Vaasan yliopisto
UNIVERSITY OF VAASA

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Digital Twin of 6G Wireless Network: Data Management and Visualization Service

School of Technology and Innovations
Master's thesis in Technology
Master's Programme in Computing Sciences
Sustainable and Autonomous Systems

Vaasa 2025

UNIVERSITY OF VAASA
School of Technology and Innovations

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Title of the thesis:	Digital Twin of 6G Wireless Network: Data Management and Visualization Service
Degree:	Master of Science in Technology
Discipline:	Sustainable and Autonomous Systems
University Supervisor:	Mohammed Elmusrati
University Evaluator:	Petri Välisuo
Company Supervisors:	Jukka Lämsä, Vili Keränen
Year:	2025 **Pages:** 46

ABSTRACT:

The 6G technology is bringing exceptional advancements in mobile networks, making it necessary to innovate data management and visualization approaches as the data volumes will be extensive and with the help of visualization tools bottlenecks can be detected. A system-level simulator is used for modelling and analysing the performance of complex telecommunications systems. The system-level simulator acts as a predictive engine of a digital twin framework running simulation data through a virtual representation of a complex system. In the context of this thesis, a digital twin can be defined as a virtual replica of a physical system in 3D spatial coordinates, using simulation data to analyse performance and to visualize resultant outcomes.

To visualize resultant outcomes, a web application is developed using Dash framework in Python. An Application Programming Interface (API) is defined for the communication between the system-level simulator and the web application. The simulator acts as a client and the web application is the server. The application is protected with Flask based authentication to ensure that only specific individuals can access the system. The application has two main components: the first for statistical comparisons and the second for three-dimensional visualization. For statistical comparisons Cumulative Distribution Functions (CDFs) and histograms are utilized. Heatmap is used to visualize the data points in three dimensional coordinates.

Finally, this thesis proves the possibility of integrating the digital twin methodologies with system-level simulations. The result of this work emphasizes that digital twins can be used to improve system performance and user experience and thus offer new opportunities for the development of telecommunications. Overall, it exemplifies a promising way forward for the advancement of more powerful and resilient communication system technology.

KEYWORDS: Digital twin, System-level simulator, Cumulative distribution function, Application programming interface.

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Abbreviations

API: Application Programming Interface.

CDF: Cumulative distribution Function.

BS: Base Station.

UE: User Equipment.

RAN: Radio Access Network.

SIM: Subscriber Identity Module.

ADC: Analog to Digital Converter.

RRU: Remote Radio Unit.

BBU: Baseband Unit.

NMT: Nordic Mobile Telephony.

GSM: Global System for Mobile Communication.

WCDMA: Wide Code Division Multiple Access.

LTE: Long-Term Evolution.

1G: First Generation.

2G: Second Generation.

3G: Third Generation.

4G: Fourth Generation.

5G: Fifth Generation.

6G: Sixth Generation.

AI: Artificial Intelligence.

AR: Augmented Reality.

VR: Virtual Reality.

LLS: Link Level Simulator.

BER: Bit Error Rate.

BLER: Block Error Rate.

PHY: Physical Layer.

MAC: Medium Access Control.

RLC: Radio Link Control.

PUSCH: Physical Uplink Shared Channel.

PDSCH: Physical Downlink Shared Channel.

SRS: Sounding Reference Signal.

MIMO: Multiple Input Multiple Output.

KPI: Key Performance Indicator.

MU-MIMO: Multi-User MIMO.

NASA: National Aeronautics and Space Administration.

HTTP: Hypertext Transfer Protocol.

URL: Uniform Resource Locator.

HTML: Hypertext Markup Language.

Mbps: Mega bit per second.

PDF: Portable Document Format.

REST API: Representational State Transfer Application Programming Interface.

JSON: JavaScript Object Notation.

1 The Evolution of Telecommunications

Telecommunication is a vital component of modern civilization; it has a long and fascinating history. From historical telecommunication technologies to today's digital networks, telecommunications have evolved through various inventions and advancements in technology. This chapter will go through the history of telecommunications, from the basic signalling techniques to advanced digital communication and go through the evolution of mobile network technologies from first generation to the upcoming sixth generation. This chapter will also explain how the telecommunication system operates with a major focus on cellular networks.

1.1 The Telegraph Era

In the early 19th century, Samuel Morse discovered the telegraph, improving long-distance communication by great leaps and bounds. Messages could be transmitted through wires by telegraph which used electrical signals (Vonage Staff, 2023). In 1832 Morse invented the first electric telegraph and continued to work on it for a couple of years. In 1838 the first electric telegraph was shown in public at the Speedwell Ironworks in Morristown New Jersey (Wikipedia contributors, 2025). The Library of Congress (n.d.) states that Morse solved the problem of message transmission over great distances with the help of Professor Leonard Gale. This allowed messages to be carried across several distances, by raising the signal intensity at prescribed times. In 1844 Morse received government funds and built a telegraph line from Baltimore to Washington D.C. The first message was "What hath God wrought!". Sent on May 24, 1844.

Telegraph line rapidly expanded throughout Europe and United States, interlinking essential cities, and allowing corporations, individuals, and governments to communicate more quickly. By 1856, distant communication lines connected New York City to Baltimore, Philadelphia, and Washington as well as destinations in between them (Anderson, 2005). The massive accomplishment in 1866, when a transatlantic telegraph cable was successfully laid, allowing for instant communication between Europe and North America (Lives Retold, n.d.). By the late 19th century, a massive network of underwater cables was being put throughout the world, changing international communication and trade. British enterprises play a significant role in developing the global cable system which aided business and imperial administration (Clulow, 2024).

The first person to make wireless telegraphy practical, sending messages through the air by radio waves instead of wires, was Guglielmo Marconi. He built on earlier discoveries in the late 1800s and created a system to send Morse code over longer distances, with no cables needed. Ships at sea needed a means of communication with other ships far away and out of sight of one another. In 1901, Marconi made it famous to transmit wireless messages across the Atlantic Ocean by displaying radio waves that could be bent around the Earth and travel a long way. He made a huge step forward that eventually enabled the use of radios and wireless devices that are used today. Due to this, he was given the Nobel Prize in Physics. Marconi's Wireless telegraphy altered the way in which people could communicate, they were now able to transmit messages over long distances wirelessly rather than taking the time to wire the telephone lines to each separate location (Dtorres, 2023).

1.2 The Advent of Telephony

In 1876, Alexander Graham Bell invented the telephone. The telephone provided immediate voice communication, which transformed professional and personal communications (Salima, 2024). The journey of Alexander Graham Bell towards inventing the telephone started with his research on harmonic telegraph, which attempted to send various messages over a single cable. Despite this, he became increasingly intrigued in communicating with the voice. On February 14, 1876, Bell filed a patent for his approach of transferring the sounds. Then on March 7, 1876, the Patent Office granted Bell a patent, now regarded among the most significant in history. On March 10, 1876, Bell successfully communicated straightforward speech when he contacted his helper Thomas Watson saying, “Mr. Watson come here I want to see you”, (Hochfelder & David, 2025). In 1878

TelForce Group (2023) demonstrated the first telephone which became operational in New Haven, Connecticut.

1.3 How Telecommunications System Work

Learning about telecommunication systems and how they work can be intriguing, particularly for non-technical readers. Considering telecommunication systems are complicated networks which link people and devices all over the world through communication over long distances. This chapter will go through some basic components and processes associated with telecommunication, specifically cellular networks.

1.3.1 The Basic Components

Cellular networks are based on three fundamental components, User Equipment (UE), Base Station (BS) and Network Core. This terminology originates from the 3rd Generation Partnership Project (3gpp) standards, which defines the cellular network architecture. The BS and UE are the part of Radio Access Network (RAN), the network core is responsible for backend operations. The RAN handles the transmission and reception of radio signals in between BS and UE.

UE is a communication device which can be for example a smartphone, tablet, or smartwatch. UE functions as a messenger which sends and receives signals. For instance, when the phone call is made, the phone turns the voice into radio signals and transmits these signals.

A BS contains antennas and radio equipment. It serves as a bridge between the UE and the larger network. For instance, imagine it as a post office which routes different mails. The BS receives signal from the UE then it connects the call to the rest of the network. For example, another cell phone or internet. It is also responsible to maintain the connection as the UE moves in between the towers while driving. The UE communicates with the BS wirelessly, from BS onwards the data is transferred through wired connection.

The last part is Network Core which serves as the brain of the entire system. It consists of databases, servers and routers which control authentication i.e., which device is authorized to access the network, routing the call to the correct location and preserving the customer information such as subscription details (Harbor View Advisors, 2022).

