most significant advantages is the accuracy it offers through virtualisation, allowing users to replicate the configuration of interfaces and routers found in real computer networks. This makes GNS3 a valuable tool for simulating and testing complex network topologies.

One of the main strengths of GNS3 is its graphical user interface, which provides a user-friendly and intuitive environment for designing and configuring network topologies. Users can drag and drop virtual network devices, such as routers, switches, and firewalls, onto the workspace and connect them to create a network layout. GNS3 supports a wide range of network operating systems, including Cisco IOS, Juniper JunOS, MikroTik RouterOS, and many others. This allows users to run actual networking software on virtual devices, making GNS3 particularly valuable for practising with real configurations and network functionalities.

The tool integrates with various hypervisors and virtualisation platforms, such as VMware, VirtualBox, and QEMU, to provide the virtualisation capabilities needed to run the simulated network devices. This ensures a realistic network environment and accurate behaviour of the emulated devices.

It also supports real-time packet capture and analysis, enabling users to inspect network traffic and troubleshoot issues. This feature is essential for understanding the flow of data in the network and diagnosing connectivity and performance problems. Additionally, the tool has a strong community of users who actively contribute to its development and provide support through forums, tutorials, and documentation. This active community ensures ongoing updates, bug fixes, and the availability of a wide range of network templates and device images.

One of the primary advantages of GNS3 over Cisco Packet Tracer is its support for various protocols like Border Gateway Protocol (BGP) and Multi-Protocol Label Switching (MPLS), allowing for a more comprehensive and flexible simulation environment for network designers and researchers.GNS3's usage extends beyond educational settings and is widely used in companies for network simulation. It allows researchers to emulate complex networks, incorporating both physical and virtual devices. Additionally, it offers some support for Long-Term Evolution (LTE) networks.

The limitations stem from its reliance on virtualisation technologies to emulate large-scale networks with thousands of devices may require substantial computational resources which can be a challenge for users with less powerful computer systems. Ensuring smooth performance and responsiveness during simulation sessions might necessitate upgrading hardware or using cloud-based solutions to handle the computational load effectively. Additionally, Users should have a good understanding of networking concepts and virtualisation to fully utilise the tool's capabilities.

# Chapter 3

# Related Work

The landscape of network management tools has predominantly focused on technical aspects of the developed tools, often neglecting the incorporation of user-friendly interfaces for data processing and presentation. Current tools tend to lack diversification in accommodating users with varying profiles, uniformly presenting all functionalities regardless of their expertise, resulting in steep learning curves [49]. Similarly, a significant body of research on network simulation tools focuses on comparative reviews of various simulators [9, 10, 50, 27, 30, 31, 26, 19]. Simulation tools development serves as an indispensable resource in the research community, enabling the development and evaluation of new protocols, as well as facilitating comparisons between novel and existing protocols. Many of the comparative reviews of these tools shed light on the technical aspects and performance metrics of network simulators; however, they rarely focus on the user experience and usability challenges encountered by day-to-day users and non-experts.

To the best of our knowledge, no prior research has undertaken a comprehensive examination of the usability of network simulation tools from a user's perspective. Our research builds upon the existing body of comparative reviews and technical evaluations of network simulation tools, expanding the scope to include insights from user experiences and user-centred assessments. By combining technical evaluations with user perspectives, we aim to provide a comprehensive and holistic understanding of the strengths and weaknesses of simulation development, enabling researchers and developers to make informed choices and optimise the usability of these essential tools.

In the subsequent sections, we will briefly outline the technical limitations identified in recent research, explore the design and usability issues by investigating research in network management tools usability, human-computer interaction design, and visualisation, and provide a domain-specific context. By exploring these areas, we aim to shed light on the usability challenges and opportunities within network simulation tools, ultimately contributing to the development of more effective and user-centric solutions.

## 3.1 Technical Shortcomings

Despite the focus on creating tools that provide high performance and accommodate many of the technical needs to build and simulate networks, many limitations still impact the accurate representation of real-time networks. Our objective is to analyse the key technical constraints of these tools, to establish a fundamental framework for essential technical attributes that should be integrated into forthcoming upgrades. This approach is aimed at facilitating the necessary changes to enhance the CORE/EMANE tool, aligning it with the specific requisites of clients operating within the defence sector and taking into consideration the special nature of operations in that sector.

Accuracy and scalability are crucial in wireless network simulations, as they determine the ability to model large-scale networks accurately [17]. When it comes to simulating wireless networks, the scalability is often limited by the simulator supplied with the operating system and directly impacts the accuracy of the results [17, 51]. Additionally, the huge number of existent tools can make selecting the most suitable simulation tool a challenging task [26].

Many of these tools use abstract simulation models. These models, while useful for certain types of analysis, may not accurately capture the reality of the complex behaviour and performance of wireless networks, which means that they will not be as accurate as real implementations [18]. To address these limitations, researchers have developed tools such as GISOO, which integrates Simulink [52] and COOJA [28] to create a virtual testbed for wireless network simulation. This virtual testbed runs real embedded code, including the full wireless communication stack, and reproduces timing and packet loss rates without the need for building abstract simulation models. This integration allows embedded wireless communication code to be emulated in GISOO without any changes, enabling the execution of the same code that has been evaluated in simulations directly on the target platform.

## 3.2 Data Processing and Visualisation

The implementation of modern networks facilitates the collection of a vast and growing volume of data. Leveraging simulation tools to make informed decisions about the appropriateness of a particular implementation or protocol heavily relies on utilising this data. Schroder et al. concluded that the quality of decision-making improves with the increasing volume of data available [53]. However, the potential to make better decisions through the processing of large datasets comes with challenges. Cognitive overload and fatigue may arise if the proper processing and display of the data are not well-suited for the task at hand, as highlighted by [54]. Ensuring that the data is presented in an easily comprehensible and meaningful manner becomes paramount to avoid overwhelming users with information.

Falschlunger et al. demonstrated that the relationship between task complexity and decision-making outcomes is mediated by information overload. The researchers found that when faced with complex tasks, individuals may experience information overload, which can negatively impact their decision-making abilities. This highlights the importance of managing information effectively in decision-making processes [55]. The study reaffirmed Gettinger et al. conclusions that well-implemented visualisations serve as an effective aid in the comprehension of large amounts of information and improve the ability to detect trends and patterns resulting in better decisions [56]. The efficiency and effectiveness of decision-making using simulation tools heavily depend on the tools' ability to handle data in a user-friendly manner, reducing cognitive load, and facilitating informed choices based on data-driven insights.

Work from the Human-Computer Interaction (HCI) research recognising the potential of visualisation and usability resources in advancing user interfaces for management applications is the most relevant to this study [49, 55, 57, 58]. These resources offer benefits to both non-specialists and experts, enhancing productivity in daily monitoring tasks [58]. Consequently, recent initiatives have proposed HCI-based usability guidelines, or heuristics, to aid in the design of user interfaces for network management tools [59]. Researchers in [60, 59] developed guidelines for network monitoring tools through experimental studies involving network administrators. They introduced "guidelines for usability design in network monitoring tools" [60, 59]. However, these guidelines have yet to be evaluated by network management tool developers to assess their usability benefits and potential need for refinement.

Graphical representation can provide a visual and intuitive understanding of the simulated network environment and alleviate the cognitive load [61]. The limited visualisation in many of these tools can make simulating complex network topologies and scenarios challenging for users to understand the interactions between nodes, links, and traffic [62]. Inadequate or complicated visualisation may lead to difficulty in identifying potential issues, bottlenecks, or inefficiencies in the network design. This in return makes debugging network simulations a specialised task that requires expert users. It also would lead many users to identify errors or anomalies in the simulated network using log files and textual outputs, which can be cumbersome and time-consuming.

Poor graphical interfaces may lack user-friendliness and intuitive navigation. Users may find it challenging to create, modify, and manage network configurations. Coupled with limited customisation options which restrict users from tailoring the visualisation according to their specific research needs. This can be especially problematic when trying to analyse and evaluate the impact of various protocols or network settings on the simulated environment. However, implementing a well-suited visualisation helps better the usability of the tool but careful consideration should be paid to the type of users and the scalability of the implemented technique. Pretorius et al. used Eye Tracking as an evaluation method to better understand the usability of the implemented visualisation, their results revealed issues in data visualisation legibility, user preferences for graphical representations, and issues of presented visualisation in some parts of the screen [62].

Yang et al. found that issues of usability in network monitoring and management tools for both network administrators and ordinary users revolve around problems related to technical knowledge requirements and lack of visualisations for the tools. Inconsistent user interfaces were also identified due to the absence of guidelines, leading to variation among suppliers, devices, and operating systems [63]. Similar issues were discussed in [44] where researchers surveyed six simulation tools to be used by students in classrooms. The tools surveyed had issues with their interfaces and ease of use. Issues with time investment to learn and use the tools were also discussed.

While specific literature directly addressing the usability challenges of network simulation tools was not identified, our investigation into related papers has provided valuable insights into design and usability concerns associated with network management tools. These findings can be extrapolated to potentially impact network simulation tools as well. The usability research has highlighted various aspects, such as catering to different user profiles, effectively handling collected data for generating meaningful insights, mitigating cognitive loads associated with learning and comprehending these tools, and addressing issues concerning poor interfaces. Utilising the insights from these studies, we devised a comprehensive approach to further probe and directly understand changes that need to be implemented while working with users of these tools. This involved the development of a questionnaire and design workshop. These methods were employed to collaboratively engage with end-users, allowing us to gain a deeper understanding of the necessary enhancements to be integrated into these tools. Through this approach, we aimed to bridge the gap between the challenges identified in the literature and the practical implementation of upgrades, ensuring that the proposed upgrades would meet the specific requirements and usability expectations of clients in the defence sector.

## 3.3 Network Simulation in Defence and Critical Operations

Network simulation tools are recognised for their benefits in various sectors, including defence. However, the effectiveness of these tools greatly depends on the specific context in which they are applied. In the defence sector, where the focus of ITSUS Consulting clients resides, there are unique differences that need to be considered when developing or choosing a tool for the job. The deployment of network simulation tools takes on a distinct significance. The following will introduce the specific domain of defence and its utilisation of network simulation tools, shedding light on the advantages, challenges, and tailored approaches that characterise this landscape.

Simulation and Modelling play pivotal roles in the planning and deployment of military systems, particularly within the realm of Command, Control, Communications, Computers, and Intelligence (C4I) [64]. In modern military operations, the concept of Network-Centric Warfare (NCW) has emerged as a transformative approach to achieving enhanced operational efficiency, real-time decision-making, and improved situational awareness [65]. At the core of NCW lies the seamless integration of information, communication, and technology to enable military forces to function as a networked entity, sharing data and insights for optimal mission outcomes. Given the critical nature of military operations, new services and applications must undergo rigorous testing under various network scenarios to identify unforeseen system behaviours. A prevalent scenario involves networks operating in potentially hostile environments, serving multiple users with diverse multimedia traffic and real-time requirements. This context raises complex issues in network design, configuration, and deployment [66].

Network simulation tools offer a range of distinct advantages when applied to defence scenarios. these tools enable the creation of virtual environments that replicate real-world network conditions. Such simulations permit defence analysts, engineers, and decision-makers to explore a multitude of scenarios and assess system behaviours in controlled settings, minimising the need for expensive and risky live tests [67]. Several network simulation tools have gained prominence within the defence sector due to their capabilities and flexibility. One such example is CORE [21], which enables the creation of diverse network topologies and facilitates the evaluation of network behaviour under various conditions [67].

Moreover, network simulation tools facilitate the evaluation of system performance under various stress factors, including network congestion, bandwidth limitations, and cyber threats. By subjecting defence systems to simulated challenges, vulnerabilities can be identified, and strategies can be developed to address potential weak points. This predictive capability significantly enhances the responsiveness and adaptability of these systems, ensuring optimal performance even under adverse conditions. Gu and Fujimoto explored the concept of remote network emulation specifically tailored for defence applications [66]. They discussed the development and deployment of a remote network emulation system called ROSENET [66], designed to test and evaluate distributed services and applications, including those relevant to modern military scenarios. ROSENET integrates remote parallel simulation servers with local network emulators to provide scalability, accuracy, timeliness, flexibility, and remote accessibility. ROSENET applications in various military contexts, such as information assurance in the Global Information Grid, quality of service in urban wireless networks, and realistic communication in military training were highlighted. The researchers also noted that the use of ROSENET is applicable when network characteristics are relatively stable. For scenarios with rapidly changing network characteristics, they suggested the use of local network emulation methods.

Despite their numerous advantages, integrating network simulation tools within defence contexts has notable challenges. One significant challenge lies in the requirement for realistic representation [67]. Military networks are intricate, involving a wide range of devices, protocols, and security measures. Ensuring that simulation models accurately mirror the complexities of these networks is essential to generate meaningful insights.

Achieving this level of accuracy demands meticulous data collection, skilled modelling, and continuous validation against real-world scenarios.

Furthermore, the dynamic nature of defence operations introduces the challenge of real-time adaptability [67]. Network simulation tools must not only replicate current conditions but also rapidly respond to changing variables. This is particularly important in scenarios where real-time decisions can have critical consequences, such as in tactical communication or intelligence sharing. One simulation tool will not provide an overall environment for optimal testing in the defence context, Suri et al. highlighted the significance of realistic simulation environments for assessing communication technologies and network architectures in complex operational scenarios [67]. The researchers introduced a comprehensive emulation framework that combines realistic military scenarios with advanced network emulation techniques. The system is aimed to facilitate experimentation and analysis of communication protocols, technologies, and networking strategies in a controlled environment. By providing a platform that mirrors the intricacies of actual military operations, the researchers emphasised the potential for effective validation and optimisation of tactical communication solutions.

# Chapter 4

# Methods

In this chapter, we present the methods employed in this study to understand simulation tools, current needs and challenges of simulation tools, from users' perspectives. A mixed-methods research design, as shown in Fig. 4.1, comprising a questionnaire and a design workshop, was utilised to answer our research questions listed in Section 1.4.

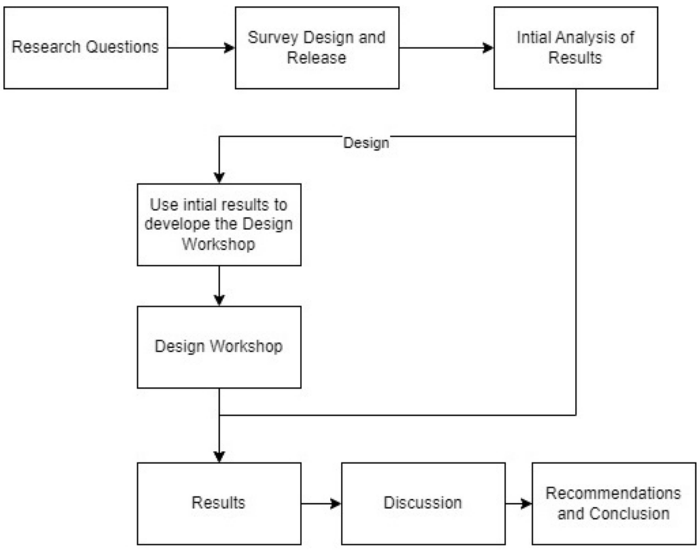



Figure 4.1: Research Design Process

## 4.1 Questionnaire Design

We conducted an ethically approved online survey that targeted ITSUS Consulting employees actively using simulation tools in their daily work. We used a convenience volunteer sampling technique which relied on contacts at ITSUS Consulting acting as gatekeepers to invite individuals who met the inclusion criteria to participate. The survey served as an initial approach to understanding the patterns and challenges associated with the usage of these tools. Specifically, it aimed to grasp essential information such as the current tools in use, their primary advantages and challenges, clients' needs and perceptions, user experiences, and visualisation preferences and requirements. By analysing the questionnaire responses, we sought to gain a better understanding of the client's requirements and limitations of the existing tools, which later informed the design of the subsequent design workshop with domain experts to delve deeper into the usability aspects.

