OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

FACULTY OF COMPUTER SCIENCE

Communication and Networked Systems

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# Communication and Networked Systems

Bachelor Thesis

# Simulation of Latency in Backhaul Networks for 5G

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# Abstract

## Abstract

The continuous development of wireless communication technologies leads to a growing number of connected devices and increasing real-time requirements. These rising demands on communication networks require heavy network densification, which in turn leads to increased costs. The use of wireless backhaul technologies, in comparison to wired ones, offers a promising alternative to meet the requirements of state of the art networks while reducing costs. The design of backhaul networks is therefore becoming increasingly important. Accordingly a simulation environment for comparing three different backhaul concepts, for the 5G technologie, is implemented. The three different concepts are namely fiber and two wireless concepts: Sub-6GHz and mmWave. The main objective of this work is the simulation of a 5G network on a selected example in a limited region. As area of study the university square of the city of Magdeburg was chosen. The work builds upon research on backhaul networks and the technologies employed. Furthermore, suitable simulation tools were identified and a simulation environment was selected, employing SUMO for the traffic simulation and OMNeT++ with Veins as interface for the network simulation. The models for all three backhaul concepts (fiber, sub-6GHz and mmWave) were implemented for Magdeburg University Square. OpenStreetMap data was imported for the traffic simulation and a traffic volume according to the statistical reports of the city of Magdeburg, random movements of pedestrians and tram and bus traffic according to the timetables of local public transport were taken into account. The evaluation was carried out for the performance parameters latency, jitter and frameloss to assess reliability.

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## CHAPTER 1

# Introduction

## 1.1 Motivation

The continuous development of wireless communication technologies and their applications lead to an ever-increasing number of connected devices and high real-time demands. The network densification caused by the increasing number of networked devices and the rising needs for higher data rates is leading to a significant increase in the required network infrastructure. Wired networks often reach their limits as they are associated with high installation and maintenance costs. Given these growing challenges and rising costs associated with wired networks, wireless backhauling is becoming an important research topic. It is argued that wireless backhauling is a promising alternative to meet the increasing demand for network resources while reducing expanses. The question of whether wireless networks can achieve the minimum requirements of 5G or even keep up with the performance of wired networks is the focus of this bachelor thesis.

## 1.2 Task

The current trends in the development of 5G require the use of high frequencies up to the 60 GHz band for short distances and small cell sizes. The expected significant increase in base station density compared to 4G poses a challenge, as the range decreases with increasing frequency and the energy requirement increases.

In order to build high-performance infrastructures, efficient backhaul networks connecting base stations with the core network are necessary. Backhaul networks will increasingly be wireless and have multi-hop characteristics. The device density can be up to $10^6$ per $km^2$ for 5G and even around 100 per $m^3$ for 6G. Accordingly, the aim of the bachelor thesis is to carry out a simulation of a 5G network in a limited region and to model the communication latency. As the subject of research serves the usage of a 5G network by traffic participants of the university square in the city of Magdeburg. The focus lies on understanding the latency behavior between the end devices (UEs) of this network. Three backhauling concepts will be examined using the example of the university square. The aim is to compare the conventional wired backhaul concept (hereinafter referred to as fiber backhaul) with two wireless concepts, specifically Sub-6GHz backhaul and backhaul with mmWave.

## 1.3 Thesis Structure

This thesis is divided into five chapters. The first chapter contains the introduction to the subject, the motivation, the description of the task and presents the realized procedure. Chapter 2 explains the basis for the work. The chapter starts with a brief introduction to the 5G technology and backhauling. It then focuses in particular on the simulation of 5G networks and traffic simulation as well as the software tools used for the simulation. Chapter 3 presents the design and implementation of the simulation in detail. Reference is made to the mechanisms described in Chapter 2 and the implementation procedure is explained. In Chapter 4 a performance analysis is carried out using various parameters that were recorded during the simulation of these scenarios. Chapter 5 concludes this thesis with a summary of the entire work. It also contains an outlook to future work with suggestions for improving the simulation.

## CHAPTER 2

# Related Work

## 2.1 5G

5G is the successor to the previous mobile communications standards GSM (2G), UMTS (3G) and LTE (4G). Its development is tightly connected to the increasing progression towards further digitalization of society and economy. The globally increasing data traffic, driven for example by streaming, big data and the Internet of Things (IoT), will require new forms of mobile networks. 5G was first envisioned by the ITU (International Telecommuniction Union) and published with clear defined performance goals[1]. The minimal requirements of this Vision can be found in Table 2.1[2].

Furthermore, the ITU has identified both future and current usage scenarios and applications that must fulfill a broad spectrum of capabilities. These scenarios are divided into three main types: Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC). As shown in Figure 2.1.

Based on this Vision standardization organizations like the 3rd Generation Partnership Project (3GPP) or IEEE develop detailed technical specifications, which are binding for

| | Usage Scenario | Downlink | Uplink |
|---|---|---|---|
| Max. Datarate | eMBB | $20Gbps$ | $10Gbps$ |
| User Experienced Data Rate | eMBB | $100Mbps$ | $50Mbps$ |
| Reliability | URLLC | $99,999\%$ | |
| Connection density | mMTC | 1 Million Devices/$km^2$ | |
| Latency | eMBB | $4ms$ | |
| | URLLC | $1ms$ | |

Table 2.1: Minimum Requirements according to IMT Vision-2020 [2]