1.3.2 Data Transmission Process in Mobile Phone Calls

The mobile phone acts as a UE, it will receive signals from the BS and connects with the BS, based on the signal strength. Then the BS checks the identity of the phone, for instance the legitimacy of Subscriber Identity Module (SIM) card. A SIM card is a small removable chip which goes into the mobile phone. It contains identification information which identifies the phone in mobile network and allows calling and utilizing mobile data. When the person speaks the phone's microphone captures the sound waves and converts them to the electrical signals. These electrical signals are further converted to digital data with the help of Analog to Digital Converter (ADC). The ADC converts them to series of bits (0s and 1s), this digital data is then transmitted as radio signals to BS. The BS converts the radio signals back into the digital data and transmits it to the core network. The core network then routes the phone call to the receiver's phone which reverses the process, converting the radio signals back into the sound waves. During the call if the UE is moving then the BS seamlessly moves the connection to the next adjacent BS without disconnecting the call (Woodford, 2025).

1.3.3 What's Inside a Base Station

A BS is a device which allows wireless communication among mobile devices and wired communication with the larger network. The main components of BS are Antennas and Radio Equipment.

The antenna receives and transmits radio signals from the phone, and they are often erected on top of roofs and towers to provide the best coverage while minimizing interference (Chung, 2025). The BS consists of a Remote Radio Unit (RRU) and Baseband Unit (BBU). The RRU transforms radio signals into digital data. Then the BBU handles digital data, such as signal processing and network communication. For instance, when a user sends a text message the antennas from the base station pick up the radio signals from the phone. These signals are converted into digital data by radio equipment before being sent to network core through fibre-optic connections (Iplook,2022).

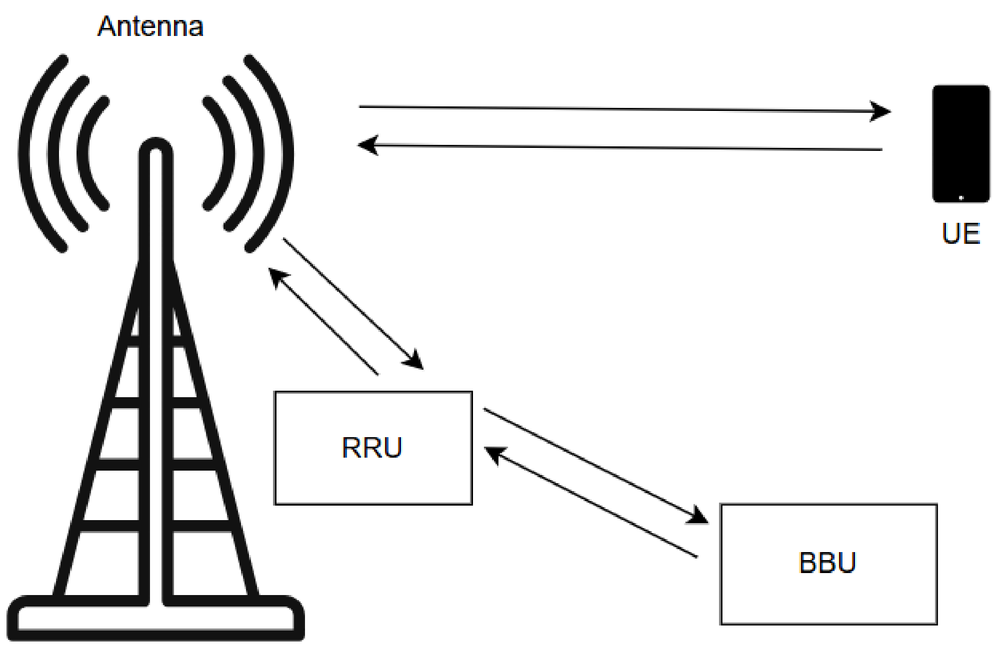

Figure 1. A simplified overview of Base Station.

1.4 Cellular Network Technologies

The development of cellular network technologies remains instantaneous and revolutionary for each new generation being better than the previous one. Analog voice transmission was the focus of the Nordic Mobile Telephony (NMT) also known as First Generation (1G) which entered the market in the early 1980s. This technology made it easier for people to stay connected, though its performance was limited by both reception problems and a lack of digital data functionality (Singh, 2023). The year 1991 saw the development of the Global System for Mobile Communication (GSM), which is also known as Second Generation (2G), in which the BBU begins to handle digital data. 2G improved phone call quality together with encryption for calls. SMS text messaging functionality became possible along with initial data communication capabilities through this technological advancement (Satpute, 2012).

The Wide Code Division Multiple Access (WCDMA), commonly known as Third Generation (3G), was introduced in 2001, which improved the data transfer rate and provided multimedia functions, such as video calls. Mobile internet access has experienced significant development because of these advancements. The Fourth Generation (4G), referred to as Long-Term Evolution (LTE), was launched in 2009 with further speed improvements to the technology and making it suitable for both online gaming and video streaming applications. This technology transformed the internet such that it became feasible to use broad multimedia applications (Vonage Staff, 2023).

The Fifth Generation (5G) was introduced in 2019 and as expected it provided better data transmission rates than the 4G, which makes live video streaming and video gaming smoother. According to Statista (2023) 5G can connect to one million devices per square kilometre. This high increase in device connectivity is important for Internet of Things (IoT), smart cities, and other applications with requirements for high device density and low latency. Altogether, 5G changed the use of technology with the help of such technologies as energy management and the acceleration of data processing (Sundarum, 2025). As of 2025, 5G has wrapped 2.25 billion connections around the world and continues to be adopted and deployed rapidly. This indicates that 5G is not just a theory anymore and is in use and to an immense extent (Sag, 2025).

The Sixth Generation (6G) is expected to be rolled out in about 2030. The 6G is expected to use higher frequency bands than the previous 5G and bring much higher capacity and lower latency. One of the targets of the 6G is to achieve one microsecond latency (Kranz & Christensen, 2023). The 6G networks are expected to integrate Artificial Intelligence (AI) into communication protocols. They will be able to manage themselves autonomously through AI. This involved dynamic adjustment to changing conditions, real-time optimization of network resources, predictive maintenance, frictionless connectively and high dependability (Keysight, 2025). With AI enabled in 6G, it will be possible to offer personalized context aware services to the users. User behaviour and preferences will be analysed by AI that will pose the ability to suggest customized experiences like adaptive streaming quality and enhanced security measures. Advanced applications such as immersive Augmented Reality (AR), Virtual Reality (VR) and intelligent industrial automation will be assisted by AI-driven 6G networks. High speed, low latency, and robust connectivity provided by 6G will facilitate these applications. Currently, the integration of AI into 6G remains in its infancy, and research into more integration is ongoing. Future activities involve addressing issues of data privacy, security, and large computational power required (Cui et al., 2025).

2 Problem Statement and Research Objectives

The 6G technology can alter communication networks by providing minimal delays, increased throughput, and wider bandwidth. The bandwidth is the range of frequencies within the communication channel. Digital twin is the virtual representation of physical equipment which provides continuous tracking and evaluation, this makes it extremely beneficial in the 6G systems. This thesis discusses the data management and visualization of a system-level simulator, which simulates and evaluates the behaviour of a telecommunication network.

2.1 Background and Motivation

Simulators are important in telecommunications in designing, testing, and optimizing communication systems. The most employed types of simulators in telecommunication systems are link- and system-level simulators. Each type has its own purpose and provides various kinds of insight into communication systems.

The main purpose of the Link-Level Simulator (LLS) is to simulate point to point communication links. The Evaluation of the performance metrics involves Bit Error Rate (BER) and Block Error Rate (BLER). BER is the number of bit errors divided by the total number of bits transmitted through a communication channel. It helps in determining the accuracy of the received data. The BLER is the number of error blocks divided by the total number of data blocks transmitted. On the other hand, system-level simulators deal with subsets of entire networks, computing performance metrics such as throughput, latency in terms of multiple BSs and UEs. Both simulators are necessary to assess the network wide behaviour and predict the performance of the system in different scenarios.

The system-level simulator employed in this thesis is helpful in the design, analysis, and optimization of RANs. It can model multiple BSs and UEs in different layers of the protocol stack such as Physical (PHY), Medium Access Control (MAC), Radio Link Control (RLC) and application layers. Multiple physical channels and reference signals are supported by the simulator, for example Physical Uplink Shared Channel (PUSCH), Physical Downlink Shared Channel (PDSCH) and Sounding Reference Signal (SRS). It comprises models of full PHY layer, different duplex modes, and several scheduling strategies. Besides, it facilitates the comparison of various data traffic models, interference, UE mobility, and link adaptation. The simulator also allows the Multiple Input Multiple Output (MIMO) configurations, the MAC logical channel priority and the RLC modes. Key Performance Indicators (KPIs) of network performance are throughput, BLER, and spectral efficiency.