The questionnaire contained 24 questions organised into three groups, addressing similar themes to facilitate participants' responses. The initial section sought general information about the users and their tools, aiming to assess the participants' level of experience, the types of tools commonly employed, key features and functionalities of these tools, and any specific limitations they encountered.

The second section aimed to gain a clearer understanding of the client's needs and their desired improvements to enhance their experience. This exploration included insights into challenges faced, user experiences, visualisation preferences, and direct feedback received from clients on previous projects.

The final section centred around visualisation and users' experience, encompassing both the clients' perceptions and the participants' perspectives regarding the importance of adopting a human-centred design approach in the development of these tools. The questions sought to identify the current needs of the clients in relation to visualisation and user experience.

The purpose of the survey was thoroughly explained to the participants, and the data collected did not contain any personally identifying information, ensuring anonymity and confidentiality. The questions were carefully informed by existing research and identified gaps in the literature. Moreover, they underwent an expert review to refine and improve their quality. Detailed information about the survey results is available in Chapter 5 and discussed in Chapter 6. The information sheets, consent forms, and the complete set of questionnaire questions are listed in the Appendix A, Appendix B and Appendix C.

## 4.2 The Design Workshop

The second phase of the data collection process involved conducting a design workshop with selected participants from ITSUS Consulting. A purposive sampling technique was used to recruit participants based on their direct involvement in using simulation tools or their interactions with clients, ensuring that the workshop comprised individuals with diverse expertise and experiences related to the subject matter. The recruitment process was facilitated by the project partners, who helped identify suitable participants for the design workshop. The workshop aimed to provide a more in-depth exploration of the participants' experiences, perceptions, and insights into the usage and challenges related to simulation tools and provided them with a chance to design the visualisation and user experience they require based on the initial answers of the questionnaire. The design workshop was conducted in an open and collaborative environment, allowing for fruitful discussions and the elicitation of valuable feedback from the participants.

During the workshop, open-ended questions were used to encourage participants to express their thoughts freely and provide rich qualitative data, additionally, participants were provided with pens and papers to complete three designing activities. The first activity focused on improving the interface of a selected tool, CORE/EMANE. The second activity focused on important data and types of visualisation to add to the tool. The final activity was a brainstorming activity to define the necessary profiles and access rights of different users. The discussions were moderated by two researchers (the author and their supervisor) to ensure the session remained focused and productive.

## 4.3 Study Participants

We recruited participants from ITSUS Consulting who directly use these tools or deal with clients. For both activities, we recruited 6 participants in total, with the possibility of some overlap among participants. The quality of the data collected in both the questionnaire and the design workshop was a crucial aspect of this study. The questionnaire's use of open-ended questions encouraged participants to provide detailed and candid insights, yielding qualitative data of good quality. Additionally, the diversified profiles and expertise of participants enriched the dataset, our participants' experiences and backgrounds are presented in Chapter 5. In the design workshop, the collaborative nature of the activities enabled the collection of real-time, firsthand experiences and feedback from participants directly engaged in using these tools within an industry context. This combination of data sources enhanced the depth and comprehensiveness of the findings.

## 4.4 Data Analysis

Data analysis of the qualitative information gathered from both the questionnaire and the design workshop followed an inductive thematic analysis approach, as outlined by Braun and Clarke [68, 69]. This analysis consisted of two primary stages: open coding and axial coding. During the open coding phase, the data was carefully reviewed multiple times. This iterative process allowed the researcher to form initial impressions of the data and identify distinct ideas, which were then coded. Subsequently, in axial coding, these codes were organised and grouped based on their connections and relationships.

The questionnaire responses were carefully scrutinised to gain an initial understanding of the patterns and challenges associated with the usage of simulation tools. The responses to open-ended questions were carefully examined to identify recurring themes and significant issues related to the participants' experiences with the tools.

For the design workshop, the discussions from the session were transcribed and carefully examined to identify recurring themes and insights related to the usability and challenges of simulation tools. The workshop discussions and illustrations provided deeper insights into the participants' experiences and perceptions regarding the usage of these tools. They shared valuable information about the limitations of current tools, the need for user-friendly interfaces, intuitive navigation, and customisation options. It was also helpful in shedding light on specific issues related to visualisations and data representation in simulation tools. Participants' preferences for different visualisation techniques, challenges in understanding complex network topologies, and the need for effective data visualisation were all explored and analysed through the sketches and the discussions that followed them.

## 4.5 Research Ethics

This study has been granted ethics approval by the Faculty of Science and Engineering sub-committee of the Swansea University Research Integrity Ethics and Governance Committee on 27/06/2023. The data collected was completely anonymous and did not contain any personally identifying data. All participants were over the age of 18. Before participating in the study, all participants were provided with a clear and comprehensive explanation of the research's purpose, objectives, and procedures. Informed consent was obtained from each participant, emphasising their voluntary participation and the freedom to withdraw at any stage without facing any consequences.

## 4.6 Limitations

While the study aimed to provide valuable insights into the usage of simulation tools among ITSUS Consulting employees, certain limitations were acknowledged. One limitation is the reliance on self-reported data, which might be subject to participants' recall bias or subjective interpretations. Moreover, the study focused solely on employees within ITSUS Consulting, which limits the generalisability of the findings to other organisations or industries.

Additionally, the sample size of the design workshop was restricted due to logistical constraints and the availability of participants. Despite these limitations, the sample size was enough to extract some of the strengths and challenges by people who use these tools. Every effort was made to maximise the rigour and strength of the study's findings through ethical considerations, a mixed-methods approach, and expert review of the survey questions. The small sample size also means that the list is not exhaustive and further research is required to provide a more exhaustive list. Further research and replication of the study with larger and more diverse samples could strengthen the robustness of the conclusions drawn from this study.

Finally, the qualitative coding for this study was carried out by a single researcher. While the use of a single coder might introduce an element of subjectivity, it is noteworthy that the coding process was thorough, systematic and followed established guidelines to ensure the reliability of the findings. Moreover, the researcher received guidance and input from experienced academic supervisors throughout the coding process, which helped mitigate potential biases. Given the scope and nature of this dissertation, the involvement of a single coder did not significantly compromise the overall validity and rigour of the study's qualitative analysis.

In our future work, we intend to address these limitations by increasing the number of participants and extending the research scope beyond ITSUS Consulting, facilitating a broader understanding of simulation tool usage across diverse organisations and domains.

# Chapter 5

# Results

In this Chapter, we present the results from both the questionnaire and the design workshop conducted with participants from ITSUS Consulting. We aimed to understand the individuals' perspectives in relation to their own use of the tools, as well as their experiences of supporting clients in using the tools. The initial insights gained from the questionnaire were instrumental in shaping the subsequent phase of our research, the design workshop.

The questionnaire provided a foundational understanding of participants' experiences, preferences, and challenges concerning the use of network simulation tools. These insights not only shed light on the tool's preference but also offered valuable perspectives on the core features and functionalities that these simulation tools are expected to possess.

The design workshop, on the other hand, allowed for a more profound exploration of the relationship between clients and ITSUS Consulting during project execution. It served as a platform where participants actively engaged in design activities aimed at refining and improving the existing tools. The discussions during the workshop played a pivotal role in guiding the enhancements required to make network simulation tools more functional and user-friendly. Ultimately, these improvements aim to ensure the attainment of optimal project conditions and enhance reliability and usability.

## 5.1 Questionnaire Results

The participants' answers shed light on the technical and usability needs and challenges in their day-to-day work. Their answers were directly linked to clients' and projects' needs, they also considered their colleagues and people who use these tools. A total number of six participants completed the questionnaire. They varied in their experience with these tools, with reported experience ranging from 1 to 20 years. This expertise level suggests a mix of both seasoned professionals and newcomers to the field.

### 5.1.1 Tools and Selection Criteria

The tool that received the highest number of mentions among our participants was CORE/EMANE. Alongside this, they reported utilising a diverse range of other network simulation tools, including Opnet, Cisco CML, GNS3, IXLoad, Wanulator, IXIA Network Emulation II, mininet, virtualisation stacks, and a Cisco proprietary emulator. Our participants reported that these tools were chosen primarily to enable testability to overcome the limitations posed by real-world communication services or degraded network conditions (3/6), to benefit from open-source options with appropriate licenses (1/6), and sometimes due to personal preferences of key decision-makers (1/6).

### 5.1.2 Key Features, Needs and Challenges

Our participants identified several essential technical features when asked about effective simulation. These encompass replicability and isolation from the underlying operating system and integration with other tools. The ability to introduce noise or disruption and dynamically manipulate parameters was mentioned by several of our participants (3/6). Physically based modelling methods, and the ability to create network topologies, protocol support, mobility models, scalability, and integration with other tools were also deemed critical. One participant mentioned user-friendly interfaces among a list of technical features. When asked about client expectations from these tools, our participants' answers showed that clients typically expect network simulation tools to offer a range of key features and functionalities that enhance their effectiveness in replicating real-world network scenarios and provide meaningful output. These features include the existence of different network metrics and characteristics.

> *"Common key features would include generic network would be bandwidth, packet loss (and distributions), Latency and Jitter."* - (QP1)

> *"It is important to have a tool that has a traffic flow control, dynamic bandwidth, dynamic latency and other network characteristics, radio WAN and MANET bearer emulation."* - (QP3)

Participants also mentioned that clients commonly expect features such as virtual network topologies, modular architecture, scalability, and integration with other tools. Only One participant completely focused on user-friendliness and simplicity.

> *"I presume clients are looking for ease of use, simple ways of constructing filters to facilitate analysis and visual interface..."* - (QP5)

Our participants offered insights into specific requirements and capabilities that are often anticipated by clients but are not adequately addressed by existing network simulation tools. They emphasised the importance of dynamic profiles to change based on needs and access instead of static ones that provide the same access to all users. They also highlighted the need for defining background traffic profiles, which can enhance the realism of simulations by mimicking real-world network conditions. A lack of robust support for simulating mobility, which is a key aspect of wireless networks, especially in dynamic environments and in degraded network conditions was also noted as a feature that is missing.

> *"There is a need to be able to load in a changing profile rather than a static one. Also, having the ability to define and manipulate background traffic. The current simulation tools offer very little support for mobility which can be a significant barrier to producing reliable results" - (QP1)*

Additionally, participants' answers highlighted the desire for greater performance and scalability as a common request, with users seeking tools capable of handling larger and more intricate simulations while maintaining optimal performance. The importance of accurate and realistic radio propagation modelling was emphasised, indicating a need for tools that offer more precise representations of wireless signal behaviour in various environments. Moreover, the anticipation of upcoming technologies such as 5G and beyond highlighted users' expectations for tools to evolve alongside the changing landscape of wireless networks. Lastly, participants emphasised the significance of an improved user interface to streamline the simulation process.

> *"We need greater performance/scalability, more accurate/realistic radio propagation, more diverse mobility models, 5G and beyond, and improved user interface." - (QP6)*

Despite the usefulness of current tools, our participants highlighted various concerns when asked about the technical limitations, scalability issues, or compatibility considerations. These encompassed issues such as the accurate modelling of physical environments and ensuring compatibility across a spectrum of virtualisation and containerisation platforms. Additionally, our participants focused on listing several unaddressed technical requirements, with notably less focus on usability and user-friendliness aspects. They emphasised the necessity for enhanced software configurability and improved interfaces. Moreover, they expressed technical demands for increased precision in radio propagation modelling, diverse mobility models, dynamic adaptability during real-time operation, and scalability in the context of emerging technologies.

### 5.1.3 User Experience and Usability

When we asked our participants about their client's perceptions of the user experience of these tools, the responses showed different perceptions regarding the client's user experience and usability of the tools. The diversity of viewpoints underscores the complexity of this domain and its intersection with the evolving landscape of technology. A common thread among the responses was the acknowledgment of the uniqueness of each tool and the influence of individual background, and familiarity with the tool in shaping their experiences using the tools, preventing a consensus on user experience.

> *"It depends on the individual's background and familiarity with the software, and the user's particular requirements and expectations. However, I would say that they feel there is room for improvement."* - (QP6)

Some participants (3/6) held a somewhat negative view of current tools, describing them as complex and difficult to configure. This sentiment suggests that certain tools might pose usability challenges, possibly leading to frustration during use.

> *"I cannot answer for clients, but from personal use, they feel like they are years behind technology advances. By this, I mean that they have interfaces that are not particularly user-friendly, and do not take advantage of the much more visual interfaces seen on most applications available today."* - (QP5)

Despite the varied opinions about the client's experiences, all participants agreed that there is a direct impact between the user-friendliness of the tool and the effectiveness of use, underscoring the pivotal role of usability in determining the tools' efficacy and overall impact.

Responses highlighted that usability and user experience significantly influence the effectiveness of tool usage. Tools with underwhelming graphical user interfaces (GUIs) may struggle to convey information effectively, potentially leading to a decrease in user engagement and productivity (2/6).

> *"I would say they are never the stars of the show with underwhelming GUIs and their ability to convey a message being limited."* - (QP1)

Several participants highlighted the difficulties encountered while using these tools, requiring workarounds to navigate through them (2/6). Participants also pointed out that tools with poor usability could lead to fewer people being able to use them effectively, ultimately leading to fewer tests being conducted (2/6), this also can be linked to another answer detailing the steep learning curve associated with these tools, noting that users might focus on learning a single feature that they perceive as essential, missing out on other valuable functionalities due to usability issues.

> *"When tools are complex and frustrating to use, people tend to avoid using them or learn how to use a single feature (the one that they think they need) and miss out on many other very useful features. There is also a steep learning curve."* - (QP5)

Usability and user experience of the visualisation component of wireless network simulation tools were considered highly important. When asked about how the current visualisation is perceived by their clients, our participants reported that their perception of visualisation features varied. While some clients find the visualisations acceptable but not exceptional (3/6), others feel the visualisation is not very good, lacks clarity, and may not effectively convey important information (3/6).

> *"The user experience of these tools is not great. It's a hard thing to get across as the spectrum may not always be visualised."* - (QP1)

All participants agreed about the importance of well-implemented visualisation. They highlighted the need for aids for configuration, ease of understanding, efficient analysis, faster decision-making, and higher adoption rates.

> *"visualisations that are well-utilised are important for ease of understanding, efficient analysis, faster decision making, higher adoption, training and a competitive advantage."*
> - (QP6)

Despite the agreed-upon importance of visualisation, current tools were reported to have less than optimal visuals. Several challenges related to visualisation were noted, including difficulty representing various bearers, constraints in visualising a changing network environment, and the need for a balance between technical complexity and visual appeal.

When asked about the challenges around producing visualisation, our participants indicated that visualisations are often constrained by software limitations. Additionally, dynamic visualisations, in particular, were deemed difficult to generate and master under similar conditions. Commonly produced visualisations reported include 2D schematics with fixed nodes, demonstrations of traffic flow and network layouts, network and traffic intensity maps, as well as tables and figures.

When asked about desired visualisations, our participants reported that visualisations like client heatmaps, RF plots, blackspots, animated demonstrations of dynamic systems, and realistic 3D visualisations are desirable. The need for various user profiles, from specialists to end-users, was considered a major step in enhancing usability and user experience both when using the tools and when visualising the data.