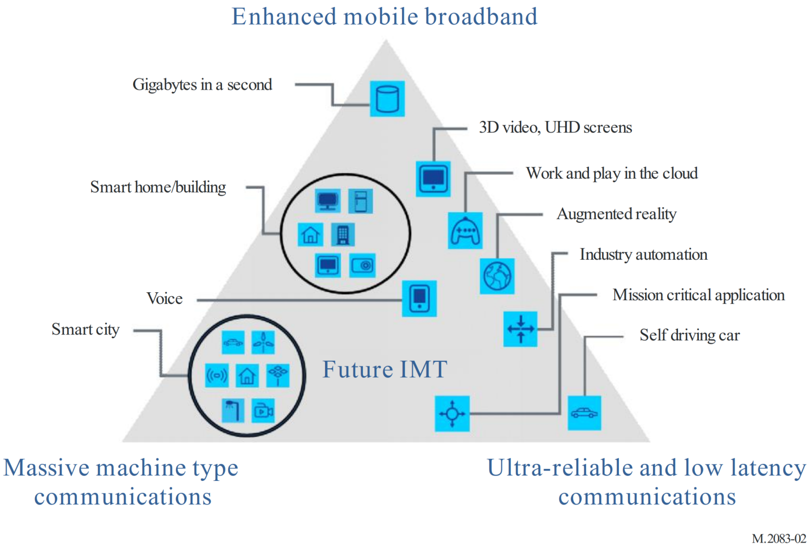


Figure 2.1: 5G Usage Scenarios [3]

the implementation of mobile communications equipment worldwide after completion and publication. With the completion of 3GPPs Release 15 the first full set of 5G standards got finalized in 2018[4]. By now 3GPP completed release 16 in 2020 and release 17 in 2022 with release 18 and 19 currently still in development[5].

## 2.2 Backhauling

Generally a Mobile radio network consists of three main components the core network, the Radio Access Network (RAN) and the User Equipment (UE) like smartphones or vehicles. In order to access the mobile radio network UEs connect to a base station, whose entireties are making up the RAN. In 5G the RAN implements the new radio (NR) technology. The Base stations are called gNBs (next generation Node B). The 5G core network (5GCN) oversees essential functionalities such as user administration and session management. Additionally, it is responsible for the transmission of user data traffic from User Equipments (UEs) through the Radio Access Network to the Internet and back. The former take place within the control plane, while the latter proceeds within the user plane. The connection between mobile base stations (BS) and the core network (CN) infrastructure is commonly known as the backhaul[6]. In general networking backhaul is a term that describes the connection of a network component situated at the outer edge to the inner network. It is therefor an integral component of the network architecture, with high influence on network performance.

In older mobile communication technologies, like 3G and 4G, backhauling mostly relied on wired connections like optical fiber. In 5G the three critical usage scenarios introduced necessitate network densification. Leading to a further impracticality of the existing macrocell architecture, prompting the implementation of small cell architectures. In the last years the network architecture has undergone a significant transformation, progressing from approximately 4-5 base stations per square kilometer in 3G to an anticipated 40-50 base stations per square kilometer in 5G [7]. With the growing demand for backhauling infrastructure, wireless backhaul emerges as a vital solution, reducing deployment challenges associated with a traditional wired backhaul. The shift toward wireless backhauling is substantiated by various factors:

- Cost-effectiveness: Wireless backhaul can be more economical than laying fiber optic cables, especially in challenging terrains or rural areas.
- Faster deployment: Wireless backhaul systems often have quicker deployment times compared to their wired counterparts.
- Scalability: Wireless solutions have better scalability, accommodating the increasing demands of 5G networks.
- Flexibility: Wireless backhaul technologies offer flexibility in base station siting, particularly advantageous in urban environments.

The advent of 5G networks has ushered in higher bandwidths, reduced latency times, and enhanced network capacity. Consequently, there's a heightened demand for more efficient backhaul solutions to effectively manage the substantial data transfer from mobile devices to central data centers. Backhauling assumes a critical role for providing high transmission rates with minimal latency and loss rates. That being said it represents a significant cost factor in building mobile networks worthy of consideration.

## 2.3 Technologies

Most 5G networks are operated in frequency bands below 6GHz. That being said, some operators in the USA launched 5G in bands above 24GHz. The propagation conditions in these frequency ranges differ significantly from those previously used for mobile communications. That is why 3GPP decided to divide the specification of the physical layer in to parts.[8] Accordingly, a distinction is made between Frequency Range 1 (FR1), which covers all frequencies below 6 GHz, and Frequency Range 2 (FR2) for all frequencies above 6 GHz, which is also known as the millimeter wave (mmWave) spectrum. Figure 2.2 shows the spectral ranges with application examples. The development of the new frequencies in the mmWave range is primarily aimed at being able to offer higher data rates. Ideally, 5G should deliver 5, 10 or even 20 Gbit/s. The mmWave spectrum offers very high bandwidths. While the maximum bandwidth of a 5G carrier is 100 MHz in FR1, carriers in FR2 can be up to 400 MHz wide.

The advantage of increased data rates is offset by a number of (possible) disadvantages. Four of the known disadvantages are described in more detail in [9]. They are briefly listed here:

- Range and coverage: At high frequency ranges antennas have low transmission ranges. While Sub6GHz antennas achieve transmission ranges of up to 2-3 kilometers, mmWave antennas usually only range up to a few hundred meters. Modern beamforming and massive MIMO technologies can mitigate this effect.
- Lack of building penetration: Because of the high reflection of high-frequency radiation mmWave arrangements posses very poor to no building penetration. At high mmWave bands line of sight is necessary.