In addition, the simulator makes it possible to simulate several aspects like BS and UE placement, mobility patterns, traffic patterns, and interference, thus creating an all-inclusive approach to assessing network scalability and resource scheduling. Simulating high fidelity PHY layer and providing Multi-User MIMO (MU-MIMO) performance measurements, the simulator provides useful information and supports RAN optimization. The capability of the simulator to model radio access technologies, antenna sets, application traffic patterns, the availability of multiple scheduling strategies and interference scenarios provide for a powerful basis for evaluating and network performance. This approach enables deep exploration of the network's behaviour under different conditions to help in building efficient and reliable RANs.

The system-level simulator has BSs physical coordinates and the UEs coordinates are generated through random seeds. These coordinates are passed on to a ray tracing software, which includes the 3D model of the scenario. The ray tracing software calculates the signal propagation, all the possible paths from the BSs to the UEs. The 3D model is beneficial as it helps to visualize the BSs and UEs coordinates in the 3D world. If there are a lot of buildings in between the BS and UE, then the signal must find alternative ways to reach the UE. It will affect the signal propagation as it will reach the UE after reflecting off or refraction through the buildings. In case of rural area, it is easy as mostly the UEs are in direct line of sight with BS. Due to multiple BSs transmitting data at the same time, there is a high chance that the UE will receive the signal from multiple BSs. Once the UE is connected to the BS then it will discard signals from other BSs which are coming towards it. These signals degrade the performance of UE receiver. This occurrence is known as interference. The existence of realistic interference in the simulation is also one of the main benefits of using a system-level simulator over LLS. The simulator also models noise, an unwanted random signal produced by every electrical component of telecommunication system. It can impact the reception of the signal, which results in further degrading the signal quality.

In the domain of system-level simulations, accurately managing and visualizing the data is necessary. System-level simulator generates substantial amounts of data which need to be managed properly to be able to get the insights. The motivation for this study comes from the volume of data, which is being generated by the simulator. It needs to be stored in a proper manner to avoid data loss. When the data is stored in a safe environment then later it can be used to visualize the patterns and behaviours more effectively.

The goal for this thesis is to develop accurate data management and visualization techniques that can handle enormous amounts of data generated by system-level simulators. By strengthening these services, the usability and effectiveness of the simulator will be enhanced and altogether it will be able to provide accurate analysis of complex systems and contribute significantly to 6G research.

2.2 Problem Statement

The system-level simulator provides valuable insights into the performance and the overall behaviour of the system. However, the copious amounts of data being generated by the simulator involve various challenges with data management and visualization.

Data management in system-level simulators includes collecting, storing, processing, and retrieving the simulation data after the simulation is performed. The key difficulties in data management include the immense amount and diversity of the data generated by the system-level simulator. In the future simulations will become more complex so adequate data management is necessary to make rapid decisions. The data contains diverse types of information such as performance indicators, error reports and simulation parameters, which must be stored and backed up. For the simulator to be effective, swift data processing is crucial. Incorrect or corrupted data can lead to false results and errors in judgement, reducing the system's reliability.

Visualization converts the raw numerical data into graphical form which is easier to understand and present. Appropriate visualization techniques can demonstrate emerging trends, patterns and irregularities which might not be seen through the raw data alone. In system-level simulators the visualization tools can help the user to track the performance of the system, detecting issues and making reasonable decisions. In visualization, the difficulty is to translate complex data into appealing graphical representation. Visualizing simulation data in an understandable and practical manner is a significant challenge. This thesis seeks to address these hurdles by creating an efficient data visualization and management service for system-level simulators.

2.3 Objectives

The primary objectives of this thesis are to examine the present state of data management and visualization methods for system-level simulator and use it as a predictive engine to develop a digital twin to visualize the simulation data in a three-dimensional view. The thesis seeks to develop a data management system that signifies accuracy of the data, scalability, and immediate handling. Furthermore, it aims to design a web application that creates interactive visualizations from simulation data. It also includes the three-dimensional models on which the simulation data will be mapped. It will also analyse the strengths and drawbacks of the system. The suggested approaches' efficiency will be tested using simulation data, with a focus on performance, reliability and ease of use, and user feedback to further develop and improve the system.

To meet these goals, this thesis will focus on some key points. First it stores the simulation results in a database so that those will be available in the future. There is also some valuable information about the simulation which should be part of the metadata, this metadata should be saved along with the simulation results. A web application will be designed which allows the user to do the statistical analysis of the simulation data and to be able to view it in a three-dimensional space with BSs and UEs. The access management privileges will be set up to control and limit the application use.

2.4 Scope of the Thesis

This thesis examines data management and visualization practices within the context of system-level simulator. The scope covers the thorough assessment of prior research to better understand the present status of data management and visualization approaches. It also entails recognizing the primary hurdles confronted in these domains, specifically working with the large amount of data which is being generated by system-level simulator. The study will create a working model which uses the suggested data management structure and visualization tools. The model will be evaluated with simulation data to validate the accuracy.

3 Literature Review

Telecommunication technologies have experienced steady progress which led to the development of 6G, which claims ultra-low latency and extraordinary data rates. To accomplish these lofty objectives, the designing and effective optimization of 6G networks demands innovative tools and processes. One such key tool is a digital twin which functions as a virtual counter part of the real network. The fundamentals of digital twin technology, with a major focus on data management and visualization in a system-level simulator for 6G networks will be discussed in this chapter.

3.1 Overview of Digital Twin Technology

Digital Twin Technology is a procedure which generates a virtual clone of a physical object. It replicates the physical entity's present state, actions, and performance. Nowadays the use of this technology has expanded into a variety of industries including telecommunications. Dr. Michael Grieves gave a presentation at the society of Manufacturing Engineers conference in 2002 where he referred to the term 'Digital Twin' technology specifically for manufacturing and aerospace industries (McDonough & Michael, 2024).

The National Aeronautics and Space Administration (NASA) introduced the digital twin technology term in 2010 while improving spacecraft system simulations with digital twin technology. The market receives a positive benefit from digital twins that enable straightforward control and monitoring of extensive complex systems (Clpritch, 2025). More businesses began to recognize digital twin benefits which led them to express interest in this technology causing digital twin technology to spread to healthcare and automotive industries. Nasa's Apollo mission in 1960 marks the actual start of digital twin technology. The Apollo mission received simulated spacecraft analysis through systems designed by Nasa during space operations. The team produced an outdoor duplicate of the orbital system that they had previously placed in space (Ferguson, 2024).

As the organizations move toward the digital era, digital twin technology develops further combined with advanced data analytics and visualization tools. Digital twins, which are based on simulation data, can represent the whole ecosystem of smart cities, making it easier to optimize them. Digital twins make it possible for the stakeholders to make timely decisions by visualizing different patterns in an uncomplicated way using dashboards. Using simulation data in digital twins can significantly improve productivity.

3.2 Visualization Techniques and Tools

Visualization plays a vital role in digital twin technology as it converts the complex data patterns into meaningful insights, the digital twin focuses on the real time data captured from the physical or simulation systems. For monitoring the behaviour of the system effective visualization techniques are required. When advanced visualization techniques are used correctly with the digital twin, it helps in the improvement of KPIs such as data throughput and communication latency.

In the literature, different visualization techniques have been explored that include spatially two dimensional and three-dimensional modelling techniques to represent physical objects in digital twins. They allow users to interpret how data points vary in space and spatial correlations. For example, three-dimensional modelling has been used by manufacturing industries to visualize factory layout as well as real time monitoring of the health of equipment (Bhoda, 2024). In both urban planning and infrastructure systems, the digital twin is used to evaluate the performance of the map, which means it assesses the performance of a digital model in representing current real conditions over a certain area. The areas for improvement are simulated, including factors such as traffic flow, infrastructure health and environmental conditions. Using these techniques, users can deal with large datasets and develop meaningful understanding of the system behaviour at the large and small scale.

Alongside static visualizations, interactive dashboards have become a popular tool for increasing user interaction with the digital twins. An interactive dashboard is a data visualization tool which allows users to do the analysis of real time data. Interactive dashboards facilitate the user to change the parameters on run time, visualize the real time data, and run the simulation from the tool. With the help of Interactive dashboards users can analyse the patterns and predict the abnormalities more easily than from the spreadsheets or static reports. Moreover, advancements in web-based visualization techniques make it easier to deploy the interactive dashboards across different platforms and makes it easy for use even for non-technical people.

The use of developing techniques like VR and AR has further increased the possibilities of visualization in digital twin systems. VR and AR configurations offer real-time experience in which the user can interact with the digital twin in three dimensions. These advanced techniques are useful for training and monitoring complicated systems. Although these technologies have their own benefits, their implementation needs specific software and hardware tools which may not be practical for all the applications.