### 5.1.4 Emerging Trends and next steps for design

When our participants were asked about future improvements of these tools and the recent technical trends that would constitute a good addition, participants recommended placing the user at the centre of the experience, focusing on user-centred design principles.

> *"The user needs to be placed at the centre of the experience, not technology."* - (QP1)

They also emphasised the importance of improving initial user experiences, reducing complexity, and enhancing configurability to make the tools more accessible to a broader user base. Lastly, our participants mentioned the integration of virtual reality, dynamic routing, and mesh networks, as additional features to be added to enhance the current tools while demanding engaging, easy-to-use interfaces.

## 5.2 The Design Workshop Results

Informed by the results of the questionnaire, we focused the discussions on the collaboration between our participants and clients while using network simulation tools, drawing on positive and negative aspects. The discussion highlighted the challenges faced by the development team to accommodate clients' demands on different projects. After that, the three design activities helped to compile a list of important features to be added to these tools to make them more effective and less time-consuming. Participants highlighted the importance of adopting a human-centric approach when designing these simulation tools, aiming to enhance usability and fully realise the tool's potential while addressing user frustrations, workarounds, and steep learning curves. It was stated that the existing limitations of these tools have hindered the creation of a collaborative environment where data can be seamlessly shared among different stakeholders and across various parts of the application. In the following sections, we will present the results of the design workshop, offering insights and recommendations provided by the participants.

### 5.2.1 The Design Workshop Participants

The six participants involved in the design workshop had a diverse range of backgrounds and professional experiences. Occupations within the group included software engineering and development, cybersecurity, data science, and roles involving both technical and corporate aspects. The educational backgrounds of the participants included fields such as computer science, cybersecurity, physics, and astrophysics. In terms of experience with network simulation tools, some members were well-versed, having used tools like CORE/EMANE, while others were relatively new to these technologies. Our participants reported experiences within ITSUS Consulting spanning from newly hired members to those with up to 5 years of experience. This amalgamation of expertise and familiarity with network simulation tools contributed to a multifaceted discussion during the workshop, providing a well-rounded perspective on the challenges and opportunities associated with these tools.

### 5.2.2 Challenges of simulation tools while working with clients

To start the discussion, we asked our participants to state what are the main challenges and frustrations they face in their different roles when they use simulation tools while involving the clients. CORE/EMANE was used as the main point of discussion since it is the most accessible simulation tool used by ITSUS Consulting. Our participants described several challenges when using CORE/EMANE in client engagements. They mentioned that demonstrations using the tool often appear ad hoc and unprofessional, leading to difficulties in conveying information to clients. Another challenge might arise when changes on the go are requested by clients during demos which can be time-consuming and involve command-line operations, disrupting the workflow and coming back with working results that cannot be verified.

> *"It always looks ad hoc, it always looks unprofessional. . . Stakeholders may ask for changes to the simulation, which can take 15 minutes of fiddling around with command-line commands. It may or may not work, and even when it does, it can be difficult to understand what is happening. This is because the tool does not provide visual outputs, and what output it does provide is often cryptic."* - (WP3)

The tool's visualisations were also criticised for their lack of clarity. Participants emphasised that the tool sometimes leaves stakeholders to interpret data independently. Mobility-related scenarios were identified as particularly problematic, causing crashes and difficulties in altering parameters on the fly.

> *"Even simple changes to the network, such as moving a node, can cause the simulation to crash. The output of the simulation is often a wall of text, which can be difficult to interpret. There is no intuitive way to know if the simulation has worked correctly. If you want to make a change to the simulation, you have to stop the simulation and start over."* - (WP3)

### 5.2.3 Open Source and APIs

The open-source nature is another strong theme that emerged from the workshop; leading to variances in data quality and library usability. Participants noted that the choice of tools for client projects could impact the quality of the datasets available. CORE/EMANE was recognised for having extensive datasets, but their quality depended on contributors' efforts. The participants raised concerns about datasets varying in quality, ranging from well-structured to hastily created ones.

> *"You have some of the ones that look nicer but are limited, they might only have Cisco stuff, or maybe they only deal with this or that. Whereas the one that tends to have the*

> *most data is CORE/EMANE. But you may get a dataset for it, that may be really good because somebody has done it very well. Or you may get somebody that's half done because they've done it for a specific project for them... it is like the old days of C and C++, you may get a really good library or you may get something that is a bit sketchy."*
> - (WP3)

### 5.2.4 Development Challenges

The discussion about the challenges faced when working with clients led us to directly discuss and emphasise the development challenges to accommodate the project's needs and implement workarounds. Although the GUI was praised for its user-friendliness in representing node types and network topology, there was a consensus that essential parameters controlling network conditions remained hidden behind the scenes. This obscurity made these parameters challenging to manipulate or visualise through the GUI. Participants emphasised the delicate balance required between providing flexibility, such as offering more parameters, and maintaining usability to keep the tool understandable.

> *"Just looking for CORE/EMANE, the GUI is quite straightforward. You see different node types, they're quite visually recognisable, you can see a network topology, you can give it a background, that's pretty much all you can see in a nice format. . . But a lot of what goes behind the scenes to give you interesting network conditions is not visible. . . And for some of these radio models, you've got hundreds of parameters that you could tweak... So from a developer perspective, the more parameters I've got, the more flexible the tool can be. But the harder it is to explain and to make consistent"* - (WP1)

Another challenge that newcomers face in the development team is the steep learning curve, especially when transitioning between different radio models or scenarios. Once they have learned the basics of the tools, developers still face the challenge of inadequate documentation. The documentation is outdated and lacks clarity, and it is often fragmented. This makes it difficult for developers to find the information they need, which adds to the learning curve. To address this challenge, the development team has resorted to collaboratively developing internal documentation. This has helped to improve the documentation, but it is still not perfect.

> *"When it comes to documentation, we found we had to put meat on what's already there and try and figure it out, piece it together and join the dots... because I found the documentation way too out of date."* - (WP2)

Participants noted that while standard routing algorithms were easy to use, customising the tool to meet specific client requests was often a challenge. This was because it required a deep understanding of the tool's inner workings and the ability to make precise adjustments that met the project's requirements.

> *"If I'm presenting it to a stakeholder, I'm not necessarily going to be able to make these changes. It would take developers time to develop it, for example, what would happen if the weather was bad? How would that affect the network? developers would have to go away and do research for the parameters that need to be changed. Whereas in an ideal world, there would be a sliding bar to adjust weather conditions."* - (WP3)

Customisation can be difficult and time-consuming, as it requires substantial research efforts by developers to identify the appropriate parameters and learn about the many parameters available in CORE/EMANE. Some of these parameters are not intuitive, and it can be difficult to understand their impact on the simulation. Additionally, the log that is available to developers lists the parameter names, but some of these names are truncated, making it even more difficult to interpret the values.

> *"The nice thing about CORE is that it comes bundled with the most common types. But obviously, they are the simplest ones that are most likely to be used in some form by people until they wish to get to more interesting scenarios. And then when you want to customise it, you kind of always have a steep learning curve of how do I get there, I've got to almost ingest everything to even start"* - (WP1)

### 5.2.5 Data Visualisation

During the discussion, the GUI design of CORE/EMANE was mentioned as easy to use but requiring new features and additions. However, many of the parameters are not visually represented. In response to the question about data visualisation and its challenges, one participant highlighted the importance of data visualisation that is clear and visually appealing. This is essential when communicating complex network simulation results to non-technical stakeholders. There was an emphasis on user-friendliness for an intuitive interface that simplifies data interpretation, making it accessible to a wider audience. Similar requests were identified in the results of our survey, where participants stressed the importance of dynamic user profiles. This led us to develop user personas and actively engage our participants in defining the specific needs and access rights for these profiles as described in Section 5.2.9.

> *"My role involves speaking to customers and ensuring they can easily interpret and visualise the data. The data must be presented in a clear and visually appealing way... This can be challenging when dealing with non-technical customers who simply want to know if something will work in a given situation. So, presenting data in an easily understandable way is a priority for us."* - (WP5)

Our participants' responses emphasised the importance of clear data visualisation and the challenges of dealing with raw, unprocessed data in complex simulations. The participants acknowledged the need for user-friendly and comprehensive visualisation tools to make sense of the data generated by simulations. Currently, CORE/EMAN does not have a built-in visualisation for different data types, users resort to using other 3rd-party tools to produce the desired visualisation.

> *"CORE does not provide any visual output. It only provides numerical output, which can be difficult to interpret. To get any visual output, you need to rely on third-party tools."* - (WP3)

### 5.2.6 How Network Simulation Tools Benefit Clients

When asked about the benefits of network simulation tools to clients, our participants stated that stakeholders highly prize the capacity to emulate and simulate complex networks. This is especially significant when dealing with scenarios involving a large number of nodes or intricate configurations that would be prohibitively expensive and challenging to recreate physically. In addition to cost considerations, these simulations serve as a valuable risk mitigation strategy. Clients can run demonstrations to assess the viability of their concepts before committing to costly hardware implementations. This proves particularly crucial in cases with extended lead times for hardware deployment, where any misjudgement can lead to substantial delays and financial repercussions.

> *"Getting 64 chips communicating with each other is difficult and expensive. This is because each chip is a network unto itself, and they need to communicate with each*

> *other in a coordinated way. Without the right simulation tools to test, this can be a complex and error-prone process."* - (WP3)

Furthermore, simulation tools provide strong support for research and development endeavours. They offer a flexible environment for experimenting with new ideas and concepts, ultimately fostering innovation. These tools are adaptable and accommodate different scenarios, making them essential for adapting to evolving client needs and exploring hypothetical scenarios. A distinguishing feature of certain simulation tools, such as CORE/EMANE, is their ability to incorporate real-world data into simulations. This capability enhances the realism and accuracy of the simulations, making them even more valuable to clients. Additionally, simulations are not only beneficial for addressing current requirements but also for preparing for future challenges. They allow for the exploration of various hypothetical scenarios, providing clients with a comprehensive view of potential developments and challenges.

It is important to recognise that while simulations offer a multitude of advantages, they are not without challenges, as detailed earlier. These challenges encompass integration complexities, manual steps in setup and execution, limitations in data sharing, and difficulties in adapting simulations to future requirements. Many of these projects span over several tools leading to fragmentation. However, our participants while acknowledging that, highlighted that the difficulty lies in developing a single tool that includes all of these features. They stated that it is often more practical to accommodate different projects by working on workarounds until a unified tool is operable.

> *"Many of these projects are proof-of-concept projects. This means that they are intended to demonstrate the feasibility of a particular idea. As a result, it is not always important if it is a kludge or a quick and dirty solution. The goal is simply to show that the idea can work. However, the downside of this approach is that it can lead to a patchwork of kludges. This is because each project is designed to meet the specific needs of a particular client. Unless someone invests in building a full-fledged system, there will always be some kludges. This is because it is not always possible to anticipate the needs of all potential customers in advance. As a result, there will always be some cases where a quick and dirty solution is the best option."* - (WP1)

Finally, one participant pointed out that the lack of a unified, proven working tool directly contributes to the lack of data sharing between different entities. This is because clients may be hesitant to share their data with other entities, as they may not want to promote their networks. This reluctance can limit the availability of data for projects, as it can be difficult to obtain data from multiple sources.

> *"From a commercial perspective, if there was a unified, proven working tool, more companies in the defence industry would be willing to share their data for the tool. This is because it would be in their best interest to do so. However, they do not want to be the only ones to do so. They would be happy to share their data if they could also see how other companies' data works in this next-generation environment. However, they will not share their data until the tool is ready."* - (WP3)

### 5.2.7 Activity 1: Designing the GUI Interface

In the first designing activity a snapshot of the CORE/EMANE interface shown in Fig. 5.1 was shared with the participants. They were first asked to indicate what they liked about the interface. Their responses are shown in Table 5.1.

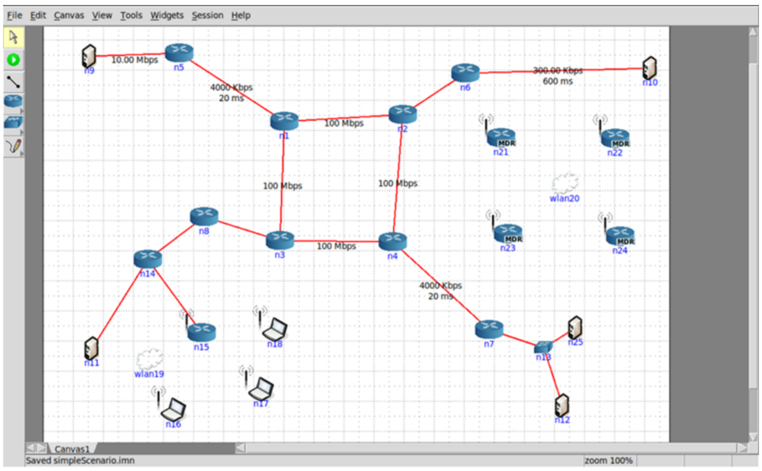



Figure 5.1: CORE/EMANE Interface

Table 5.1: CORE/EMANE Interface Positive Features

| Positive Feature | Feedback | Quotes |
|---|---|---|
| Clear and User-Friendly Design | The clear and user-friendly design of CORE/EMANE interface was appreciated, emphasising the ease of dragging nodes around and customising the interface for better usability. | *"I think it's clear. And you can drag those nodes around, you can make it nice."* - (WP2) |
| Intuitive Icons | The icons were described to be representative enough for users to quickly grasp their functions, even with minimal prior knowledge. | *"The icons are mostly intuitive. You can sort of see the wireless radio ones... if you had even just a little bit of knowledge, you probably would be able to explain."* - (WP1) |
| Identification of Nodes | It was pointed out that the interface effectively distinguishes wireless nodes by featuring a small antenna icon, aiding users in identifying these specific nodes. | *"You can detect the ones that are wireless because they've got a little antenna."* - (WP3) |

CORE/EMANE Interface Positive Features (continued)

| Positive Feature | Feedback | Quotes |
| --- | --- | --- |
| Editing Capabilities | The interface provides editing capabilities. Users can conveniently modify connections by right-clicking, adjusting bandwidth, adding labels, and managing various properties to suit their needs. | *"With a diagram, you're able to right-click the connections and change the bandwidth. You can change properties and draw labels."* - (WP5) |

After that participants were given the task of using papers and pens to design the added features and functions they would like to see added to the tool's interface. Participants were given the choice to jot down on the printed interface or use blank papers to complete the task. All the drawings for this activity are included in Appendix D. As an example, Fig. 5.2 depicts the required features to be added to the interface like adding radius, battery life meter, and other capabilities. Table 5.2 lists the features our participants decided would be helpful to be added to the interface.