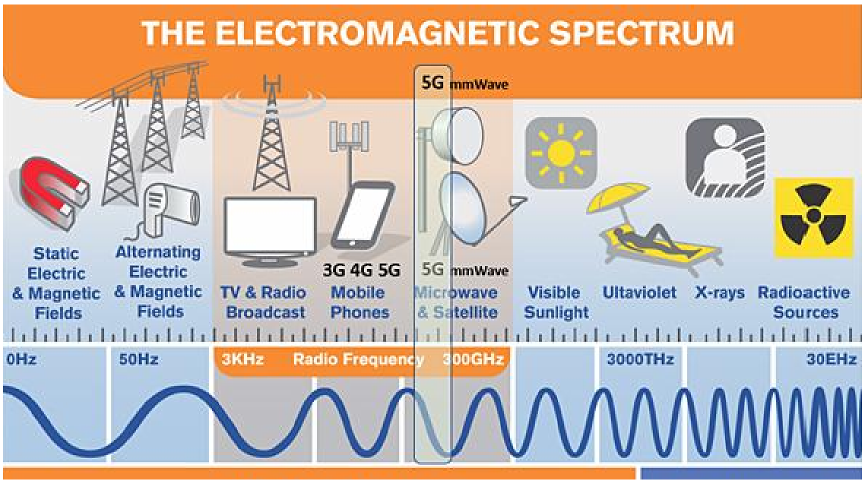


Figure 2.2: Electromagnetic Spectrum [10]

- Water as mmWave inhibitors: High-frequency mobile radio technology in the mmWave range acts as a water insulator which reduces performance in high humidity and heavy rain.

The biggest disadvantage of such high frequencies is that data transmission is only reliable when there is line of sight between the transmitter and receiver and generally at smaller distances. This is why FR2 cells are mainly useful inside buildings or in urban areas. Due to the short range, 5G mobile radio stations or at least 5G small cells are required at very short distances, which drives up the costs of expansion enormously.

| Frequency | Range | Strengths | Weaknesses |
|---|---|---|---|
| Microwave Frequencies | <40GHz | exclusive use from licensing, high range, can operate without LoS | high costs of licensing, suffers from interference, low throughput |
| V-band | 57-71 GHz | no license costs, resistant to interference, higher bandwidths available compared to lower bands, quick deployment | no exclusive use from licensing, requires LoS, severely affected by oxygen absorption, limited range |
| E-band | 71-76 and 81-86 GHz | light-licensing, high throughput, resistant to interference, higher range than other mmWave bands, adaptable to different conditions, quick deployment | requires LoS, severely affected by heavy rainfall, still less range than microwave |
| W-band | 92-110 GHz | slightly better than D-band in terms of attenuation and range, high bandwidth, resistant to interference | smaller contiguous regions available than D-band, short range |
| D-band | 110-170 GHz | light-licensing, contiguous regions available for higher channel sizes, high throughput, resistant to interference | affected by atmospheric attenuation, higher free space path loss compared to lower bands, less mature than lower bands, short range |
| Sub-THz Frequencies | 170GHz-1THz | unlicensed usage, quasi-immunity to interference, high bandwidth | very short range, LoS requirement |
| Fiber-optic | - | ranges up to 80km, quasi-immunity to interference, high throughput | very long deployment time, higher deployment costs than other wireless alternatives |
| Copper | - | ranges up to 15km, quasi-immunity to interference | very long deployment time, higher deployment costs than other wireless alternatives, performance not adequate for future deployments |

Table 2.2: Overview of possible Frequencies and Wired Alternatives[11]

## 2.4 Simulation Environment

For the purpose of creating the simulation, the exclusive focus was on open-source software and frameworks, primarily meant for academic and research purposes. It is here to state that very few simulators currently provide a complete protocol stack of currently upcoming mobile communication technologies. After comparing some of the network simulation tools, the Objective Modular Network Testbed in C++ (OMNeT++) got selected. OMNeT++ provides further models needed to implement all simulation parts. This decision was further supported by Weber et. al.[12] who presented and evaluated different VANET-Simulators. As the usage scenario conducted is close to the Vehicle-to-Infrastructure variant of VANET, the findings of Weber et. al. should hold true for our simulation as well. Table 2.3 shows an overview of VANET-simulators taken for this evaluation. The final simulation environment also contain additional model besides OMNeT++ that are needed for further functionalities. Namely these include the INET Framework, the Veins (Vehicles in Network Simulation) Framework and the Simu5G Framework. Further SUMO (Simulation of Urban MObility) was used, for which Veins functions as interface towards OMNeT++. Figure 2.3 shows the entirety of the used simulation stack. In the following these tools will be discussed further.

### 2.4.1 OMNeT++

OMNeT++ is a an extensible, modular, component-based C++ simulation library and framework. It is designed for building simulators for a wide variety of networks, including wired and wireless communication networks among others[13]. The open-source simulation environment was developed primarily for academic use and is published under Academic Public License. While OMNeT++ is not a network simulator itself, it works as a network simulation platform providing basic functionalities for creating event based simulators. Its component based architecture provides users with the possibility to write their own domain specific modules which can be initialized and used within the OMNeT++ simulation Framework. An OMNeT++ model consists of hierarchically nested modules. The module hierarchy is structured as follows. At the top level is the system module, which can con-