3.3 Related Work and Existing Solutions

The digital twin concept has drawn a lot of attention in the past few years; a lot of research is ongoing on the visualization techniques used in their applications. A survey done by the GRIDD research team focuses on the significance of visualization methods for digital twins. The survey analyses different visualization methods based on their data types, system complexity and use cases. For researchers and professionals who are looking into data visualization tools, this classification can be an essential resource.

Along with the efficient data visualization methods, accurate data management strategies are also necessary for the smooth operation of digital twins. The data management process involves effective solutions for data storage which can handle substantial amounts of data generated through simulations. Then with the help of visualization tools the raw data can be processed into meaningful data. Machine learning can also be used with digital twins to further improve the predictive skills by investigating real-time inputs in addition to the past data from the simulations (GRIDD, 2024).

Kapil et al. (2024) published a literature review which investigates the feasibility of digital twins across various industrial sectors. The study highlights the importance of digital twins and how they can be used to increase the decision-making process across several industries by more accurately integrating the real time data with the advanced visualization techniques. The use of AI with these systems can increase productivity by automating regular operations such as abnormalities detection and recommendation to set the performance enhancement parameters.

Fett et al. (2023) study highlights the design and implementation of digital twins. The literature review evaluates the research areas which can be further explored to assist actual implementation of digital twin technology. It underlines the need for some methodical ways to model the user needs in the designing of digital twin system. This basic study also highlights the visualization tools which might be applied to the large-scale digital twins.

Furthermore, the current solutions demonstrate the significance of merging accurate data management strategies with advanced visualization tools to enhance the user experience with complicated datasets generated by the simulator. Interactive dashboards made with framework like Dash enable users to go through the scenarios dynamically and closer to the reality, while also visualizing the KPIs for instance throughput in real-time scenarios such as 6G networks.

4 Implementation

This chapter explains the implementation process of how the raw data files generated from the system-level simulator are saved in a common place for easy access, furthermore these files are uploaded to a web application which converts these raw files into meaningful data. The implementation flow further converts this meaningful data into graphical plots for analytical purposes. The web application is also equipped with a 3D visualization tool which emulates the actual physical locations of the cellular communication equipment.

In the beginning, a simulation result file, 3D models and the coordinates of BSs and UEs were given. The simulation file opens in Python with the help of SciPy, which is an open-source Python library used for scientific computing. It contains a loadmat function which can read the MATLAB files and convert the data into Python dictionaries (Virtanen et al., 2020). Data extraction algorithms are used to get the data from the simulation file.

The 3D models are processed separately; they are loaded into Python using trimesh library. Trimesh is used for loading three dimensional triangular meshes (Dawson-Haggerty et al., 2019). After successfully processing the models, the coordinates of BSs and UEs are also loaded. The simulation data is then mapped on these 3D models.

The processing of simulation file and 3D models are both done separately, and everything is loaded from the specified path. A web application is designed to combine all the algorithms in one place. The web application is based on Dash, an open-source Python framework which is used for building analytical web applications.

After the data is extracted from the simulation file the SQLite database is used to store the file, and it is linked with the web application. SQLite is a lightweight database which is portable and easy to configure as it does not require complex server settings. Instead of loading the data from a specific folder or a path, a new upload feature is developed for both the simulation file and the 3D models. The end user can now upload the simulation result file on runtime, and it will be saved in the database. The 3D models and coordinates of BSs and UEs are loaded in two steps, first it uploads the model and then in the second step it processes the coordinates. Then users can map the simulation data on these coordinates by filtering the simulation file.

4.1 Authentication

The web application is protected with Flask base authentication system to make sure that only restricted people can access it. Flask is a lightweight python web framework used for building web applications. The Flask module uses GET and POST, which are commonly used Hypertext Transfer Protocol (HTTP) methods for web communication. HTTP is a protocol designed to allow communication between the client and the server. The GET is used to request data from a source, or a server and the POST is used to send the data to the server. A flask application server is set up in the beginning and the routes are defined for different Uniform Resource Locators (URLs).

When the user navigates to the web application URL, a GET request is sent to the Flask server. The server processes this request by sending the Hypertext Markup Language (HTML) login page. Now when users enter the credentials and submit the form, the server processes the POST request by ensuring that user entered the right credentials if so then user will be logged in otherwise error message will be displayed. When the user presses the logout button the GET request is sent to server and it processes the request by logging the user out back to the login page.

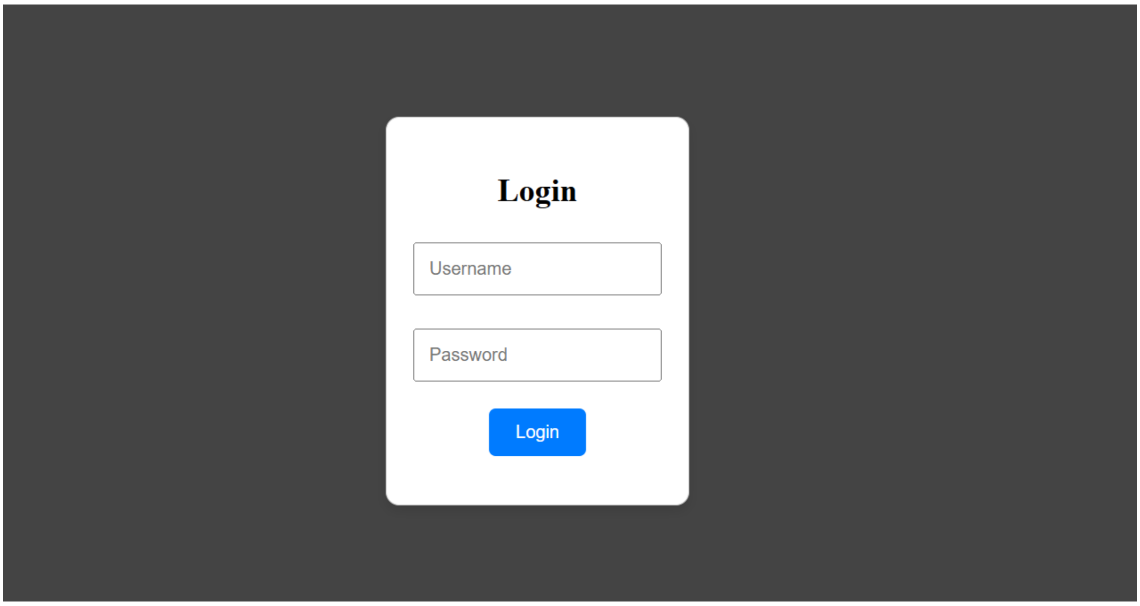

Figure 2. User Authentication.

After successfully logging into the web application, the user can start doing the analysis. The web application is divided into two main components, the first one provides detailed statistical analysis, and the second one is for 3D visualization.

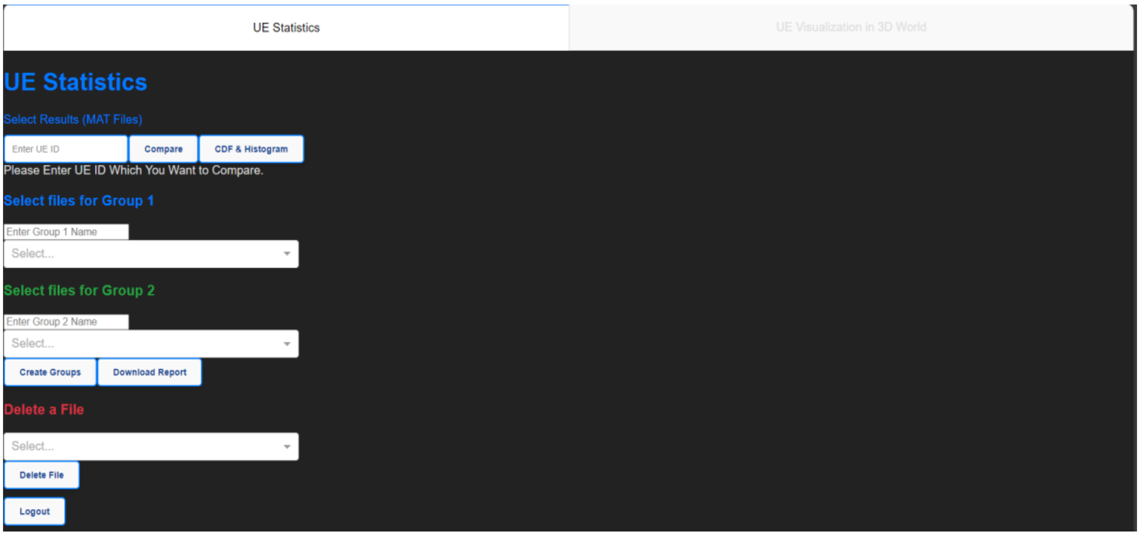

Figure 3. Layout of first tab.