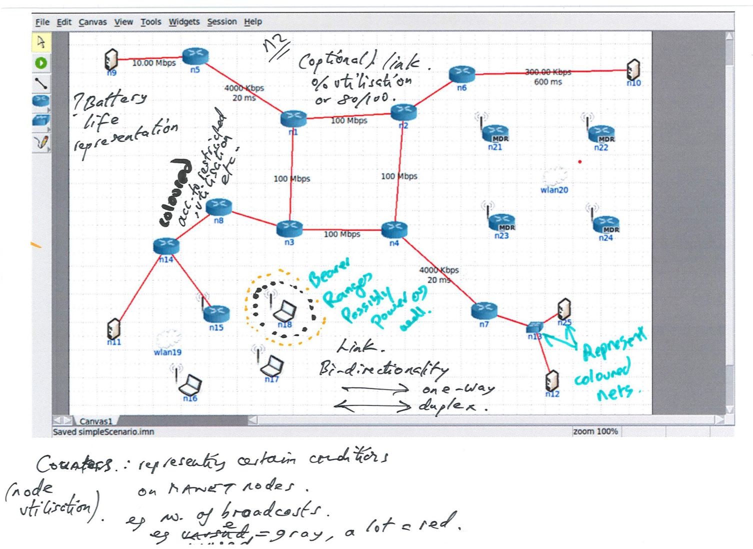



Figure 5.2: Activity 1- Participants Added Features

Table 5.2: CORE/EMANE Suggested Added Features

| Suggested Feature | Category | Explanation | Quotes |
|---|---|---|---|
| Network Conditions Toggle | Visualisation | Allows users to switch on/off visual indicators to quickly identify network conditions like congestion or bottlenecks. | *"I find it useful to have a way to turn on and off certain features of the tool so that I can see the effects visually. For example, I can turn on the visualisation of fat connections to see at a glance which connections are likely to be bottlenecks."* - (WP1) |
| Network Topology Toggle | Visualisation | Provides the option to switch between a full network topology view and a simplified view for easier analysis of specific links and conditions. | *"I would prefer to see a simple network topology like the one presented, but I would also like the ability to toggle on additional information, such as bandwidth. This would allow me to see at a glance which links are precarious, or likely to become bottlenecks."* - (WP1) |
| Link Overlap and Radius | Visualisation | Displays areas of overlap between wireless nodes to help users understand potential interference or connectivity issues. | *"It would be useful to see how much overlap there is in the wireless radius because the radius might be bigger than expected"* - (WP1 ) |

CORE/EMANE Suggested Added Features (continued)

| Suggested Feature | Category | Explanation | Quotes |
|---|---|---|---|
| Wireless Connectivity Visuals | Visualisation | Enables users by a glance to recognise which node is connecting to which WLAN. | *"In a wireless network, if I had a dotted line to understand which node is connecting to which WLAN, I'd know if it were configured to connect to the wrong WLAN, and that's why it's not talking to its neighbours."* - (WP1) |
| Property Customisation and Interface Legends | Customisation | Permits users to select and display specific properties or details of network nodes, enhancing the ability to tailor node information. | *"It might be useful to have some sort of key or legend. WP1 mentioned you could right-click on the nodes and get all different sorts of properties. So, it might be nice just to be able to choose which of those properties are displayed next to each of the nodes."* - (WP4) |
| Node Differentiation | Customisation | Allows users to assign different icons or labels to nodes to distinguish their types, aiding in identifying critical network components. | *"Adding the ability to change node icons to indicate different types of nodes, different types of routers, and so on."* - (WP4) |

CORE/EMANE Suggested Added Features (continued)

| Suggested Feature | Category | Explanation | Quotes |
|---|---|---|---|
| Node Annotation, Notes, and Text Customisation | Customisation | add the ability to add textual notes or annotations to nodes, facilitating documentation and highlighting essential node information. | *"adding the ability to change names and texts directly... to be done easily on the diagram, just click on the name to change it. Also, add the ability to add notes and annotation to nodes and simulations "* - (WP4) |
| Battery Life | Reliability/ Visualisation | Add the ability to visualise the remaining battery life of devices or nodes in the network, allowing users to assess the impact of battery levels on network performance. | *"Battery life is something that would be very useful. If you run through different scenarios, you can show that the battery changes."* - (WP3) |

CORE/EMANE Suggested Added Features (continued)

| Suggested Feature | Category | Explanation | Quotes |
|---|---|---|---|
| Parameter Sliders | Visualisation/ Customisation | Add a slider to adjust and visualise different network parameters like traffic and different conditions like weather, helping users analyse network behaviour under varying conditions. This type of slider can also be extended to other types of parameters to enable testing under dynamic conditions | *"Traffic volume slider, to increase or decrease the traffic and monitor what would happen..."* - (WP5) |
| Alternate Path Indication | Reliability/ Visualisation | Adding the ability to highlight the presence of alternative paths for data transmission to enhance network reliability assessment and fault tolerance. | *"Adding total reliability, showing if there's at least one alternate path for every source, destination, combination, or not, and then assess if it is metrically reliable, if not, flag something up."* - (WP2) |

CORE/EMANE Suggested Added Features (continued)

| Suggested Feature | Category | Explanation | Quotes |
|---|---|---|---|
| Network Connectivity/ Segmentation Visualisation | Visualisation | Visualise network connectivity, potentially with colour coding or partitioning, to help users identify network segments and potential vulnerabilities. | *"To visualise network segmentation, the tool can colour-code different segments of the network. It can start with a single box to represent the entire network. If the network becomes segmented, the box can split into two..."* - (WP3) |
| Event Simulation Controls | Customisation | Controls for simulating network events, such as traffic and link changes. | *"...to have the ability to not just detect when events have happened, but to create them artificially, like ramp up the traffic, see what happens, delete selected links automatically, and then re-establish them, just to see what will happen and to test."* - (WP2) |
| Performance Thresholds | Customisation | Allow users to set performance thresholds for different types of data (e.g., voice, video) to assess how well each performs under varying network conditions. | *"You could set some kind of thresholds for what data you want to be passing over your network, and therefore how well each of those are performing, this can be useful..."* - (WP6) |

### 5.2.8 Activity 2: Required Visualisation and Data Types

After the first activity, the participants were asked to use paper and pens to draw different graphs and visualisations that they would like to see in the tool, an example is shown in Fig. 5.3. All of the drawings from this activity are included in Appendix E. Table 5.3 lists the visualisations and data our participants discussed and agreed would be helpful to add to the tool.

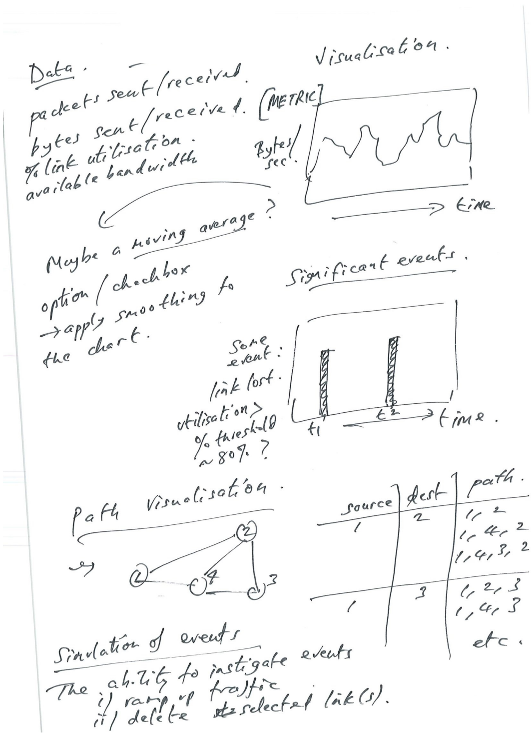



Figure 5.3: An Example of Required Visualisations

Table 5.3: CORE/EMANE Suggested Visualisation

| Visualisation | Explanation | Data/Feature | Quotes |
|---|---|---|---|
| Bandwidth | visualises available bandwidth on network links. | Available bandwidth, Utilised bandwidth | *"I would like to see a visualisation of the bandwidth usage for different links in the network. This would show me how much bandwidth each link is using, and whether it is being maxed out. This information could help identify bottlenecks in the network."* - (WP1) |
| Colour-Coded Delay | Displays link delays using colour coding for quick assessment. | Delay | *"It would be helpful to visualise delay in a colour-coded way so that I can see which links are experiencing more delay than others. This would allow me to identify areas of the network that need to be improved."* - (WP1) |

CORE/EMANE Suggested Visualisation (continued)

| Visualisation | Explanation | Data/Feature | Quotes |
|---|---|---|---|
| Path Visualisation | Provides a visual representation of different paths including the best path to a destination. This can be combined with the alternate path indication in Table 5.1. | Path | *"I would like to be able to toggle different visualisation options to see what is most useful for me. For example, I could toggle the best path to see the shortest path between two nodes, or the best path to avoid a certain node. This would allow me to quickly see different perspectives of the network and make informed decisions about how to optimise its performance"* - (WP1) |
| Device Health Indicator | Visual indicator showing the health of network devices. | Device health | *"If a device is dropping a lot of packets, it is likely to be a faulty device. This can cause problems with the performance of the network. It would be helpful to have a visualisation that shows which devices are dropping packets so that I can quickly identify and troubleshoot any problems."* - (WP1) |

CORE/EMANE Suggested Visualisation (continued)

| Visualisation | Explanation | Data/Feature | Quotes |
|---|---|---|---|
| Node Reachability Graph/ Colour Coding | Illustrates network reachability, showing connections to nodes, this can be done by using different colours to represent different levels of connectivity. | Network reachability | *"It would be helpful to have a visualisation that shows me which nodes in the network are reachable from a particular node. This would be useful for troubleshooting network issues, such as when a broken connection occurs."* - (WP1) |
| Node Transmission Heatmap | Heatmap displaying the number of times each node transmits data. | Transmission frequency | *"The number of times a node transmits can be used as a metric, and it can be represented as a heatmap. This can help identify nodes that are broadcasting a lot of traffic, which could indicate a bottleneck in the network and/or determine security risks."* - (WP3) |

CORE/EMANE Suggested Visualisation (continued)

| Visualisation | Explanation | Data/Feature | Quotes |
|---|---|---|---|
| Traffic vs. Throughput Graph | Graph depicting the relationship between traffic and network throughput. | Traffic volume, Throughput | *"I think it would be helpful to graph traffic versus throughput after running a simulation. This would show how the throughput changes as the traffic increases. This information could be used to assess the performance of wireless access points and their range."* - (WP6) |
| Black Spots | Highlights network black spots or areas with connectivity issues. Another suggestion was to represent the Wi-Fi range as Pac-Man to account for obstacles or constraints like mountains affecting signal propagation. | Black spot locations, Connectivity status | *"If you've got a geographical map, You can highlight black spots on the map to show areas with poor connectivity."* - (WP5) |

CORE/EMANE Suggested Visualisation (continued)

| Visualisation | Explanation | Data/Feature | Quotes |
|---|---|---|---|
| Bandwidth Utilisation Graph | Graphical representation of bandwidth utilisation over time with a moving average checkbox. | Bandwidth/ time | *"It would be helpful to visualise the data received over time with respect to the bandwidth. Also, It would be helpful to have a checkbox that allows you to apply a moving average to the data. This would smooth out the data and make it easier to see the general trends, rather than the individual spikes."* - (WP2) |
| Event Detection Indicator | Visual indicator for significant events in network data. | Event data, Threshold exceeded events | *"Not just raw data, but like significant events... This could be done by creating a bar chart where the height of each bar represents the amount of data received in a given period. If something significant happens, like losing a link or exceeding a certain threshold, the graph should highlight it."* - (WP2) |

CORE/EMANE Suggested Visualisation (continued)

| Visualisation | Explanation | Data/Feature | Quotes |
|---|---|---|---|
| Interactive Graphs | Generate interactive graphs that allow users to visualise network data, possibly on a node-by-node basis. | Network data, Node-specific data | *"If different sliders that can be used to change the data in the simulation are implemented, this could be used to produce graphs of the data on a node-by-node basis."* - (WP5) |
| Customisable Dashboards and Reports | Allow users to create custom dashboards and reports, configuring them according to their specific requirements, providing the ability to include or exclude various visual elements. | User preferences, All Data Types | *"You can have a dashboard that you can configure to your own requirements... This means that you can choose which widgets to display, how they are arranged, and how they are customised."* - (WP5) |

### 5.2.9 Activity 3: User Profiles

The survey responses pointed out a significant demand and limitation concerning dynamic profiles within the existing tools. In addition, the workshop discussions brought to light the necessity to accommodate a range of users' requirements and needs, including individuals with limited technical know-how (e.g. some of the participants' clients and management teams). Consequently, it became evident that developing a typology of user needs was imperative.

We created a list of six personas: researchers, network engineers, developers, management, clients, and end-users, based on the insights collected from the questionnaire responses, intending to incorporate these personas into the development of dynamic profiles. Our participants were then provided with descriptions of these personas along with their respective needs. We asked our participants to brainstorm the requirements and access privileges for each persona. To facilitate this process, we divided the participants into two groups. The first group, comprising technically adept participants, tackled personas 1 to 3, which were more technically oriented. The second group, focused on personas 4 to 6. All participants' notes can be found in Appendix F. Table 5.4 lists the personas used with their definitions and needs, then Table 5.5 lists the profile capabilities and data access rights suggested by our participants.

Table 5.4: Personas Descriptions and Needs

| Persona/Profile | Description and needs |
| --- | --- |
| Researchers | Researchers are typically engaged in studying and analysing various aspects of network technologies. Their duties involve conducting experiments, gathering data, and deriving insights from network simulations. They need tools that offer detailed data collection capabilities, flexibility in experimenting with different scenarios, and robust analysis features to draw meaningful conclusions from their research. |
| Network Engineers | Network engineers are responsible for the design, implementation, and maintenance of network infrastructure. Their tasks include configuring network components, optimising network performance, and troubleshooting connectivity issues. They require simulation tools that allow them to model and test network configurations before actual deployment, ensuring reliability and optimal performance. |

Personas Descriptions and Needs (continued)

| Persona | Description and needs |
| --- | --- |
| Development Teams | Development teams focus on creating and improving the simulation tools themselves. They are responsible for coding, debugging, and enhancing the tool's features. Their needs encompass user-friendly interfaces for tool development, efficient coding environments, and the ability to integrate new functionalities seamlessly |
| Management | Management personnel oversee the broader aspects of project implementation. They need to make strategic decisions based on simulations' outcomes. Their requirements include clear visualisations of simulation results, concise summaries, and the ability to make informed decisions about resource allocation and project direction. |
| Clients | Clients are the stakeholders who fund or commission the projects. Their primary concern is achieving their desired outcomes within the allocated budget and time frame. For them, simulation tools should offer clear presentations of the project's progress, understandable visualisation, flexibility when editing, potential risks, and alignment with project goals. |

Personas Descriptions and Needs (continued)

| Persona | Description and needs |
| --- | --- |
| Non-Specialist End-Users [1] | Non-specialist end-users are individuals who will eventually use the technology or system that the simulation is being developed for. They are typically users of the system without any specialised technical or diagnostic roles. They need interfaces that are intuitive and easy to use. The system should integrate smoothly with the existing systems they use. They are looking for workflows that enhance the efficiency of their tasks. |
| Specialist End-Users | Specialist end-users have a deeper involvement in the technology or system. They may include operators or experts in a specific field related to the system's functionality. They need access to diagnostic tools and capabilities to assess the system's performance and troubleshoot issues. Additionally, their roles may require them to have a deeper understanding of the system's technical aspects. |

[1] We first gave one description for end-users but a further distinction was added by our participants stating there are two levels of end-users, specialist and non-specialist as detailed in Table 5.5

Table 5.5: Profile Capabilities and Data Access

| Persona/Profile | Profile Capabilities/ Access Rights | Quotes |
|---|---|---|
| Researchers | - Researchers should have access to change almost every parameter without altering the core functionality.<br>- They can request functionality changes from developers.<br>- They can alter the laws of physics within their simulation by entering and manipulating parameters beyond what is allowed in real life.<br>- All changes should not be committed but discarded after the session. | *"They effectively got free rein to effectively alter the laws of physics in their simulation if they need to."* - (WP1, WP2, WP3) |
| Network Engineers | - Network engineers should have limited access to parameters.<br>- They cannot change core functionality but can configure components.<br>- Any parameter customisation must be aligned with actual physical hardware capabilities and what it allows. | *"The only parameters they get to change are what the router or firewall would allow them to change in reality."* - (WP1, WP2, WP3) |