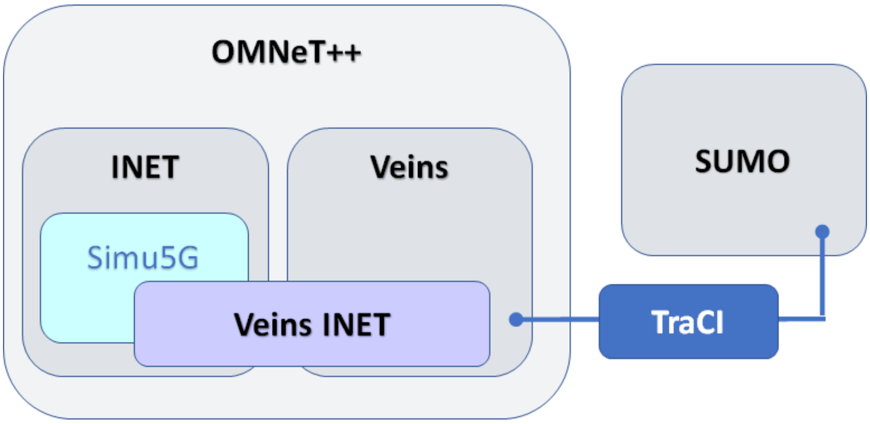


Figure 2.3: Simulation Toolstack

| Simulator | Last Release | License | Network Simulator | Mobility Simulator |
|---|---|---|---|---|
| NetSIM | 2021 | proprietary | own | SUMO |
| Veins | 2020 | open-source | OMNET++ | SUMO |
| Eclipse MOSAIC | 2020 | open-source | NS-3<br>OMNeT++,<br>SNS and<br>Eclipse<br>MOSAIC Cell | SUMO,<br>VISSIM |
| EstiNet | 2020 | proprietary | own | own |
| ezCar2X | 2020 | proprietary | NS-3 | SUMO |
| VENTOS | 2018 | open-source | OMNeT++ | SUMO |
| VANETsim | 2017 | open-source | own | own |
| GrooveNet | 2013 | open-source | NS-2 | own |
| VNS | 2012 | open-source | NS-3,<br>OMNeT++ | own |
| iTETRIS | 2010 | open-source | NS-3 | SUMO |
| NCTUns | 2010 | proprietary | NS-2 | own |
| CityMob | 2009 | open-source | NS-2 | own |
| TraNS | 2009 | open-source | NS-2 | SUMO |
| FreeSim | 2008 | open-source | NS-3 | own |
| STRAW | 2007 | open-source | Jist/SWAN | own |
| VanetMobiSim | 2007 | open-source | NS-2 | CanuMobiSim |

Table 2.3: List of VANET Simulators[12]

tain submodules at the following levels, which in turn can contain modules or submodules. Modules which contain submodules are called compound modules. The modules at the lowest level are called simple modules. Simple modules describe behavior via algorithms written in C++ using the OMNeT++ simulation class library. Modules communicate via the exchange of messages. Modules have gates as input and output interfaces for sending messages (Figure 2.4). Modules are created using the Network Description language (NED) and saved in separate *.ned files. The NED language is used to describe not only the individual modules but also the individual channels and the underlying network. Finally every simulation of a network scenario needs an *.ini file, that defines starting values loaded upon the start of a simulation run. *.ini files are written via XML Format. In the simulations each message to be sent represents a simulation step. The simulation time progresses by sending messages with a time delay. Messages are temporarily placed in an event list and subsequently dispatched to the corresponding receiver modules at their respective arrival time. When the event list is empty the simulation ends.

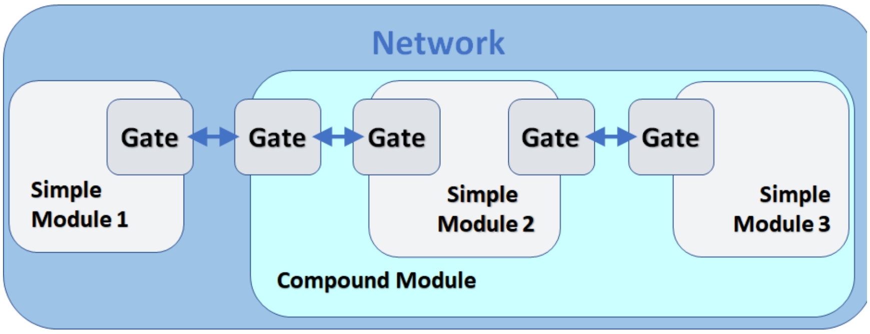


Figure 2.4: OmneT++ Network Structure

### 2.4.2 INET

INET[14] is a model library for OMNeT++. It provides protocols, agents and other models for modeling communication networks and is therefore particularly useful when developing and validating new protocols or exploring new scenarios. INET supports a wide range of communication networks, including wired, wireless, mobile, ad hoc and sensor networks. It includes models for the internet stack (TCP, UDP, IPv4, IPv6, OSPF, BGP, etc.), link layer protocols (Ethernet, PPP, IEEE 802.11, various sensor MAC protocols, etc.), sophisticated support for the wireless physical layer, multiple application models, and many other protocols and components. It also provides support for node mobility, advanced visualization, network emulation and more. The INET Framework can be seen as the primary model library for OMNeT++. Numerous simulation frameworks build upon INET as a foundation and expand it in specific directions.

### 2.4.3 Simu5G

Simu5G[15] is a collection of OMNeT++ models designed for simulating the data plane of the 5G RAN and the core network. Simu5G is based on 3GPPs release 16. It enables the simulation of 5G communication in both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes and incorporates heterogeneous gNBs (macro, micro, pico, etc.). Simu5G also implements the X2 interface for its gNBs. gNBs communicate over the X2 interface to support handover and intercell interference coordination. Together with INET Simu5G can be used to create end-to-end simulation scenarios of varying complexity involving arbitrarily complex TCP/IP networks including 5G NR layer-2 interfaces[14]. Additionally Simu5G provides a large variety of models for mobility of UEs, including vehicular mobility. It allows to instantiate many different user applications and provides aid for evaluating these. Furthermore it can be used to model cellular Vehicle-to-Everything (C-V2X) scenarios.