4.2 Comparison Function

The simulation file is first uploaded using the upload feature and then stored in the database. A comparison function is developed to compare the statistics of different simulation files based on the user IDs. In the search box the web application user can enter the user ID from the simulation files and then press the compare button. The web application will go through all the simulation files which are stored in the database and search for the specific user ID. If the user ID is found in the file, then it will display some useful parameters related to that specific user ID. If the user id is not found in the file, then it displays a message stating that the user id is not found in the file. The data is displayed both in numeric and graphical form.

In Figure 4, the user entered user ID 75 and then it tries to find the user ID in every simulation file which is stored in the database. In this scenario, only five simulation files are saved in the database. The application does not find the user id in the first three files but in the fourth file the user ID 75 is found, and its statistics are displayed. The data rate is plotted as a bar graph for quick analysis.

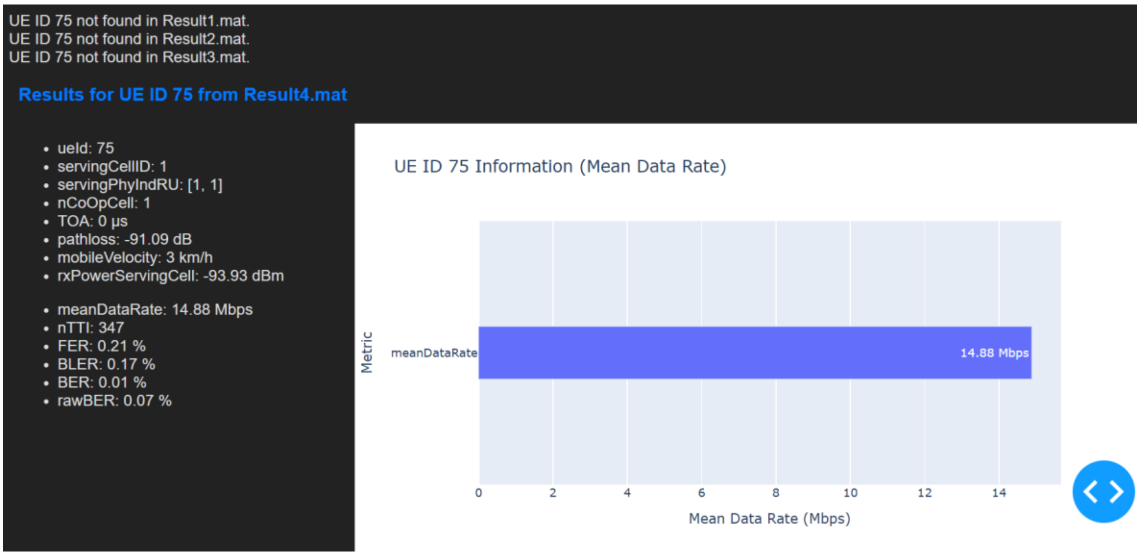

Figure 4. Search by user ID (1).

Figure 5 is the continuation from the previous one. It graphically displays some other parameters. The system then moves to the fifth simulation file and goes through it to find the user id but unable to do it so displays the not found message.

Figure 5. Search by user ID (2).

4.3 CDF and Histogram

The user can also visualize the distribution of throughput in the form of CDF and histogram. CDF is a function which shows the probability that how likely the value will be less than or equal to some number. In the simulation results, CDF can help in understanding the possibility of obtaining different data rates. The histogram displays the distribution of data. It creates frequency bars with specific ranges and the height of bars are used to represent how many data points lie in that range.

The CDFs of five simulation files are displayed in Figure 6 below and we can see that the maximum data rate is achieved in “Result1” which would be around 41 Mega bit per second (Mbps). The data rate in “Result3” and “Result5” are between 8Mbps to 29Mbps. The user can select the desired simulation file from the side menu and do a comparison of multiple files.

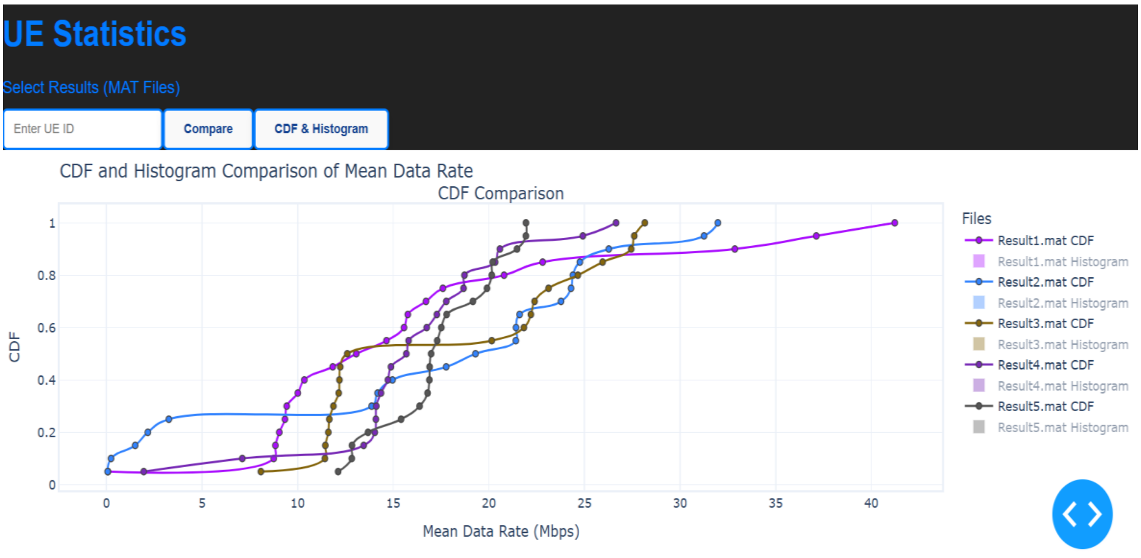

Figure 6. CDF comparison of simulation files.

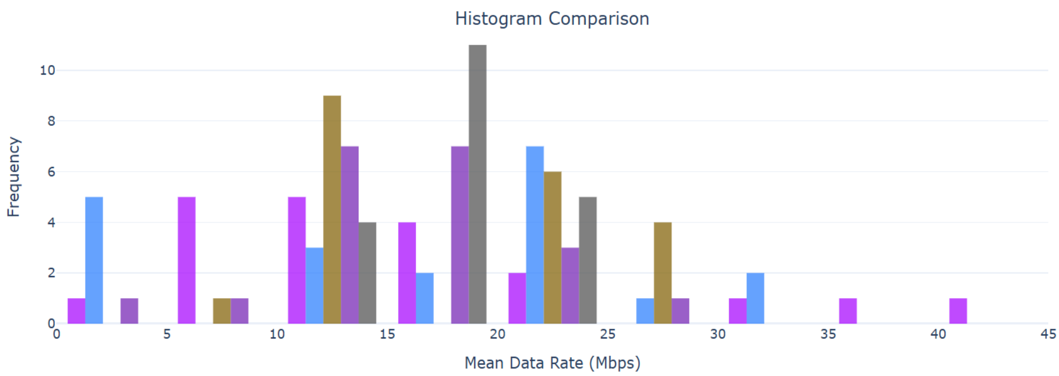

Figure 7. Histogram comparison of simulation files.

Then users can also view the histogram just below the CDF. The same five simulation files are represented here. From Figure 7, it can be observed that “Result5” contains the greatest data points, approximately 11 from 15-20Mbps range, and “Result3” has the maximum points in between 10-15Mbps. Most data points lie between 10-25Mbps for all the simulation files.

4.4 Grouping of Simulation files

Up to this point, the user has been dealing with single simulation files but now with the help of grouping feature the user can group multiple files and view the CDF of grouped files. The combining of different simulation data files allows the user to get a better look at trends or patterns which may not be seen from just a single file. The user can first name the groups and then select the simulation files in each group. After selecting the files, the create groups button can be pressed to view the grouped results. In Figure 8, two result files are selected in the first group and three in the second.