Profile Capabilities and Data Access (continued)

| Persona/Profile | Profile Capabilities/ Access Rights | Quotes |
|---|---|---|
| Development Teams | - Developers have access to all parameters and can change functionality.<br>- They can add, remove, or modify parameters and code.<br>- Developers play a crucial role in making or breaking the system. | *"They have access to all the parameters, and they can change the parameters, change the functionality. They get to add and remove parameters, change the way things work, and change the way the code works. A developer realistically can make or break the system."* - (WP1, WP2, WP3) |
| Management | - Management should have access to dashboards and reports.<br>- They should be provided with simple indications of how the project is performing. | *"In terms of management, they don't care how it works, they just want to see the final results. Reporting is the most important thing for them. Some sort of a dashboard or exportable report, and they can benefit from a simple indication of how the project is doing."* - (WP4, WP5, WP6) |

Profile Capabilities and Data Access (continued)

| Persona/Profile | Profile Capabilities/ Access Rights | Quotes |
|---|---|---|
| Clients | - Clients should have the ability to look at different test scenarios by having the ability and enough indications to make assessments on which scenarios work best. This can be done by presenting them with different comparisons of scenarios.<br>- They should have limited access to parameters.<br>- They should have the ability to make top-level changes easily by manipulating parameters. In addition to having the ability to use sliders for adjustments, for example, to assess the impact of adding a large amount of traffic.<br>- They should have the ability to view identified problems and vulnerabilities to make informed decisions. | *"You could have limited edition, limited access to parameters. So the customer could turn around, and say, Well, what if that Wi-Fi was suddenly taken out? And what if we put x in instead of y? So they can change the parameters, but they don't want to get into the nitty-gritty of it. They want top-level changes to show results based on scenario changes. For example, the client could ask to change the Wi-Fi settings to reflect a sandstorm, but they would not ask for granular changes."* - (WP3) |

Profile Capabilities and Data Access (continued)

| Persona/Profile | Profile Capabilities/ Access Rights | Quotes |
|---|---|---|
| Non-Specialist End-Users | - Non-specialist end-users should have basic access to the system's features without delving into technical or diagnostic aspects.<br>- They should have clear and understandable visual representations of system status and performance.<br>- They should have the ability to make top-level changes and make small changes; however, they do not require extensive customisation capabilities. | *"We have two distinct types of end-users: non-specialist and specialist. A non-specialist end-user is someone who uses the software to perform basic tasks, such as moving objects around. A specialist end-user is someone who uses the software to investigate problems or do testing."* - (WP3) |
| Specialist End-Users | - Specialist end-users should have extensive access to the system's technical parameters and diagnostic features.<br>- They should have the ability to use the system for testing different scenarios and making informed decisions.<br>- They should have the ability to make rapid changes to assess the system's behaviour without the involvement of development teams. | *"The specialist end-user needs more access to diagnostics than the normal end-user. This is because they need to be able to see more information to troubleshoot problems or do testing."* - (WP3) |

# Chapter 6

# Discussion

This chapter will discuss the prominent results and insights gained from our participants in the questionnaire and workshop. The results of our study have provided a comprehensive understanding of the technical and usability needs and challenges associated with network simulation tools. Through the data gathered from both the questionnaire and the workshop, we have gained a clearer understanding of the requirements and constraints associated with these tools. We have compiled and categorised a list of features for potential future development, guided by the valuable input provided by our participants.

Participants primarily highlighted technical aspects when discussing limitations, reflecting their professional backgrounds and training. Regarding technical features and needs, participants emphasised several critical aspects for effective simulations. These encompassed repeatability, isolation from the underlying operating system, integration with other tools, the ability to introduce noise and manipulate parameters, and support for physically based modelling methods, network topologies, and protocol support. Scalability and integration with other tools were also deemed essential.

The usability and user experience of network simulation tools were a central focus of the design workshop. Participants held diverse perceptions regarding clients' user experiences and the usability of the tools, highlighting the complexity of this domain. Some participants expressed negative views of current tools, describing them as complex and challenging to configure. However, there was no consensus on user experience due to the subjective nature of this aspect. Despite the varied opinions, all participants agreed on the direct impact of user-friendliness on the effectiveness of tool usage. Our participants also highlighted the influences of well-implemented data visualisation, particularly in communicating complex simulation results to non-technical stakeholders.

## 6.1 Focus on Technical Features/ Issues

It is a common observation throughout the study that participants tend to focus on technical aspects when discussing limitations of network simulation tools, detailing what technical features would be useful, and only discussing usability issues and features when explicitly prompted. This can be attributed to the participants' perspectives and the dynamics of working with these complex tools. Many participants approach their work with the primary goal of achieving certain technical functionalities or outcomes. They may be conditioned to prioritise these functionalities during their evaluations, often overshadowing usability concerns. They might perceive usability as secondary to functionality.

Another possibility might be that participants may not perceive usability issues as limitations in themselves but rather as impediments to achieving technical goals. Thus, they might discuss usability only when it becomes a significant hindrance. Lastly, the nature of network simulation tools is highly technical; as a result, participants may view these tools primarily as means to technical ends which can make them more prone to prioritising technical aspects in their assessments.

## 6.2 Technical Shortcomings

Our participants highlighted many of the technical shortcomings they face in their day-to-day work, from lack of replicability to constraints in manipulating parameters and maintaining the reliability of the simulation scenario. The network simulation tools utilised in different scenarios are usually tools that were built for general simulation and general use without any focus on the context of areas of operation. When these tools are used in a specific industry, many of the limitations of these context unaware tools become apparent.

Our findings align with the emphasis that there is a notable distinction between the simulation environments used for commercial purposes and those required for military applications [70]. The researchers argued that commercial communication simulation software is not directly suited for military contexts. Therefore, to adapt these tools for military communication network modelling and simulation, a comprehensive evaluation is needed to align them with the specific requirements of military communication simulations.

This evaluation process allows for necessary modifications to be made to the existing tools to meet the unique demands of military scenarios.

## 6.3 Usability Shortcomings

While much of the focus in network simulation tools often revolves around technical functionalities, our findings, in alignment with related research in network management tools research, bring to the forefront the crucial issue of usability faced by users and clients when implementing projects.

Our participants' experiences shed light on the diverse perceptions of clients' user experiences when interacting with these tools. This diversity underscores the complexity of this domain and how it intertwines with the evolving technology landscape. Clients generally struggle with the interfaces to understand the numerical outputs of these tools. Simple means to manipulate different simulation scenarios by altering simple parameters or changing conditions is a common request by clients. These sentiments reaffirm [54] conclusions that handling a substantial amount of data to make decisions is a very challenging task if the methods employed for processing and presenting the data are not tailored to the specific task at hand.

It is noteworthy that our findings reveal a common thread among participants – the direct relationship between user-friendliness and the effectiveness of tool usage. This connection reinforces the pivotal role that usability plays in determining the efficacy and overall impact of network simulation tools. The fact that usability issues can potentially hinder these tools from realising their full potential resonates with findings from usability research indicating that perceived ease of use and output quality were significantly associated with perceived usefulness [71, 72].

The challenges highlighted in our findings underscore the importance of the graphical user interface (GUI) in these tools. While the GUI in the highlighted tool, CORE/EMANE, was praised for it is simplicity and clarity in a user-friendly manner, our participants pointed out that essential parameters controlling network conditions are not easily accessed. This lack of customisation makes these parameters challenging to manipulate or visualise through the GUI leading to a steep learning curve, which, in turn, can limit the tools' accessibility to users with varying technical proficiency levels [49].

## 6.4 Fragmentation and Multi-Tool Utilisation

Our findings shed light on a prevalent issue in the domain of network simulation tools, demonstrating that tools like CORE/EMANE which was originally developed with a military context in mind, still exhibit many of the shortcomings commonly found in general-purpose network simulation tools. Our findings align with prior research that has indicated the persistence of challenges across various simulation platforms when used for specific domains and industries [70].

Our findings highlighted that fragmentation makes it challenging to maintain consistency across the project and can result in disjointed simulations and intensive investments of effort and time. It becomes difficult to maintain consistency across different phases of a project when each tool operates with its own set of interfaces, configuration procedures, and data formats. Additionally, different simulation tools may not integrate seamlessly, leading to compatibility issues.

Incompatibility can lead to time-consuming workarounds and may even require custom development to bridge the gaps between tools. It is not uncommon for simulations to produce outputs that are incompatible with each other, making analysis and interpretation difficult. In addition to compatibility challenges, the increased learning curve associated with multiple tools can slow down project progress. Team members must invest time in learning how to use each tool effectively. This complexity may result in a knowledge gap within the team, where some members are proficient in one tool while others are experts in another, further complicating collaboration. As projects grow in complexity or scale, the challenges associated with using multiple tools become more pronounced. Scalability becomes an issue when juggling multiple tools, data sharing and results across multiple tools can be cumbersome; this can lead to data loss, errors, and additional manual work.

## 6.5 Open Source Nature of the Tools

Many of the utilised simulation tools in public and research are open source, our participants highlighted the issues arising from the open-source nature of CORE/EMANE resulting in inconsistent documentation and mismatched APIs. While these tools present opportunities for innovative research and experimentation, their limitations in documentation, version control and API integration should be carefully considered by users and researchers.

Unlike commercial simulators, open source projects often suffer from insufficient resources and contributions dedicated to documentation [73]. As a result, understanding and tracing codes across different versions can become challenging, hindering efficient development and troubleshooting. This aligns with [26, 12] conclusions that although these tools benefit from openness and community contributions, they are affected by the lack of proper documentation. With a broader range of contributors, maintaining systematic and complete documentation becomes more difficult, leading to potential gaps in understanding and utilising the tools.

Another related shortcoming is the lack of robust version control support and API integration. As open-source simulation tools evolve with new features and updates, the lack of version control can make it hard to manage changes and ensure backward compatibility [74, 75]. Users may find it challenging to migrate from older versions to newer ones, impacting the longevity and applicability of open-source simulation tools.

# Chapter 7

# Conclusion and Recommendations

As the demand for network simulations continues to increase, our research has provided valuable insights into the needs, challenges, and opportunities that professionals face while using network simulation tools. Through a combination of questionnaire responses and a design workshop, we have explored the technical and usability aspects of these tools, shedding light on the current state of affairs and identifying areas for improvement.

It is imperative to address the technical and usability issues plaguing these tools. Equal efforts should be made to introduce new technical capabilities coupled with usability considerations to ensure making the most out of their functionality. In light of our findings, it is evident that network simulation tools can benefit from enhancements that prioritise user-centric design, simplicity, and flexibility. By making tools more user-friendly and adaptable to various scenarios, we can enhance their overall effectiveness and impact. Integration of emerging technologies can add exciting new dimensions to these tools, making them more engaging and powerful.

Our research describes the importance of continuous improvement in network simulation tools to meet the evolving demands of professionals in diverse industries. By prioritising user experience, simplifying interfaces, and embracing emerging technologies, we can unlock the full potential of these tools, ultimately advancing the field and contributing to more efficient and innovative network simulations.

## 7.1 Recommendations

The features and upgrade requirements gathered form important contributions for the next steps in developing and enhancing these tools for better usability, efficiency, and adaptability in different contexts and industries. For that, the following recommendations should be taken into consideration for any development of new tools or upgrades for current tools:

- **User-Centred Design:** One of the prominent recommendations from this study is the importance of placing the user at the centre of the tool development process. This entails creating flexible tools with flexible user profiles that accommodate the needs of each user group. This approach prioritises the user's needs, preferences, and experiences, ensuring that tools are intuitive, efficient, and ultimately more effective. It underscores the importance of creating tools that meet technical requirements and are also user-friendly and accessible.

- **Reducing Complexity by Enhancing Interfaces and Implementing Data Visualisation:** This includes streamlining the user interface and reducing the obscurity of essential parameters. Any new development or upgrade should consider improving graphical user interfaces (GUIs) to convey information effectively and enhance user engagement and productivity. Additionally, it is necessary to enhance the visualisation components of these tools to aid configuration, understanding, analysis, and decision-making.

- **Technical Upgrades:** Technical upgrades and customisation play a vital role in the effectiveness of network simulation tools. To enhance their adaptability, software configurability should be a focus. This means allowing users to customise various tool parameters to align with their specific requirements, thus increasing the tools' flexibility. Additionally, performance and scalability should not be overlooked. As simulation scenarios become more complex, it is essential to ensure that the tools can handle these increased demands while maintaining optimal performance. The accuracy of radio propagation modelling should be continuously improved to provide realistic representations of network behaviour across various environments.

- **Incorporating Vulnerability Assessment Capabilities:** It is vital as network environments become more complex to address security concerns while using these tools by incorporating vulnerability assessment capabilities directly into the tools. This would allow users to identify potential weaknesses in their network configurations, applications, or devices during the simulation phase, facilitating proactive security measures. This integration can provide valuable insights into network vulnerabilities and assist in developing robust security strategies.

# Bibliography


[1] "The network simulator," https://www.isi.edu/nsnam/ns/, accessed July 20th, 2023.

[2] T. R. Henderson, S. Roy, S. Floyd, and G. F. Riley, "ns-3 project goals," in *Proceedings of the 2006 Workshop on ns-3*, 2006, pp. 13–es.

[3] "Riverbed Support: OPNET Modeler," https://support.riverbed.com/content/support/software/opnet-model/modeler.html, accessed: 27th November 2023.

[4] S. Dinesh and G. Sonal, "Qualnet simulator," *International Journal of Information & Computation Technology, ISSN*, pp. 0974–2239, 2014.

[5] A. Varga, "Omnet++," in *Modeling and tools for network simulation*. Springer, 2010, pp. 35–59.

[6] W. Du, H. Zeng, and K. Won, "Seed emulator: an internet emulator for research and education," in *Proceedings of the 21st ACM Workshop on Hot Topics in Networks*, 2022, pp. 101–107.

[7] K. Gökarslan, "Menes: Towards a generic, fully-automated test and validation platform for wireless networks," *arXiv preprint arXiv:2006.02270*, 2020.

[8] L. Veltri, L. Davoli, R. Pecori, A. Vannucci, and F. Zanichelli, "Nemo: A flexible and highly scalable network emulator," *SoftwareX*, vol. 10, p. 100248, 2019.

[9] T. A. R. V, E. Gamess, and D. Thornton, "A survey of wireless network simulation and/or emulation software for use in higher education." in *ACM Southeast Conference*, 2021, pp. 63–70.

[10] A. Nayyar and R. Singh, "A comprehensive review of simulation tools for wireless sensor networks (wsns)," *Journal of Wireless Networking and Communications*, vol. 5, no. 1, pp. 19–47, 2015.

[11] D. Mahrenholz and S. Ivanov, "Real-time network emulation with ns-2," in *eighth IEEE international symposium on distributed simulation and real-time applications*. IEEE, 2004, pp. 29–36.

[12] J. Pan and R. Jain, "A survey of network simulation tools: Current status and future developments," *Email: jp10@ cse. wustl. edu*, vol. 2, no. 4, p. 45, 2008.

[13] J. Wang, P. Hu, Y. Zhang, and J. Wang, "A comparison of discrete event simulator and real-time emulator for mobile ad hoc network," in *International Conference on Machine Learning and Intelligent Communications*. Springer, 2022, pp. 63–74.

[14] A. Zarrad and I. Alsmadi, "Evaluating network test scenarios for network simulators systems," *International Journal of Distributed Sensor Networks*, vol. 13, no. 10, p. 1550147717738216, 2017.