### 2.4.4 Veins

Veins[16] is an open source framework for the simulation of vehicle networks based on OMNeT++, the event-based network simulator, and SUMO, the road traffic simulator. Other components of Veins are responsible for setting up, running and monitoring the

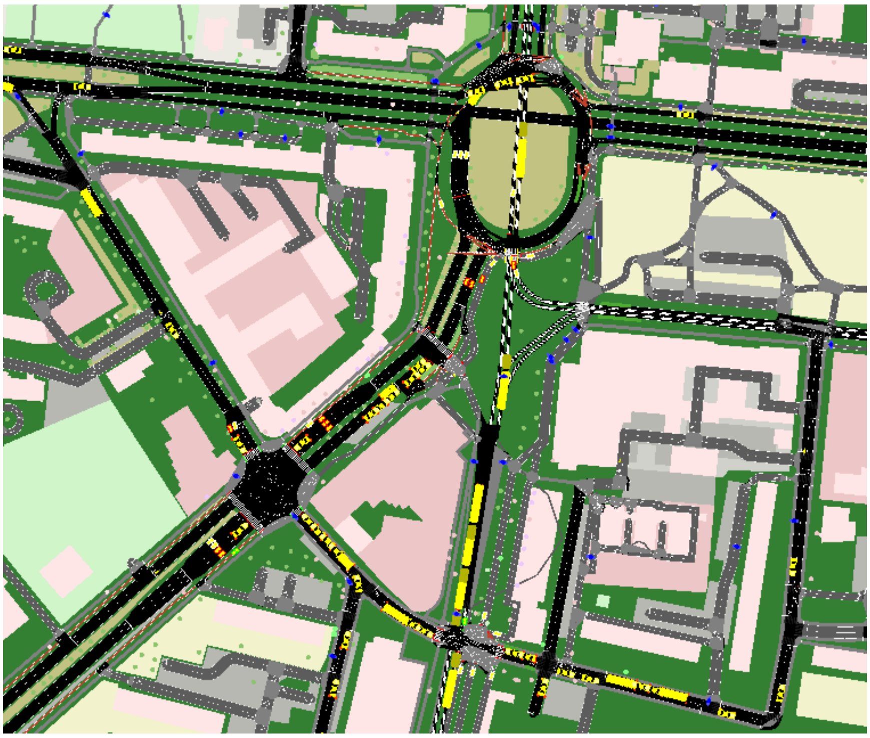


Figure 2.5: SUMO Traffic Example

simulation. Overall, the simulator instantiates an OMNeT++ node for each vehicle in the simulation and then pairs the movements of the nodes with the movements of the vehicles in the road traffic simulator (i.e. SUMO). In this case, both the network and mobility simulations can run in parallel. This is made possible by the Traffic Control Interface (TraCI) in the form of bidirectional coupled simulation. TraCI is a standardized connection protocol and enables OMNeT++ and SUMO to exchange messages (e.g. with mobility traces) during the running simulation via a TCP socket.

### 2.4.5 SUMO

SUMO is a widely used open source traffic simulation software offered by the DLR (Deutsches Zentrum für Luft- und Raumfahrt) since 2001. It allows the user to model traffic systems that can include road vehicles and public transportation as well as pedestrians. SUMO contains various supporting tools, such as for route finding, importing networks from OpenStreetMap (OSM)[17] and much more. The simulation in SUMO is in discrete time with a standard step length of 1s, while the minimum time step is 1ms. The simulation process for SUMO is limited to a maximum duration of 49 days [18]. With the OSMWebWizard, the real road network can be easily downloaded and edited. In the editor, changes such as inserting traffic lights, configuring road connections, defining the number of lanes on a road, etc. can be made. Figure 2.5 shows an example of traffic at the Magdeburg University Square inside the SUMO GUI.