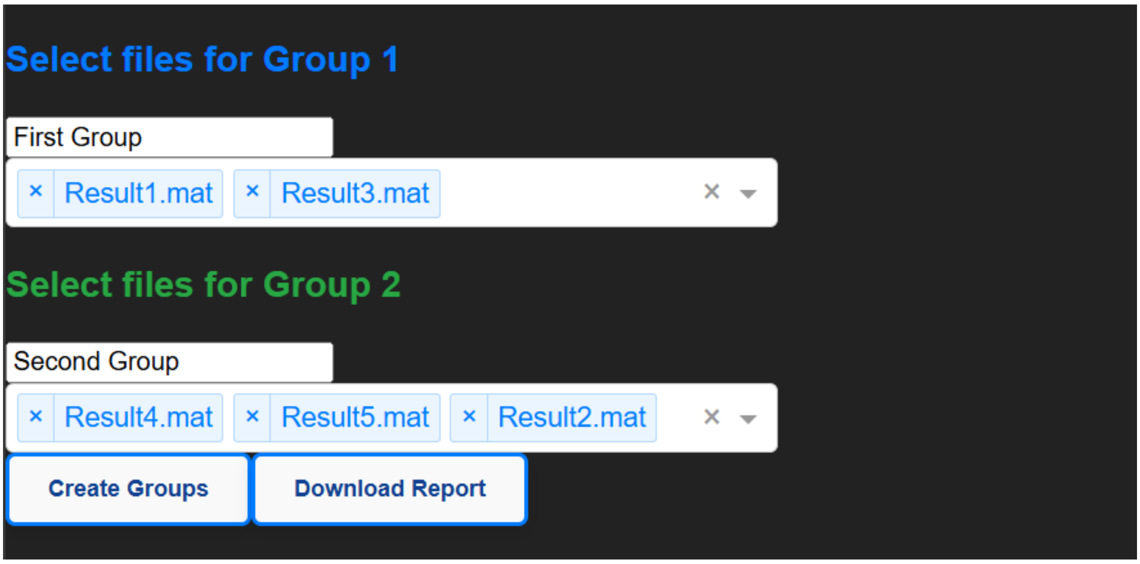

Figure 8. Creating groups of simulation files.

After pressing the create groups button, the user can see the group comparison results. First it displays the mean of the data rate of both the groups, and it also shows which files are in which group for better understanding.

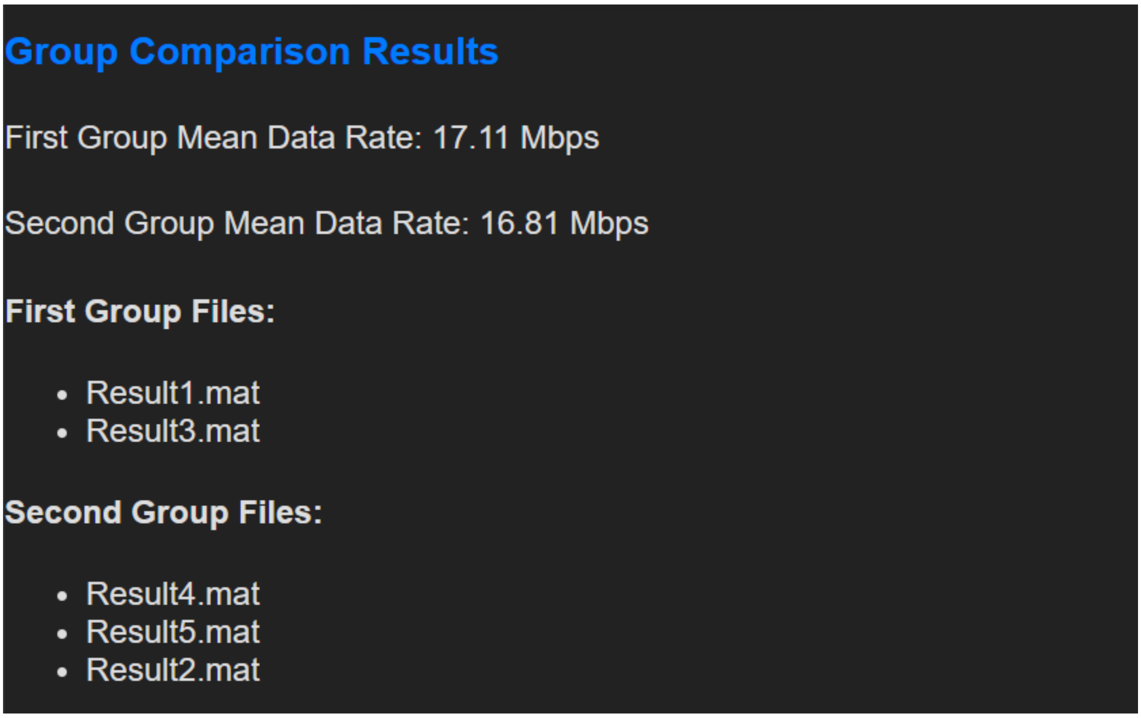

Figure 9. Group comparison results.

To make the data rates clearer and comprehensible, a bar graph is used for visualization purposes. From Figure 10, it can be observed that the mean data rate is better in the first group.

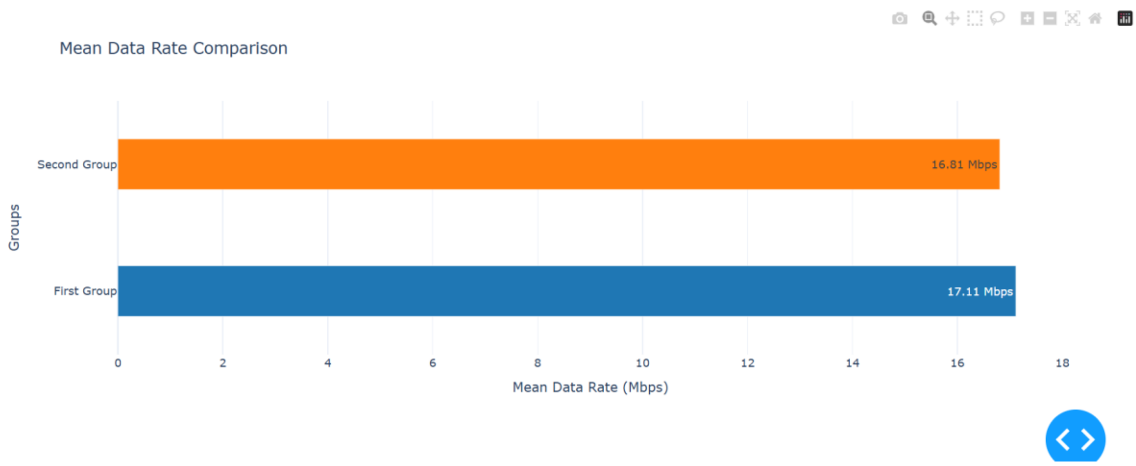

Figure 10. Mean comparison of groups.

The CDFs of both the groups are also plotted and it can be seen again that the first group is performing better than the second group.

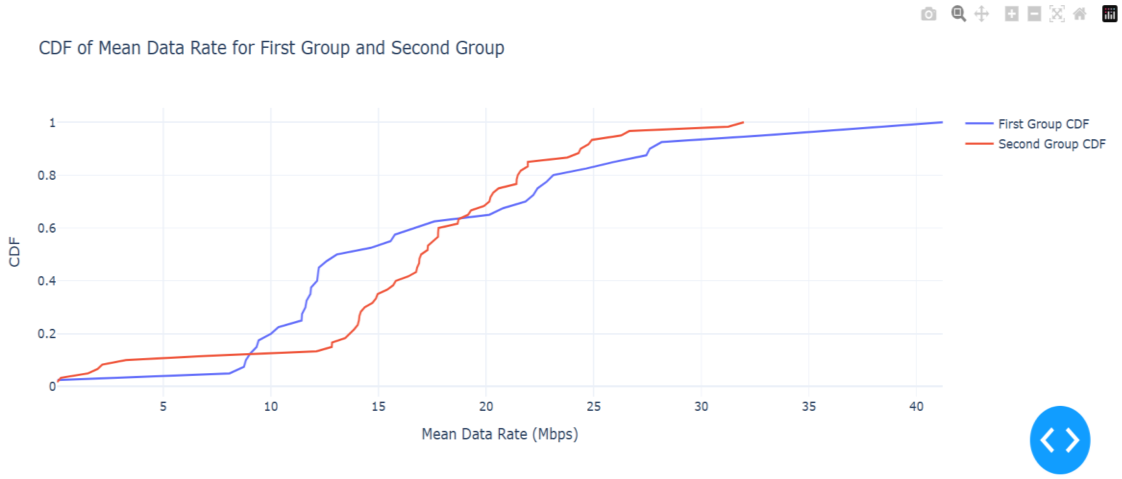

Figure 11. CDF comparison of groups.

In Figure 8, the download report button can be seen. So, after all the analysis users can press that button to save the comparison results in a Portable Document Format (PDF). The PDF will be saved on the user's computer and can be used later to compare with some other results.

Figure 3 shows that the last function on the first tab is the delete file function, which deletes unnecessary files from the database. Users can select the file and press the delete button to get rid of the unused files.