[15] A. El-Mouaffak and A. E. B. El Alaoui, "Considering the environment's characteristics in wireless networks simulations and emulations: Case of popular simulators and wsn," in *Proceedings of the 3rd International Conference on Networking, Information Systems & Security*, 2020, pp. 1–4.

[16] R. Beuran, L. T. Nguyen, T. Miyachi, J. Nakata, K.-i. Chinen, Y. Tan, and Y. Shinoda, "Qomb: A wireless network emulation testbed," in *GLOBECOM 2009-2009 IEEE Global Telecommunications Conference*. IEEE, 2009, pp. 1–6.

[17] M. Kojo, A. V. Gurtov, J. Manner, P. Sarolahti, T. O. Alanko, and K. E. Raatikainen, "Seawind: a wireless network emulator." in *MMB*, 2001, pp. 151–166.

[18] J. Lessmann, P. Janacik, L. Lachev, and D. Orfanus, "Comparative study of wireless network simulators," in *Seventh International Conference on Networking (icn 2008)*. IEEE, 2008, pp. 517–523.

[19] H. Sundani, H. Li, V. Devabhaktuni, M. Alam, and P. Bhattacharya, "Wireless sensor network simulators a survey and comparisons," *International Journal of Computer Networks*, vol. 2, no. 5, pp. 249–265, 2011.

[20] P. Zheng and L. M. Ni, "Empower: A network emulator for wireline and wireless networks," in *IEEE INFOCOM 2003. Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies (IEEE Cat. No. 03CH37428)*, vol. 3. IEEE, 2003, pp. 1933–1942.

[21] J. Ahrenholz, C. Danilov, T. R. Henderson, and J. H. Kim, "Core: A real-time network emulator," in *MILCOM 2008-2008 IEEE Military Communications Conference*. IEEE, 2008, pp. 1–7.

[22] M. Berman, J. S. Chase, L. Landweber, A. Nakao, M. Ott, D. Raychaudhuri, R. Ricci, and I. Seskar, "Geni: A federated testbed for innovative network experiments," *Computer Networks*, vol. 61, pp. 5–23, 2014.

[23] B. Chun, D. Culler, T. Roscoe, A. Bavier, L. Peterson, M. Wawrzoniak, and M. Bowman, "Planetlab: an overlay testbed for broad-coverage services," *ACM SIGCOMM Computer Communication Review*, vol. 33, no. 3, pp. 3–12, 2003.

[24] G. Judd and P. Steenkiste, "Using emulation to understand and improve wireless networks and applications," in *Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation-Volume 2*, 2005, pp. 203–216.

[25] D. M. Nicol, "Scalability of network simulators revisited," in *Proceedings of the Communication Networks and Distributed Systems Modeling and Simulation Conference*, vol. 28, 2003.

[26] A. Sethi, J. Saini, and M. Bisht, "Wireless adhoc network simulators: Analysis of characterstic features, scalability, effectiveness and limitations," *International Journal of Applied Information Systems (IJAIS)*, vol. 5, no. 9, 2012.

[27] S. M. Bilalb, M. Othmana *et al.*, "A performance comparison of network simulators for wireless networks," *arXiv preprint arXiv:1307.4129*, 2013.

[28] C. Thomson, I. Romdhani, A. Al-Dubai, M. Qasem, B. Ghaleb, and I. Wadhaj, "Cooja simulator manual," 2016.

[29] P. Levis and N. Lee, "Tossim: A simulator for tinyos networks," *UC Berkeley, September*, vol. 24, p. 99, 2003.

[30] A. R. Khan, S. M. Bilal, and M. Othman, "A performance comparison of open source network simulators for wireless networks," in *2012 IEEE international conference on control system, computing and engineering*. IEEE, 2012, pp. 34–38.

[31] A. Kumar, S. K. Kaushik, R. Sharma, and P. Raj, "Simulators for wireless networks: A comparative study," in *2012 International Conference on Computing Sciences*. IEEE, 2012, pp. 338–342.

[32] S. G. Gupta, M. M. Ghonge, P. D. Thakare, and D. P. Jawandhiya, "Open-source network simulation tools: An overview," *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, vol. 2, no. 4, pp. 1629–1635, April 2013.

[33] K. Antonopoulos, C. Panagiwtou, C. Antonopoulos, N. Voros, and G. Keramidas, "Characterization of wifi modules using an open-source network simulator," in *2021 6th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM)*, 2021, pp. 1–8.

[34] A. S. Toor and A. Jain, "A survey on wireless network simulators," *Bulletin of Electrical Engineering and Informatics*, vol. 6, no. 1, pp. 62–69, 2017.

[35] P. Owczarek and P. Zwierzykowski, "Review of simulators for wireless mesh networks," *Journal of Telecommunications and Information technology*, 2014.

[36] R. Chaudhary, S. Sethi, R. Keshari, and S. Goel, "A study of comparison of network simulator-3 and network simulator-2," *International Journal of Computer Science and Information Technologies*, vol. 3, no. 1, pp. 3085–3092, 2012.

[37] A. Abuarqoub, F. Al-Fayez, T. Alsboui, M. Hammoudeh, and A. Nisbet, "Simulation issues in wireless sensor networks: A survey," in *The Sixth International Conference on Sensor Technologies and Applications (SENSORCOMM 2012)*, 2012, pp. 222–228.

[38] P. Chhimwal, D. S. Rai, and D. Rawat, "Comparison between different wireless sensor simulation tools," *IOSR Journal of Electronics and Communication Engineering*, vol. 5, no. 2, pp. 54–60, 2013.

[39] V. Venkataramanan and S. Lakshmi, "A case study of various wireless network simulation tools," *International Journal of Communication Networks and Information Security*, vol. 10, no. 2, pp. 389–396, 2018.

[40] S. Lohier, A. Rachedi, E. Livolant, and I. Salhi, "Wireless sensor network simulators relevance compared to a real ieee 802.15. 4 testbed," in *2011 7th International Wireless Communications and Mobile Computing Conference*. IEEE, 2011, pp. 1347–1352.

[41] I. Jawhar, "A flexible object-oriented design of an event-driven wireless network simulator," in *2009 Wireless Telecommunications Symposium*. IEEE, 2009, pp. 1–7.

[42] A. Rachedi, S. Lohier, S. Cherrier, and I. Salhi, "Wireless network simulators relevance compared to a real testbed in outdoor and indoor environments," in *Proceedings of the 6th International Wireless Communications and Mobile Computing Conference*, 2010, pp. 346–350.

[43] D. L. RAJA, "Study of various network simulators," *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, no. 12, 2018.

[44] T. A. R. V, E. Gamess, and D. Thornton, "A survey of wireless network simulation and/or emulation software for use in higher education." in *ACM Southeast Conference*, 2021, pp. 63–70.

[45] J. Ahrenholz, T. Goff, and B. Adamson, "Integration of the core and emane network emulators," in *2011-MILCOM 2011 Military Communications Conference*. IEEE, 2011, pp. 1870–1875.

[46] R. Mohtasin, P. Prasad, A. Alsadoon, G. Zajko, A. Elchouemi, and A. K. Singh, "Development of a virtualized networking lab using gns3 and vmware workstation," in *2016 International conference on wireless communications, signal processing and networking (WiSPNET)*. IEEE, 2016, pp. 603–609.

[47] P. Gil, G. J. Garcia, A. Delgado, R. M. Medina, A. Calderon, and P. Marti, "Computer networks virtualization with gns3: Evaluating a solution to optimize resources and achieve a distance learning," in *2014 IEEE Frontiers in Education Conference (FIE) Proceedings*. IEEE, 2014, pp. 1–4.

[48] R. Emiliano and M. Antunes, "Automatic network configuration in virtualized environment using gns3," in *2015 10th International Conference on Computer Science & Education (ICCSE)*. IEEE, 2015, pp. 25–30.

[49] D. Quiñones and C. Rusu, "How to develop usability heuristics: A systematic literature review," *Computer standards & interfaces*, vol. 53, pp. 89–122, 2017.

[50] R. Chéour, M. W. Jmal, A. Lay-Ekuakille, F. Derbel, O. Kanoun, and M. Abid, "Choice of efficient simulator tool for wireless sensor networks," in *2013 IEEE International Workshop on Measurements & Networking (M&N)*. IEEE, 2013, pp. 210–213.

[51] L. Riliskis and E. Osipov, "Maestro: an orchestration framework for large-scale wsn simulations," *Sensors*, vol. 14, no. 3, pp. 5392–5414, 2014.

[52] D. K. Chaturvedi, *Modeling and simulation of systems using MATLAB and Simulink*. CRC press, 2017.

[53] H. M. Schroder, M. J. Driver, and S. Streufert, "Human information processing: Individuals and groups functioning in complex social situations," *(No Title)*, 1967.

[54] N. H. Lurie and C. H. Mason, "Visual representation: Implications for decision making," *Journal of marketing*, vol. 71, no. 1, pp. 160–177, 2007.

[55] L. Falschlunger, O. Lehner, and H. Treiblmaier, "Infovis: The impact of information overload on decision making outcome in high complexity settings," 2016.

[56] J. Gettinger, S. T. Koeszegi, and M. Schoop, "Shall we dance?—the effect of information presentations on negotiation processes and outcomes," *Decision support systems*, vol. 53, no. 1, pp. 161–174, 2012.

[57] V. Bajpai and J. Schönwälder, "A survey on internet performance measurement platforms and related standardization efforts," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1313–1341, 2015.

[58] V. T. Guimaraes, C. M. D. S. Freitas, R. Sadre, L. M. R. Tarouco, and L. Z. Granville, "A survey on information visualization for network and service management," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 285–323, 2015.

[59] F. L. Verdi, H. T. de Oliveira, L. N. Sampaio, and L. A. Zaina, "Usability matters: A human–computer interaction study on network management tools," *IEEE Transactions on Network and Service Management*, vol. 17, no. 3, pp. 1865–1878, 2020.

[60] S. A. Silveira, L. A. Zaina, L. N. Sampaio, and F. L. Verdi, "On the evaluation of usability design guidelines for improving network monitoring tools interfaces," *Journal of Systems and Software*, vol. 187, p. 111223, 2022.

[61] W. Dilla, D. J. Janvrin, and R. Raschke, "Interactive data visualization: New directions for accounting information systems research," *Journal of Information Systems*, vol. 24, no. 2, pp. 1–37, 2010.

[62] M. C. Pretorius, A. P. Calitz, and D. van Greunen, "The added value of eye tracking in the usability evaluation of a network management tool," in *ACM International Conference Proceeding Series*, vol. 150, 2005, pp. 1–10.

[63] J. Yang and W. K. Edwards, "A study on network management tools of householders," in *Proceedings of the 2010 ACM SIGCOMM workshop on Home networks*, 2010, pp. 1–6.

[64] S. Marsden and J. Vankka, "Tactical network modeller simulation tool," in *MILCOM 2015-2015 IEEE Military Communications Conference*. IEEE, 2015, pp. 1087–1092.

[65] M. Fewell and M. G. Hazen, *Network-centric warfare: its nature and modelling*. DSTO Systems Sciences Laboratory, 2003.

[66] Y. Gu and R. Fujimoto, "Remote network emulation for defense applications," *The Journal of Defense Modeling and Simulation*, vol. 5, no. 2, pp. 83–107, 2008.

[67] N. Suri, A. Hansson, J. Nilsson, P. Lubkowski, K. Marcus, M. Hauge, K. Lee, B. Buchin, L. Mısırhoğlu, and M. Peuhkuri, "A realistic military scenario and emulation environment for experimenting with tactical communications and heterogeneous networks," in *2016 International Conference on Military Communications and Information Systems (ICMCIS)*. IEEE, 2016, pp. 1–8.

[68] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qualitative research in psychology*, vol. 3, no. 2, pp. 77–101, 2006.

[69] ——, "Can i use ta? should i use ta? should i not use ta? comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches," *Counselling and psychotherapy research*, vol. 21, no. 1, pp. 37–47, 2021.

[70] F. Yao, Q. Liang, R. Xu, and L. Tong, "Some key issues on modeling and simulation of military communication network," in *2012 International Conference on Computer Science and Electronics Engineering*, vol. 1. IEEE, 2012, pp. 532–535.

[71] L. Mlekus, D. Bentler, A. Paruzel, A.-L. Kato-Beiderwieden, and G. W. Maier, "How to raise technology acceptance: user experience characteristics as technology-inherent

determinants," *Gruppe. Interaktion. Organisation. Zeitschrift für Angewandte Organisationspsychologie (GIO)*, vol. 51, no. 3, pp. 273–283, 2020.

[72] F. D. Davis, "Perceived usefulness, perceived ease of use, and user acceptance of information technology," *MIS quarterly*, pp. 319–340, 1989.

[73] C. Ayala, Ø. Hauge, R. Conradi, X. Franch, J. Li, and K. S. Velle, "Challenges of the open source component marketplace in the industry," in *Open Source Ecosystems: Diverse Communities Interacting: 5th IFIP WG 2.13 International Conference on Open Source Systems, OSS 2009, Skövde, Sweden, June 3-6, 2009. Proceedings 5*. Springer, 2009, pp. 213–224.

[74] A. Jaaksi, "Experiences on product development with open source software," in *IFIP International Conference on Open Source Systems*. Springer, 2007, pp. 85–96.

[75] J. Merilinna and M. Matinlassi, "State of the art and practice of opensource component integration," in *32nd EUROMICRO Conference on Software Engineering and Advanced Applications (EUROMICRO'06)*. IEEE, 2006, pp. 170–177.

# Appendix A

# Questionnaire and Workshop Information Sheet

## A.1 Questionnaire Information Sheet

**Project Title:**

Using Human-Centred Approach and ML Techniques to Automate/Visualise Anomaly and Vulnerability Detection in Critical Communication Systems Context

**PARTICIPANT CONSENT FORM**

**(Version 2.0, Date: 03/07/2023)**

**Contact Details:**

Principal investigator: Manal Ghanem (2220761@swansea.ac.uk).

Co-investigator: Nicholas Micallef (nicholas.micallef@swansea.ac.uk).

Co-investigator: JonathanLee Jones (jonlj@itsusconsulting.com).

**Invitation Paragraph**

You are hereby invited to take part in the study as a research participant. Thank you for taking an active interest in this project and please carefully read the rest of the information laid out on this page before proceeding with the rest of the study.

The sponsoring organisation is ITSUS Consulting. The company offers advanced information and communication technology (ICT) solutions tailored to clients who operate critical communication systems. The company works in partnership with leading international aerospace, defence, and public sector organisations to deliver intricate digital transformation initiatives. Since their establishment in 2008, the company remained committed to fostering lasting relationships through collaborative and innovative approaches in the fields of security, cyber, data science, ICS, and AR/VR.

**What is the purpose of the study?**

The current state-of-the-art tools for designing experimental testbeds in the market have limitations that impact their usability and adoption. The aim of this project is to improve the usability and effectiveness of wireless network emulation and simulation tools by taking user experience into consideration. The project aims to address the limitations of existing tools and explore new avenues for enhancing the user experience and performance analysis in network research and development. By combining insights from network experts, stakeholders, and end-users, the project seeks to bridge the gap between technical functionality and user-centric design.

The project has several aims and research questions, including identifying the features required for the visual interface, mapping and visualising network and sensor data, adapting the visualisation to different factors and conditions, automating the detection of anomalies and vulnerabilities, and presenting the detected anomalies and vulnerabilities in an intuitive and interactive manner.

**Why have I been chosen?**

You have been invited to take part in this study because you were identified as a potential end-user of this tool. The results of this study will be used to identify the features required for the visual interface, suggest enhancements and deepen the understanding of the limitations and benefits of these tools.