# CHAPTER 3

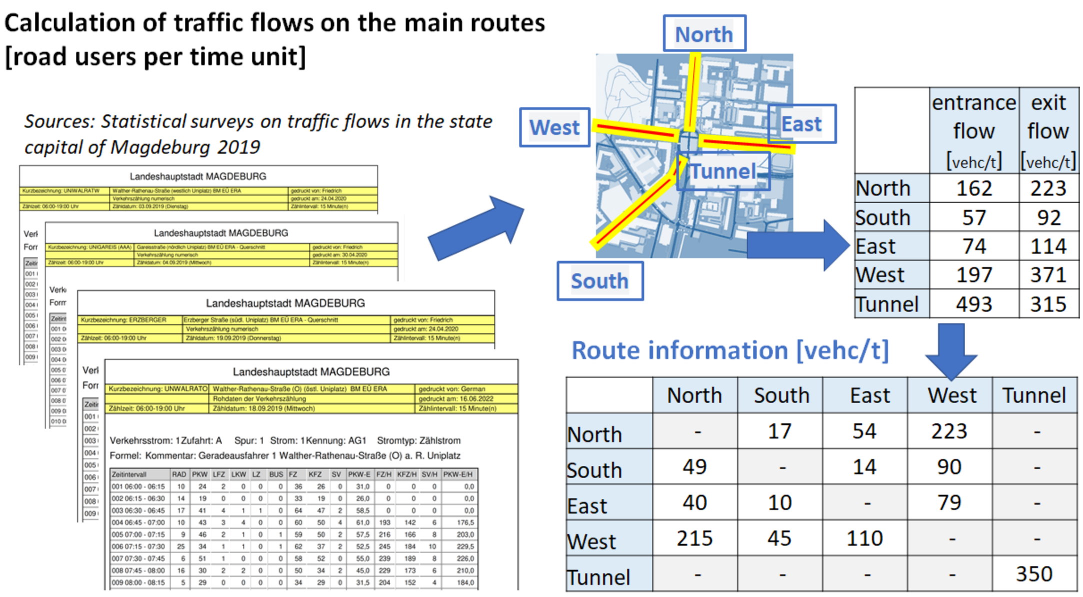
# Thesis Contribution

To investigate the feasibility of sub 6GHz and mmWave for 5G wireless backhauling, a network spanning Magdeburg University Square was modeled and simulated . The simulation was also carried out for a wired configuration in order to compare it to the two wireless concepts. This chapter explains in more detail how the test environment is set and why certain parameters were selected. These include the geographical data, the vehicle traffic, the network topology and its parameters.

## 3.1 Conception

### 3.1.1 Traffic Concept

The simulation extends an area of 1000 by 1000 meters, centered around Magdeburg University Square. To generate sample traffic for the simulation, it was decided to replicate the typical everyday road activity around Magdeburg University Square. With traffic participants engaging in common mobile applications. Figure 3.1 shows the calculation of traffic flows taken to serve as input for the SUMO traffic simulation. The starting point was the statistical surveys of the city of Magdeburg[19][20][21][22][23]. The traffic flows were summarized according to the road layout in northern, southern, eastern and western directions. The tunnel was considered separately. The statistical data had to be converted from road specific entry and exit flows into route information. The entry and exit flows are shown in the table in Figure 3.1 as an example. The route information was determined in several calculation steps. Figure 3.1 shows a typical calculation result for a scenario in the matrix. As these calculations only depict traffic for the primary routes used for traveling from one district to another, traffic for minor streets was estimated by randomly generated vehicles. To account for the subsequent interfere with the main traffic flows the vehicle count was adjusted accordingly. Public transport schedules, provided by the Magdeburger Verkehrsbetriebe (MVB)[24], for 10 different transport lines operating within the simulated area were integrated. Additionally bicycles, pedestrians, trucks, and motorcycles, all moving along random routes within the simulation were introduced. In summary, the traffic generation strategy aimed to closely replicate real-world scenarios while efficiently incor-



**Calculation of traffic flows on the main routes [road users per time unit]**

*Sources: Statistical surveys on traffic flows in the state capital of Magdeburg 2019*

| | entrance flow [vehc/t] | exit flow [vehc/t] |
|---|---|---|
| North | 162 | 223 |
| South | 57 | 92 |
| East | 74 | 114 |
| West | 197 | 371 |
| Tunnel | 493 | 315 |

**Route information [vehc/t]**

| | North | South | East | West | Tunnel |
|---|---|---|---|---|---|
| North | - | 17 | 54 | 223 | - |
| South | 49 | - | 14 | 90 | - |
| East | 40 | 10 | - | 79 | - |
| West | 215 | 45 | 110 | - | - |
| Tunnel | - | - | - | - | 350 |

Figure 3.1: Calculation of Traffic Flows on the Main Routes

| Feature | Feature value | Comment |
|---|---|---|
| Building height | 15 m | Abstraction to a uniform building height |
| Speed | 30 to 50 km/h | According to Open-Street map |
| Number of gNBs | 16 | |
| Simultaneously simulated vehicles | approx. 250 to 400 | |

Table 3.1: Characteristics of the Traffic Model

porating a variety of traffic types and modes of transportation into the simulation. More characteristics of the traffic model can be seen in Table 3.1.

### 3.1.2 Network and Backhauling Concept

A network topology that features 16 base stations organized in a 4 by 4 square configuration was constructed for the Magdeburg University Square. The base stations (gNodeBs) are positioned at 200-meter intervals. This strategic spacing was chosen to provide an installation suitable for mmWave antennas while avoiding potential signal degradation due to increased distances. Furthermore, in alignment with the pursuit of network densification, we opted to configure our base stations as small cells. To ensure reliable connectivity of the base stations to the core network, static routes were employed, establishing connections from each gNodeB to a core network gateway, as illustrated in the Figure 3.2. These static routes consist of 0 and 2 hops, forming our backhauling network. Each hop of these routes

| Concept | Sub-6GHz | mmWave | Fiber |
|---|---:|---:|---:|
| Carrier frequency | 3.6 GHz | 60 GHz | - |
| Band | C | V2 | - |
| Bandwidth (MHz) | 90 MHz | 90 MHz | - |
| Max. Throughput gNB in Mbit/s | 100 Mbit/s | 100 Mbit/s | 10 Gbit/s |
| Transmission power gNB | 39 dBm | 39 dBm | |
| Antenna height gNB | 4 m | 4m | - |

Table 3.2: Backhaul Configuration Parameters

is then connected using Sub-6GHz, mmWave, and fiber in three distinct configurations. Notably, we decided to utilize the same network topologies for all three setups. This choice was deliberatly aimed at minimizing differences between the networks and allowing us to concentrate on assessing the influence of the backhauling technologies themselves, rather than the network structure.

For the wired configuration a 10Gbit/s connection was chosen, with INET providing a suitable model. For wireless configurations we started with the INET model for WiFi. This was discarded after the initial test phase. We then decided to change our wireless configurations to represent the 5G configuration currently used by the Telekom Deutschland[25]. As this seemed to be a close approximation of reality. This included a Frequency of 3.6GHz with a Bandwidth of 90MHz. For mmWave the center frequency was changed from 3.6GHz to 60GHz.