4.5 Automation and API

Thus far, the simulation result files and 3D models and coordinates of BSs and UEs are loaded into the web application with the upload feature. The problem that occurs with this approach is that it puts too much burden on the end user. Every time the user uses the service, they must manually upload the new simulation result files, 3D models and coordinates of BSs and UEs. It also requires sharing the models and coordinates with the users who want to do the analysis, since these are confidential data so sharing with every user is restricted.

To overcome these hurdles, a new automation approach is used in which the 3D models and 3D coordinates of BSs and UEs are automatically loaded from the backend and can be fetched directly on runtime. This helps to prevent confidential data from being compromised by eliminating manual data provision to each user. For simulation file upload a new solution was proposed, instead of uploading the files on runtime, they can be sent through the API. An API is designed between the system-level simulator and the web application, which can send the result file to the web application automatically after the simulation is finished. An API is a basic interface which enables communication between different software applications. It can use any type of method for communication.

A Representational State Transfer (REST) API is utilized for communication between the simulator and the web application. The REST API is a type of API which uses specific rules and methods for communication between different software programs through the internet, commonly using HTTP (Waseem et al., 2020). Standard methods are utilized in REST API like to get the information GET is used and to send the information POST is used.

The system-level simulator acts as a client and the web application acts as server. The client encodes the data in JavaScript Object Notation (JSON) format and sends a POST request to the server. Upon receiving the request, the server validates the data in JSON format and does decoding, then sends the appropriate response back to the client. JSON is a lightweight data format commonly used for transferring data between different systems. This reduces the burden on the end user as the simulator automatically transmits the simulation file to the web application through REST API when the simulation is completed.

4.6 Three-Dimensional Visualization

The second component of the web application regarding 3D visualizations is illustrated in the layout of the tab shown in Figure 12. Once a scenario is selected from the drop-down menu the 3D model and 3D coordinates of BSs and UEs associated with the selected scenario are loaded. Then, another drop-down menu is presented to select a simulation file, so that the active UEs from that simulation file can then be mapped onto the 3D model.

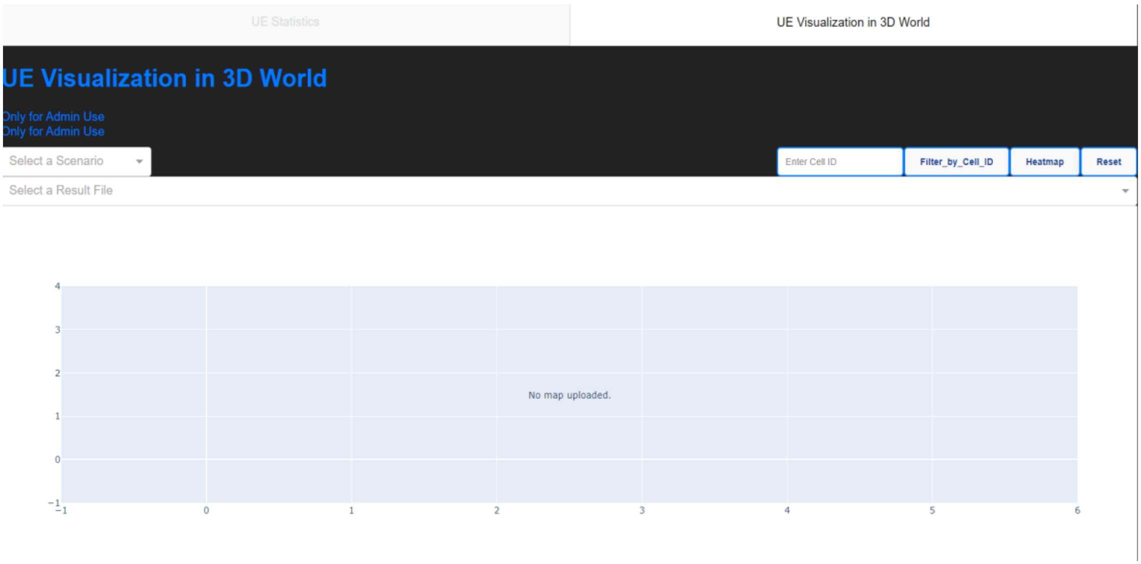

Figure 12. Layout of second tab.

In Figure 13, The “test scenario” model is selected from the drop-down menu, after selecting the model its map and coordinates are loaded. The black data point is the BS and the blue data points surrounding it are the UEs of the whole scenario.

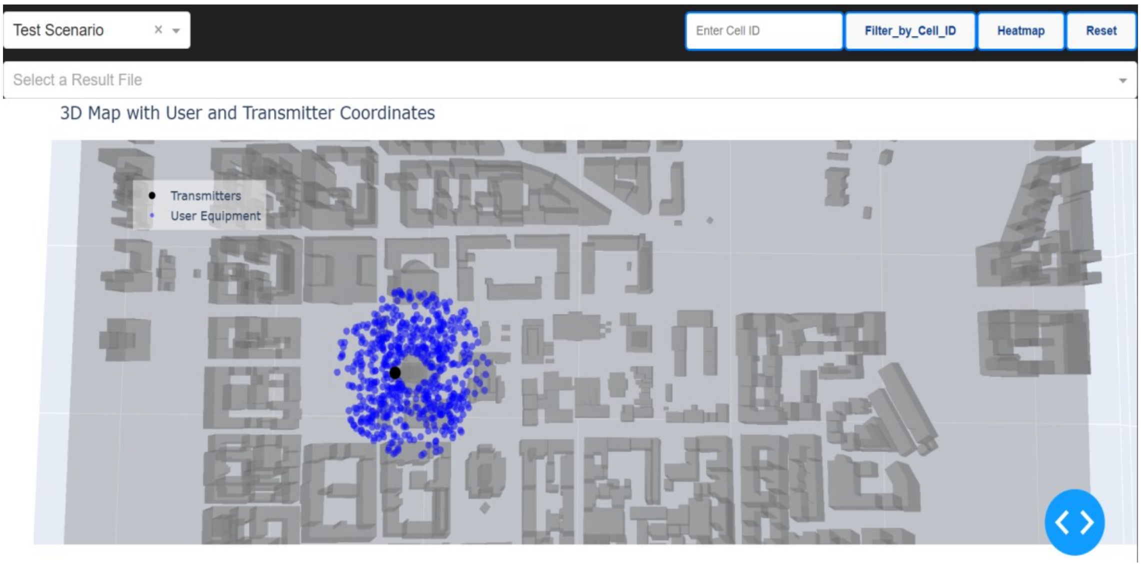

Figure 13. An example of a 3D model with coordinates of BSs and UEs.

After this user can select the simulation result file from the drop-down menu. In Figure 14, user selected the “Result3” file, the blue data points represent active UEs in the “Result3” file and the data points marked as grey are non-active UEs in the file.

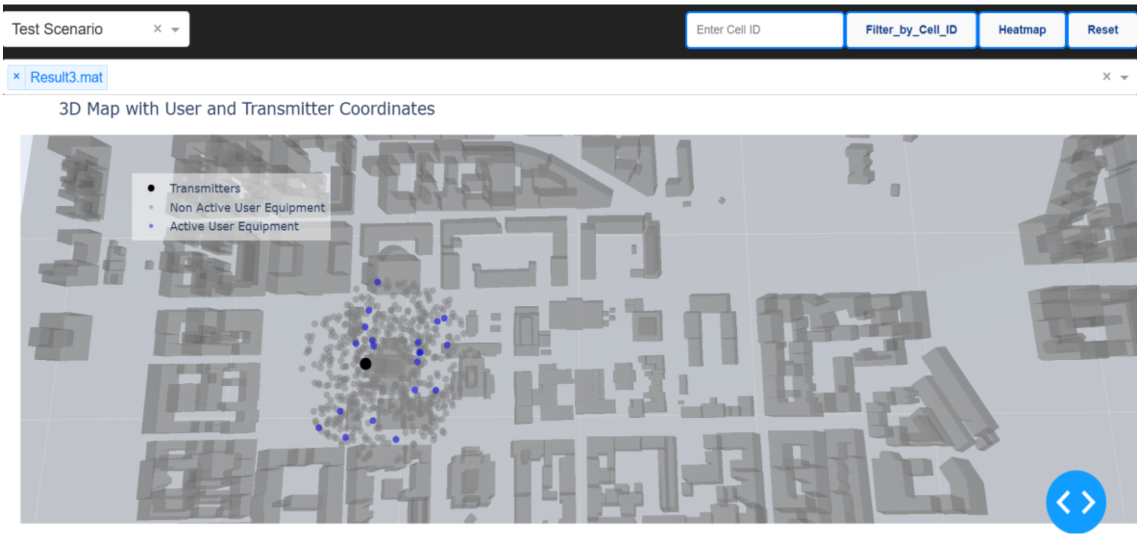

Figure 14. Simulation data mapped on the model.