**What will happen to me if I take part?**

If you decide to take part in this study, you will be expected to complete the following questionnaire and might be invited later to participate in a focus group to further discuss the insights gathered.

**What are the possible disadvantages of taking part?**

There are no physical risks involved for participants, however, taking part in the questionnaire and the focus group will take time out of the participants' day to complete and attend.

**What are the possible benefits of taking part?**

The benefit of taking part is helping the researchers better understand the tools, their uses, limitations, and advantages.

**Will my taking part in the study be kept confidential?**

The study will not collect personally identifiable information or sensitive information. The collected information will be used solely for the study. Results from the study will be published in a scientific paper.

**What if I have any questions?**

If you have any further questions about taking part in the study, please feel free to contact the principal investigator Manal Ghanem (2220761 @swansea.ac.uk)

## A.2 Design Workshop Information Sheet

**Project Title:**

Using Human-Centred Approach and ML Techniques to Automate/Visualise Anomaly and Vulnerability Detection in Critical Communication Systems Context

**PARTICIPANT CONSENT FORM**

**(Version 2.0, Date: 12/07/2023)**

**Contact Details:**

Principal investigator: Manal Ghanem (2220761@swansea.ac.uk).

Co-investigator: Nicholas Micallef (nicholas.micallef@swansea.ac.uk).

Co-investigator: JonathanLee Jones (jonlj@itsusconsulting.com).

**Invitation Paragraph**

You are hereby invited to take part in the study as a research participant. Thank you for taking an active interest in this project and please carefully read the rest of the information laid out on this page before proceeding with the rest of the study. The sponsoring organisation is ITSUS Consulting. The company offers advanced information and communication technology (ICT) solutions tailored to clients who operate critical communication systems. The company works in partnership with leading international aerospace, defence, and public sector organisations to deliver intricate digital transformation initiatives. Since their establishment in 2008, the company remained committed to fostering lasting relationships through collaborative and innovative approaches in the fields of security, cyber, data science, ICS, and AR/VR.

**What is the purpose of the study?**

The current state-of-the-art tools for designing experimental testbeds in the market have limitations that impact their usability and adoption. The aim of this project is to improve the usability and effectiveness of wireless network emulation and simulation tools by taking user experience into consideration. The project aims to address the limitations of existing tools and explore new avenues for enhancing the user experience and performance analysis in network research and development. By combining insights from network experts, stakeholders, and end-users, the project seeks to bridge the gap between technical functionality and user-centric design. The project has several aims and research questions, including identifying the features required for the visual interface, mapping and visualising network and sensor data, adapting the visualisation to different factors and conditions, automating the detection of anomalies and vulnerabilities, and presenting the detected anomalies and vulnerabilities in an intuitive and interactive manner.

**Why have I been chosen?**

You have been invited to take part in this study because you were identified as a potential end-user of this tool. The results of this study will be used to identify the features required for the visual interface, suggest enhancements and deepen the understanding of the limitations and benefits of these tools.

**What will happen to me if I take part?**

If you decide to take part in this study, you will be expected to attend a design workshop.

**What are the possible disadvantages of taking part?**

There are no physical risks involved for participants, however, taking part in the focus group will take time out of the participants' day to attend and participate.

**What are the possible benefits of taking part?**

The benefit of taking part is helping the researchers better understand the tools, their uses, limitations, and advantages.

**Will my taking part in the study be kept confidential?**

The study will not collect personally identifiable information or sensitive information. The collected information will be used solely for the study. Results from the study will be published in a scientific paper.

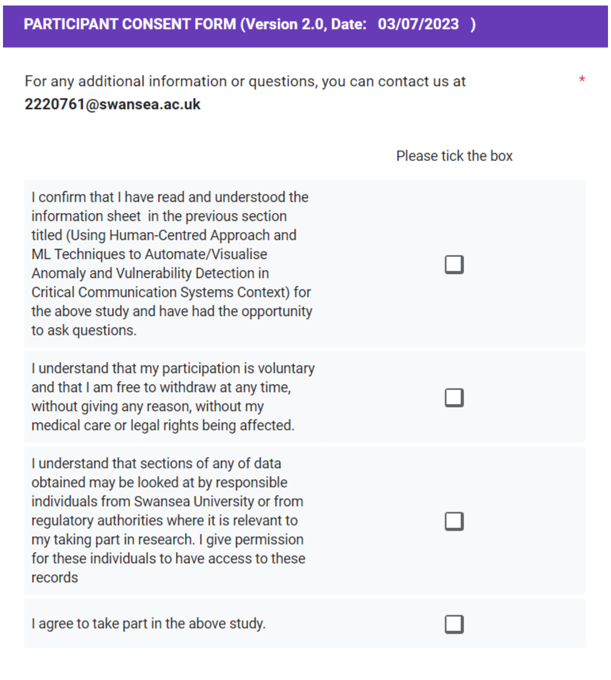
**What if I have any questions?**

If you have any further questions about taking part in the study, please feel free to contact the principal investigator Manal Ghanem (2220761 @swansea.ac.uk).

# Appendix B

# Questionnaire and Workshop Consent Forms

## B.1 Questionnaire Consent Form



**PARTICIPANT CONSENT FORM (Version 2.0, Date: 03/07/2023 )**

For any additional information or questions, you can contact us at **2220761@swansea.ac.uk** *

| | Please tick the box |
|---|---|
| I confirm that I have read and understood the information sheet in the previous section titled (Using Human-Centred Approach and ML Techniques to Automate/Visualise Anomaly and Vulnerability Detection in Critical Communication Systems Context) for the above study and have had the opportunity to ask questions. | ☐ |
| I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. | ☐ |
| I understand that sections of any of data obtained may be looked at by responsible individuals from Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records | ☐ |
| I agree to take part in the above study. | ☐ |

Figure B.1: Questionnaire Consent Form

## B.2 Design Workshop Consent Form

**PARTICIPANT CONSENT FORM**
**(Version 2.0)**

**Project Title:**

***Using Human-Centred Approach and ML Techniques to Automate/Visualise Anomaly and Vulnerability Detection in Critical Communication Systems Context***

**Contact Details:**

For any additional information or questions, you can contact us at 2220761@swansea.ac.uk

**Please tick the box**

1. I confirm that I have read and understood the information sheet in the previous section titled 12/07/2023 (version number 2.0) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. I understand that sections of any of data obtained may be looked at by responsible individuals from Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records. ☐
4. I agree to audio recording of the session. ☐
5. I agree to take part in the above study. ☐

| ____________________ | ____________ | ____________________ |
|---|---|---|
| Name of Participant | Date | Signature |
| ____________________ | ____________ | ____________________ |
| Name of Person taking consent | Date | Signature |
| ____________________ | ____________ | ____________________ |
| Researcher | Date | Signature |

Personal data collected on this form will be processed in line with the General Data Protection Regulation 2016 and the Data Protection Act 2018. Further information about how your data is managed is available on the University Research Privacy Notice.
https://www.swansea.ac.uk/about-us/compliance/data-protection/research-privacy-notice/

Figure B.2: Design Workshop Consent Form

# Appendix C

# Questionnaire Questions

**The Tools**

1. What wireless network emulators and simulators are used by your clients?
2. Why have these tools been selected?
3. How many years of experience do you have using these tools?
4. What are the key features and functionalities that clients typically expect from a wireless network emulator or simulator?
5. Are there any specific requirements or capabilities that are frequently requested/expected but the tools do not provide them?
6. Which features are considered essential for effective network emulation and simulation?

   **Clients Perceptions/ Needs**

7. How do clients perceive the user experience and usability of wireless network emulators or simulators?
8. How do usability and user experience impact the effectiveness of using these tools?
9. Are there any specific pain points or difficulties reported by end-users?
10. For which contexts or scenarios do clients typically use network emulators or simulators?

11. Are there any contexts or scenarios that current tools cannot replicate effectively?
12. How do clients currently perceive the visualisation feature of these tools?
13. What types of visualisations are commonly produced?
14. Are there any limitations or challenges experienced when producing visualisation?
15. Can you share any specific feedback or suggestions from clients regarding the visualisation aspect of wireless network emulators or simulators?
16. Are there any particular visualisations or features that you would like to visualise, but are currently unavailable or not adequately supported by existing tools?
17. Have there been any specific requests for improvements or new features in this area?

**User Experience and Visualisation**

18. Are there any emerging trends or advancements in wireless network emulation and simulation that should be considered for the design of the visualisation component?
19. Are there any new technologies, protocols, or standards that will impact the visualisation requirements?
20. How important is the usability and user experience of the visualisation component of a wireless network emulator or simulator?
21. The needs of which user groups or stakeholders should be taken into account when considering the usability and user experience of visualisation components in wireless network emulators or simulators?
22. Are there any specific concerns or challenges related to the visualisation of wireless network emulators or simulators that you would like to mention?
23. Are there any technical limitations, scalability issues, or compatibility considerations?
24. Are there any additional insights or recommendations that you would like to share regarding the usability and user experience visualisations in wireless network emulators or simulators?

# Appendix D

# Design Workshop-Activity 1: Participants' Sketches

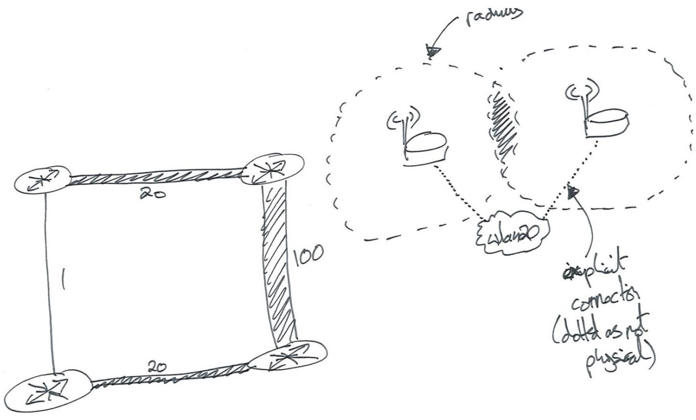



Figure D.1: Design Workshop: Activity 1 Sketches (WP-1)

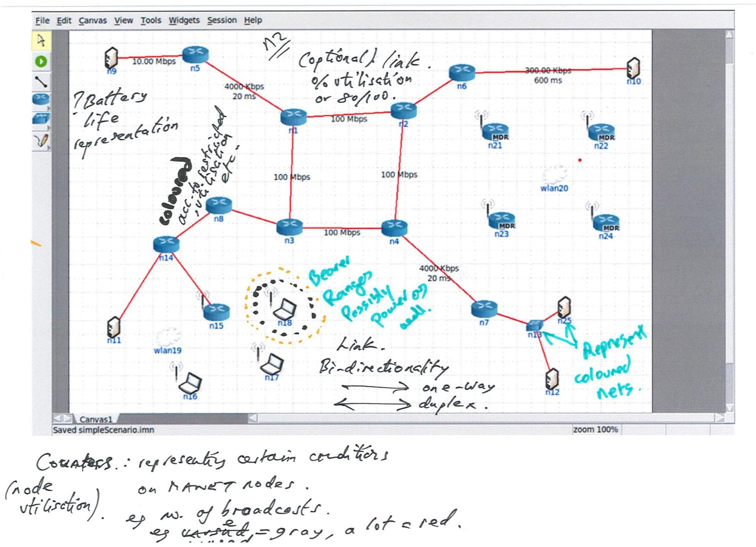



Figure D.2: Design Workshop: Activity 1 Sketches (WP-2, WP3)

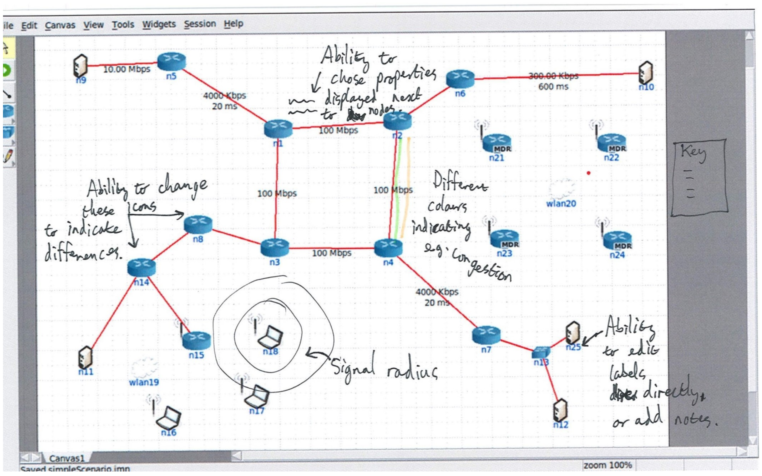



Figure D.3: Design Workshop: Activity 1 Sketches (WP-4)

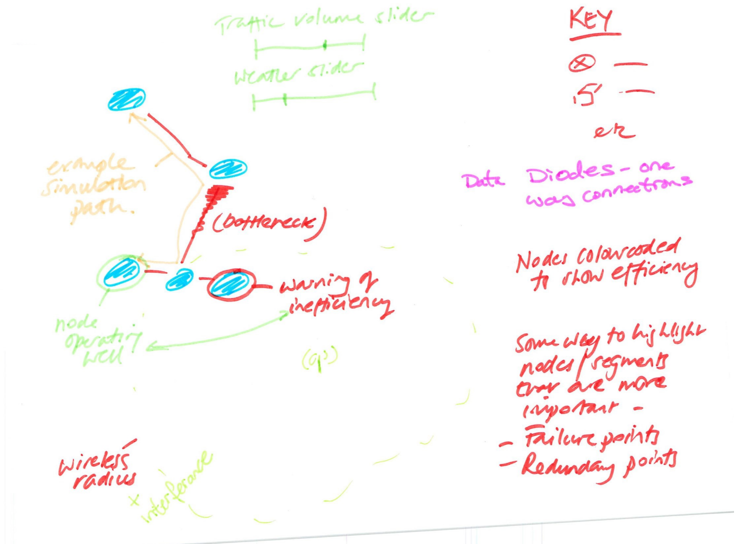



Figure D.4: Design Workshop: Activity 1 Sketches (WP-5, WP-6)

## Appendix E

# Design Workshop-Activity 2: Participants' Sketches

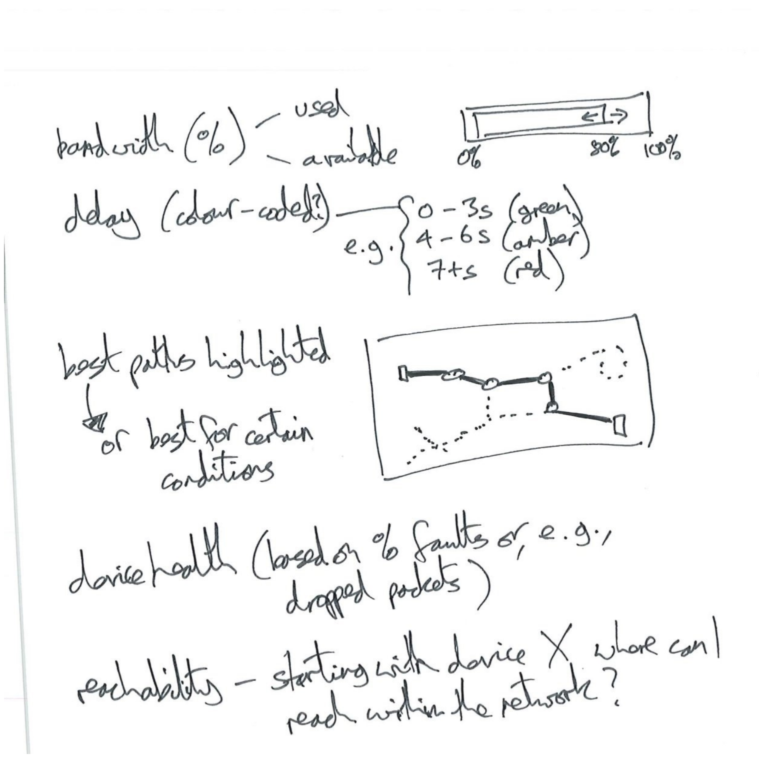



Figure E.1: Design Workshop: Activity 2 Sketches (WP-1)