For the UE applications, we opted for common mobile communication applications such as Voice over IP (VoIP), Video on Demand (VoD) and burst traffic, which simulates normal internet surfing. These applications placed particular demands on the performance characteristics of the 5G communications network. In particular, low latency is required for real-time-dependent applications such as VoIP and online gaming. High bandwidth is important for data-intensive applications such as video streaming and packet loss is relevant for applications that require reliable data transmission, e.g. video conferencing. The performance parameter jitter is particularly important for applications with variable data rates, such as voice transmission. The performance parameters are defined in more detail in section 4.1. In this work, VoIP traffic was considered in particular, as the latency analysis is at the centre of the task. For the configuration of traffic generation we mostly relied on Simu5Gs work on implementing these applications.

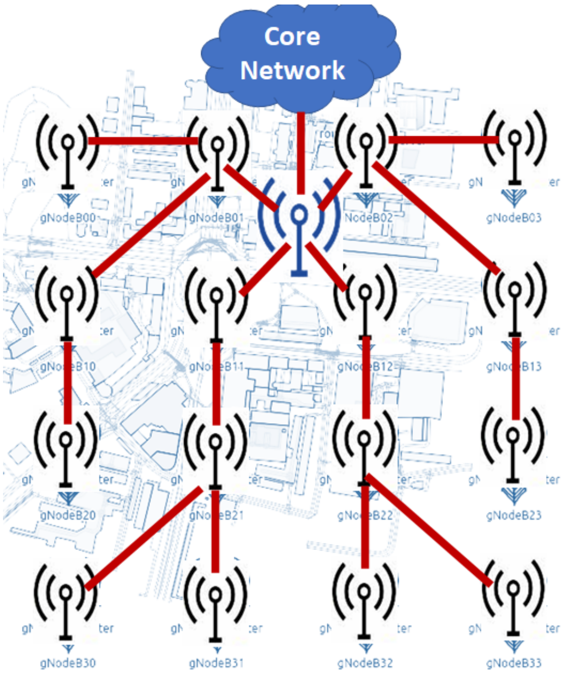


Figure 3.2: Static Network Routes

## 3.2 Implementation

### 3.2.1 Traffic Implementation

The first of the two main parts of the simulation implementation was the creation of a traffic simulation with SUMO. Figure 3.3 shows the workflow for creating the traffic simulation. The following steps were implemented:

- Conversion of the OpenStreetMap data into a SUMO configuration file using the OSMWebWizard
- Verification and editing of the transferred data with the nededit tool from SUMO to correct incorrect data
- Integration of route data of different vehicle types

These steps are explained in more detail below.

Figure 3.3 shows the workflow for setting up the traffic simulation. In order to realistically depict the traffic situation OpenStreetMap data got utilized. In the first step of the workflow, the python scripts provided by SUMO were used to extract data from OpenStreetMap and convert it into a SUMO simulation configuration. These scripts are called OSMWebWizard, which is also one of the starter recommendations for first time SUMO users, in order to quickly start generating realistic simulations. Starting the OSMWebWizard opens a GUI inside the web browser providing a representation of the OpenStreetMap map interface alongside an options panel. The GUI allows the selection of a specific location

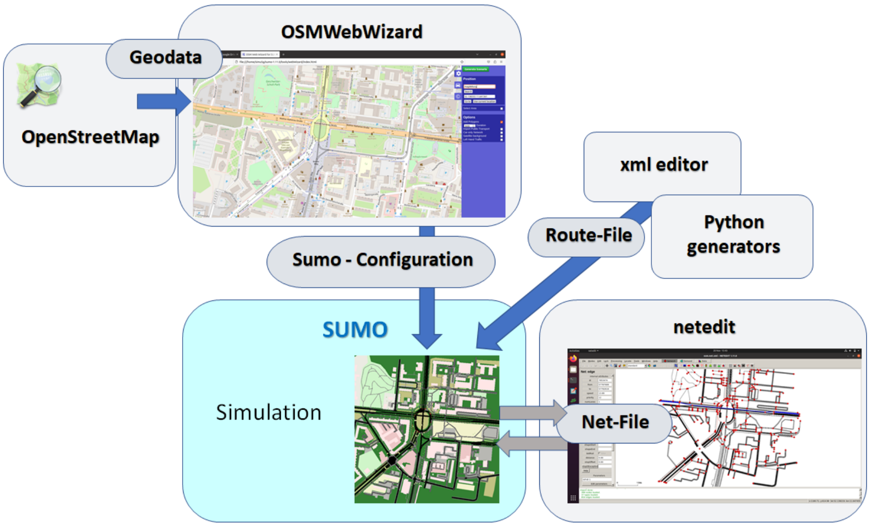


Figure 3.3: Workflow SUMO Implementation

and the needed map area. The selected area at Magdeburg University Square is shown in Figure 3.4. It covers an area of 1000m x 1000m. The street types including pedestrian paths and tram routes were imported via the OSMWebWIzard. The OSM data from this area is then converted by the OSMWebwizard into a SUMO *.net.xml file. This contains streets as edges, intersections as junctions and also adds traffic lights, bus stations and more. Furthermore the OSMWebwizard provides many more options like adding building polygons, an option for left handed traffic, the generation of random traffic including cars, pedestrians, public transport and so on. The options for building and traffic generation got selected. For the later option a high Through Traffic Factor was set to assure that generated traffic participants are more likely to start and end their routes at an edge on the boundary of the simulation area. These options generate many more xml files, including route files representing vehicle traffic, which are then combined with the *.net.xml file via the *.sumocfg file, creating a full SUMO simulation configuration. This generated simulation configuration now must be verified, as it can not be assured that all data is converted properly. Also while OSM data is generally reviewed and reliable in cities, everyone can contribute data to the OSM data set raising at least minor doubts about their accuracy.