A heatmap is a visual tool which uses colours to show the intensity of data values in a specific area. In this case, it helps to see how mean data rates vary across distinct parts of the 3D model, with colours indicating higher or lower rates. The distribution of mean data rates in “Result3” file is shown in Figure 15, the dark green UE is achieving the highest mean data rate and the dark red or close to red UEs have lower mean data rates. Detailed information can be presented to the user regarding each specific UE when the user hovers over the UEs. As shown in Figure 15, the UEID and mean data rate is shown along with the BS to which the UE is connected. In this case, there is only one BS. The sidebar is also useful to quickly analyse data rates in the simulation file. It provides colour scale and association between colour and data rate.

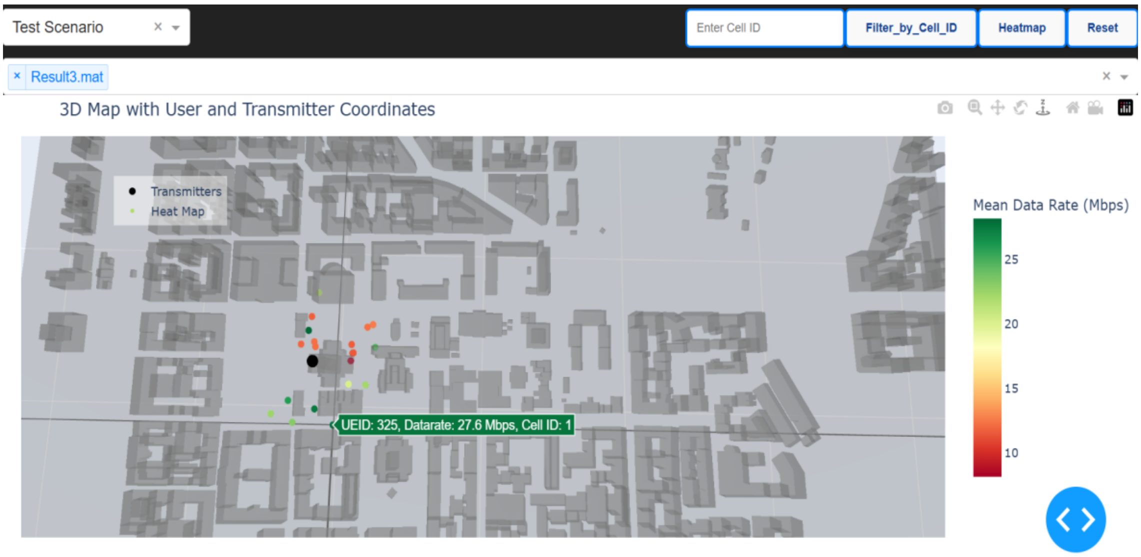

Figure 15. Heatmap of simulation data.

The filter by cell ID function is used to filter the UEs connected to specific BS. In the given scenario there is only one BS and all the UEs are connected to it. The “Reset” button can be utilized after the analysis to close the current visualization and open the other scenarios.

Currently the simulation file is being saved in the database and then the required data is extracted. If more data is needed, it needs to be extracted from the file as well. To overcome this a new functionality has been designed in which the whole simulation data is saved along with the simulation file in the database. The simulation data is in a nested structure. To save it in the database, data flattening is necessary. Flattening is the process of converting complex structured data into simple and single non-nested structure format. Once the data is flattened, it is saved in the database with every field having its own column. Now there is no need to extract the data from the file as it can be directly queried from the columns.

5 Results and Discussion

This chapter will discuss the outcomes of the thesis and the comparative analysis of different approaches which were used and provide recommendations for future work. The goal of the thesis was to have a system where the system-level simulator results are stored and can be viewed later for research purposes. SQLite database serves the purpose of storing the simulation results and histograms and CDFs are used for the comparison of multiple simulation results. Visualization tool supports multiple scenarios across different countries, allowing the user to visualize the simulation data in 3D coordinates.

5.1 Comparative analysis

The comparative analysis goes through different approaches which were used in the thesis and describes their limitations and why there is a need for the innovative approach.

5.1.1 Centralized Data Processing and Visualization

The system-level simulator generates the result file, which contains large amounts of simulation data. The 3D models and coordinates of BSs and UEs are processed separately. The simulation output data is combined with these models to visualize the results in three dimensions. The 3D models and coordinates algorithms were created separately and data extraction from the simulation file was done separately. A web application was developed where both algorithms merged in one place. Previously the analysis was done using separate scattered tools, now the same features are available in a single centralized location.

5.1.2 Development of the Upload Feature

In the initial phase the upload feature was developed which allows the user to upload the simulation result file in the web application during the runtime. Then the web application stores this file in the database. The 3D models of different cities and the coordinates of BSs and UEs were also being uploaded by the user on run time.

The main advantage of this method is its simplicity; it allows users to upload the simulation file and run the analysis without needing to use multiple tools for visualization and analysis. However, there are multiple drawbacks to this approach. It creates too much work for the end user to handle and the chances of error increases in manual upload process as humans tend to make mistakes. The 3D models and coordinates of BSs and UEs are confidential data, and requiring every user to have access to these models and coordinates for analysis on the web application is impractical. So, the development of a new phase is proposed to further improve the user experience.

5.1.3 API Development and Automation

In the second phase the API is developed for communication between the simulator and the web application. The simulator will send the result file to web application with an API and then the result file is stored into the database automatically without any user interference. Three dimensional models and their coordinates are also automated, now with the dropdown menu user can select the scenario and the model and its coordinates will be loaded.

The user involvement at the run time is now minimized, the API takes the place of manual uploading the simulation result file. The advantage of this approach is that it reduces the work of end user now the user can start the simulation and when it finishes the API will send the result to the web application and then user can start the analysis. The chance of error is reduced as compared to manual uploading and it is time efficient as well. The downside of this approach is that it only saves the simulation result file in the database. The data is then extracted out of the file and processed. A new solution was proposed which said that along with the file all the data of the simulation file and its metadata should also be saved in the database.

5.1.4 Development of Data Extraction and Storage Algorithm

In the last phase of thesis, a new feature is developed which fetches the data from the simulation file and saves it into the database with the same column names which were in the simulator. Previously only the simulation file was being saved but now along with the file the whole data of the simulation is stored in the database. This approach is the most feasible as it will be easy to query the data from the columns instead of opening the simulation file and extracting out from it.

5.2 Future Work

There are various potential modifications and suggestions for future work which help to make the system more efficient. One key area to consider is three-dimensional visualization. Currently the system only visualizes the throughput. Future research can concentrate on displaying several fields. Furthermore, allowing users to visualize the beamforming on the map will improve the understanding of coverage areas. It will aid in determining the beneficial effects of beamforming techniques. Beamforming is a technique in wireless communications where the transmitted signals from an array of multiple antennas are directed towards a receiving target. This method increases signal strength and coverage and reduces interference.

Developing a more comprehensive authentication system could also be the next step where users can register and login with their credentials. The direction in which the transmitters are pointing would also be a good addition and provide clear understanding of the coverage area of each transmitter. Some transmitters share the same location but with different tilt angles positioning. The user can identify immediately by looking at the map which transmitter is pointing in which direction.

5.3 Conclusion

The results generated by the system-level simulator usually contain large volumes of data. To save this data a data storage facility is built where the data can be stored and can be found later when needed. In the past there was a chance of losing the results to overcome this, a safe place for storing the results was necessary. The SQLite database is utilized for saving simulation results because it is a single file database which is easily portable and does not require a complex server configuration.

A web application is designed based on Flask, Plotly and Dash. The purpose of this web application is to facilitate the user getting more insights into the simulation results. A REST API is used for communication between the Simulator and the web application. The user can access the results through the web application which are being fetched from the database.

Histogram and CDF are utilized to get insights from multiple result files. CDF was mainly used to observe the results in the past but now with the added histogram alongside the CDF will facilitate the user analysis. The user can also merge multiple files into groups and view the group CDF.

To better visualize the simulation results three dimensional scenarios are loaded into the web application and based on the coordinates the BSs and UEs mapped on the model. Once the coordinates are mapped then users can view the connected UEs. Heatmap represents the data rates of UEs in assorted colours which can be easily understood from the three-dimensional visualization.

The implemented architecture proves that both graphical and 3D visualization techniques provide efficient and meaningful results. The developed web application allows the user to upload any specific scenario, map, and simulation file which in an instance is converted into meaningful data displayed on the user’s dashboard allowing the user to choose between the preferred method of visualization. The designed web application is an efficient way of saving valuable resources such as time and engineering effort as it autonomously extracts and presents meaningful data.

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