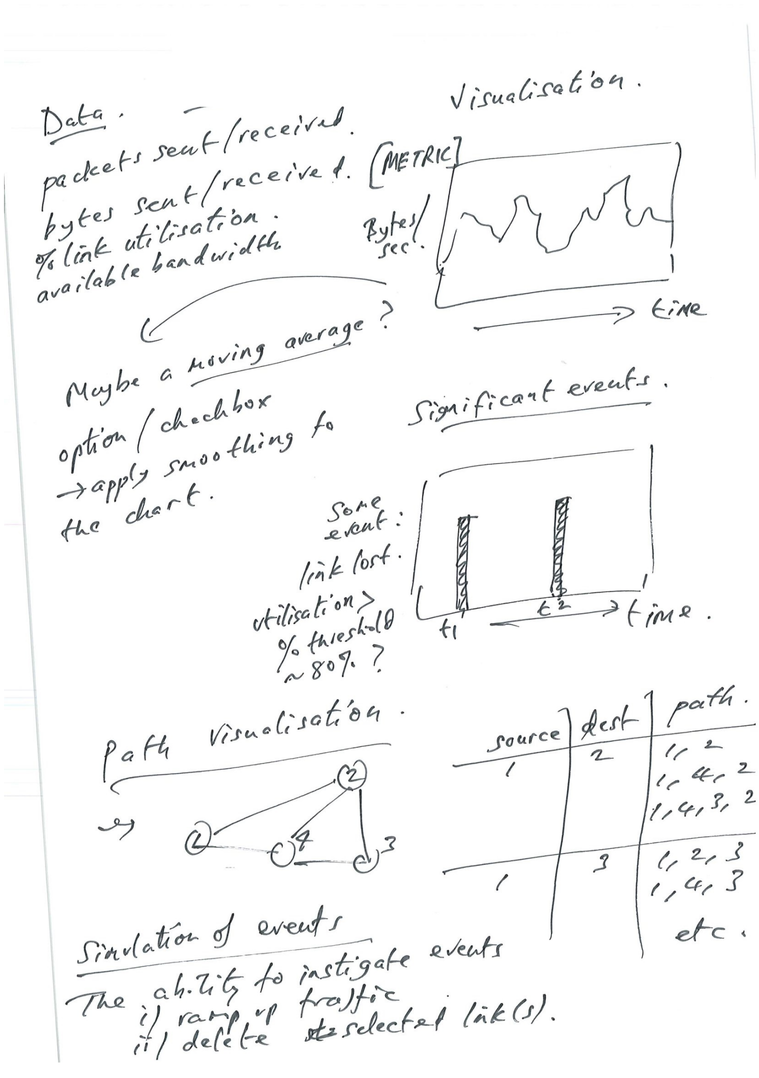



Figure E.2: Design Workshop: Activity 2 Sketches (WP-2)

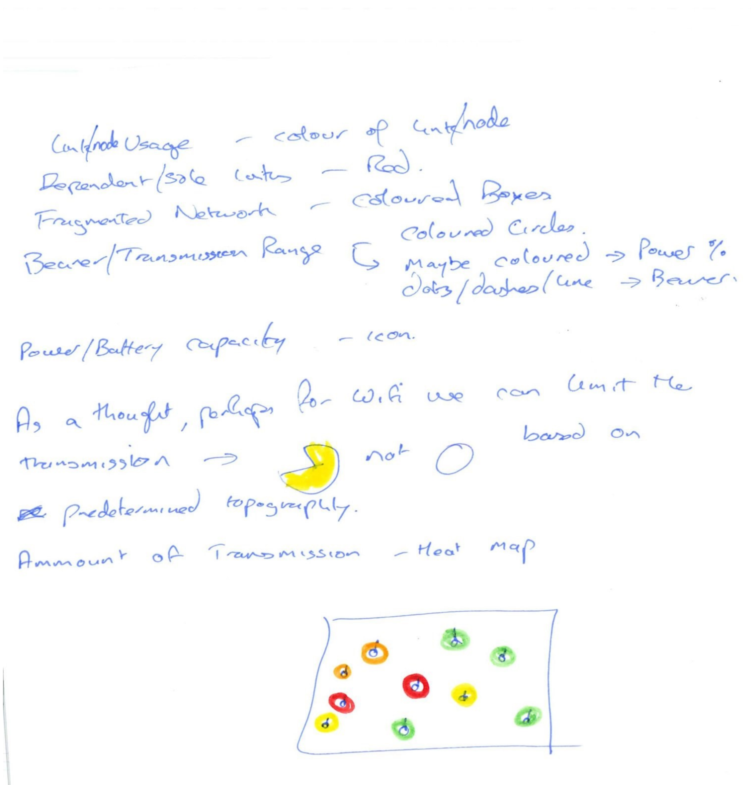



Figure E.3: Design Workshop: Activity 2 Sketches (WP-3)

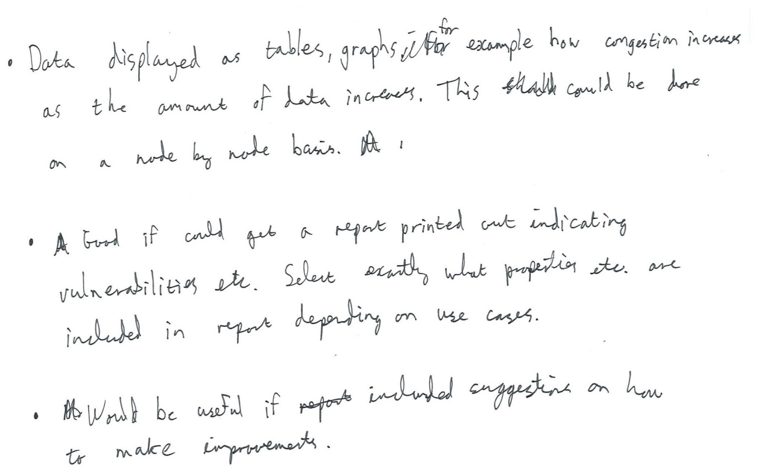



Figure E.4: Design Workshop: Activity 2 Sketches (WP-4)

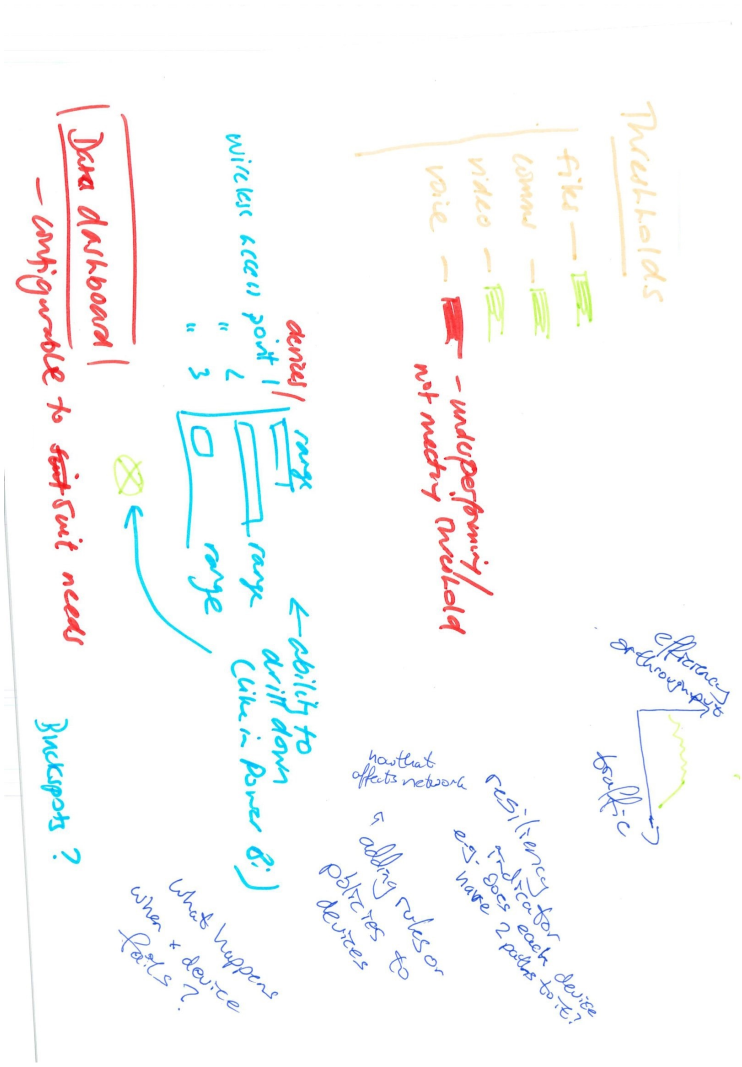
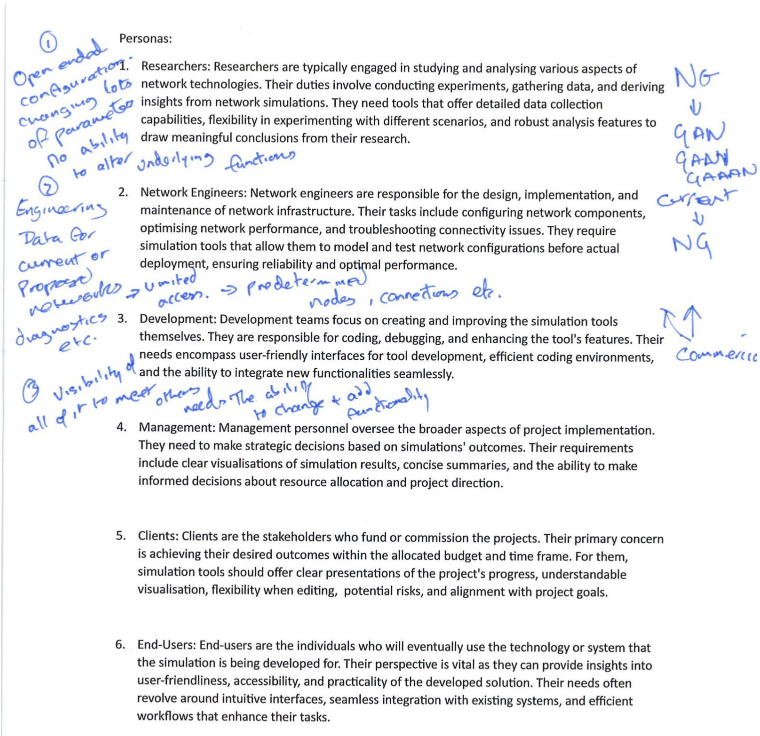



Figure E.5: Design Workshop: Activity 2 Sketches (WP-5, WP-6)

# Appendix F

# Design Workshop-Activity 3: Participants' Notes



Personas:

1. Researchers: Researchers are typically engaged in studying and analysing various aspects of network technologies. Their duties involve conducting experiments, gathering data, and deriving insights from network simulations. They need tools that offer detailed data collection capabilities, flexibility in experimenting with different scenarios, and robust analysis features to draw meaningful conclusions from their research.

2. Network Engineers: Network engineers are responsible for the design, implementation, and maintenance of network infrastructure. Their tasks include configuring network components, optimising network performance, and troubleshooting connectivity issues. They require simulation tools that allow them to model and test network configurations before actual deployment, ensuring reliability and optimal performance.

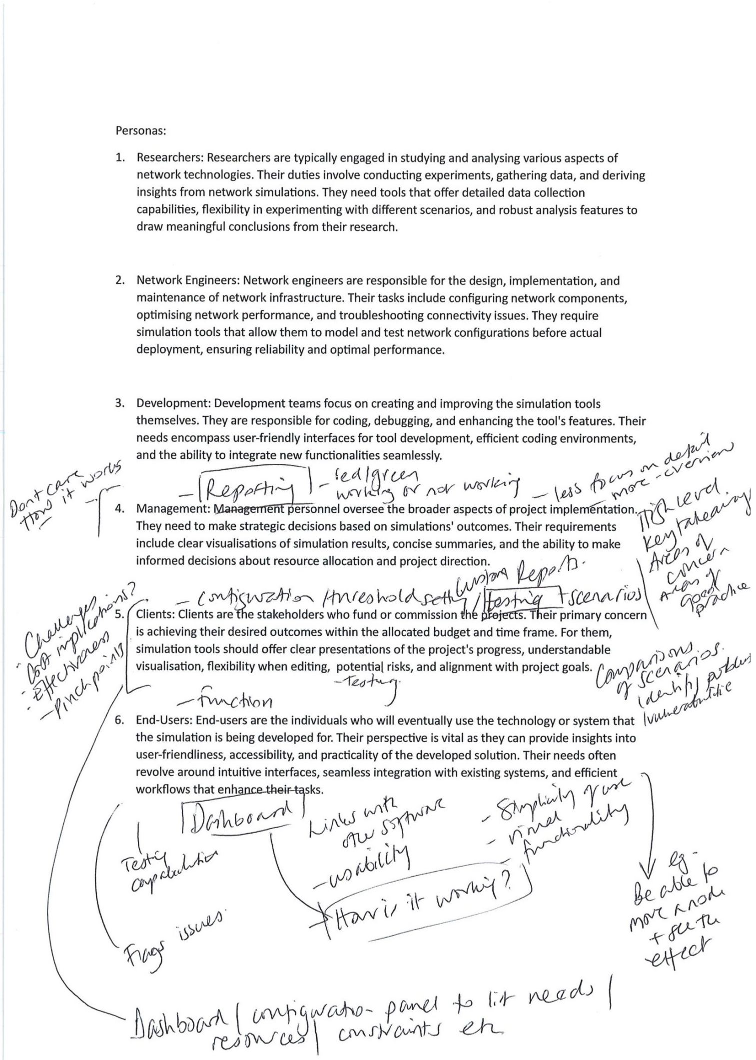
3. Development: Development teams focus on creating and improving the simulation tools themselves. They are responsible for coding, debugging, and enhancing the tool's features. Their needs encompass user-friendly interfaces for tool development, efficient coding environments, and the ability to integrate new functionalities seamlessly.

4. Management: Management personnel oversee the broader aspects of project implementation. They need to make strategic decisions based on simulations' outcomes. Their requirements include clear visualisations of simulation results, concise summaries, and the ability to make informed decisions about resource allocation and project direction.

5. Clients: Clients are the stakeholders who fund or commission the projects. Their primary concern is achieving their desired outcomes within the allocated budget and time frame. For them, simulation tools should offer clear presentations of the project's progress, understandable visualisation, flexibility when editing, potential risks, and alignment with project goals.

6. End-Users: End-users are the individuals who will eventually use the technology or system that the simulation is being developed for. Their perspective is vital as they can provide insights into user-friendliness, accessibility, and practicality of the developed solution. Their needs often revolve around intuitive interfaces, seamless integration with existing systems, and efficient workflows that enhance their tasks.

Figure F.1: Design Workshop: Activity 3 - Personas 1-3 Notes (WP-1, WP-2, WP-3)



Personas:

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Figure F.2: Design Workshop: Activity 3 - Personas 4-6 Notes (WP-4, WP-5, WP-6)