There were problems especially at intersections and junctions. At intersections, roads had to be added, incorrect and inefficient traffic routing had to be corrected, some traffic lights were removed, crosswalks and bus stops were slightly altered and much more. The big traffic circle had to be converted into one-way traffic and redundant (non-existent) roads had to be deleted. For adjustments of these problems netedit was used. Netedit is a graphical network editor included in SUMO. It can be used to create traffic networks from scratch and to modify all aspects of existing networks. The user interface is closely based on that of sumo-gui. With the netedit GUI, the necessary changes were possible without direct access to the *.net.xml file.

Once the Sumo traffic network had been verified and corrected, the last step in the workflow was to enter the route data for all traffic participants before running simulation experiments. The following route information was generated:

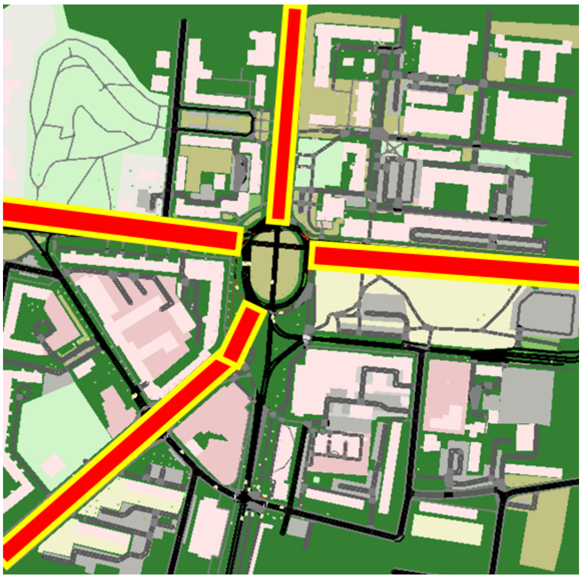


Figure 3.4: Simulation Area and Major Traffic Routes

- Car traffic: Routes according to the statistical traffic surveys of the city of Magdeburg. The calculation of the data was explained in section 3.1. The driving speeds correspond to the road traffic regulations and were taken from OpenstreetMap.
- Means of local public transport:
  - 7 tram lines with a frequency of 10 min in both directions
  - 3 bus lines with a frequency according to the public transport plans in two directions
- Pedestrians: random generation

### 3.2.2 Network Implementation

The second part of the simulation implementation concerns the OMNeT++ modeling of the 5G network with backhaul and the use of Veins to integrate OMNeT++ and Sumo. Three different scenarios are compared in this work:

- a fiber backhaul
- a wireless backhaul with sub-6GHz
- a wireless backhaul in the mmWave

This requires the creation of two OMNeT++ models. One model for the fiber concept and one model for the wireless concepts, with the second model parameterized differently for Sub-6GHz and mmWave. Figure 3.5 shows the workflow for setting up the OMNeT++ simulations.

The first modeling phase concerns the compilation of the C++ simulation codes. The second modeling phase comprises the execution of an OMNeT++ simulation. In this phase, the

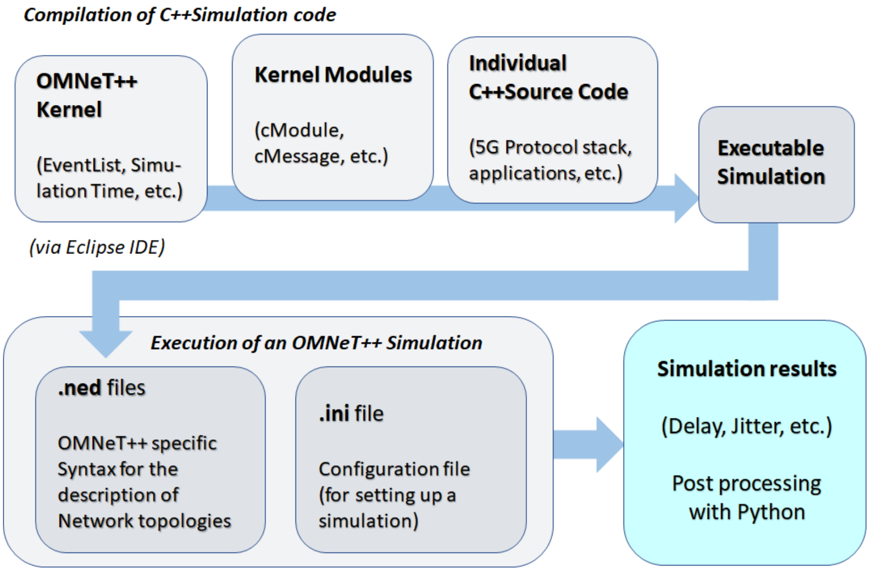


Figure 3.5: Workflow OMNeT++ Implementation

5G network structure is described in the *.ned file. For this purpose, all submodules of the network module are defined and, if necessary, connected via their gates. Both developed models have approximately the same structure and contain the following elements:

- 16 submodules for the 16 base stations (gNB)
- 16 submodules for the 16 routers
- Submodules for the connection to the core network and its simulation
- Submodules for IP configuration, for visualization and for the physical environment
- Submodules for regulating the 5G RAN
- Veins Manager

The fiber model uses the Ethernet model provided by INET, which is an appropriate abstraction of fiber. Since wireless connections are initialized via the ini-file, but this does not apply to Ethernet, additional connections between the routers must be defined inside the *.ned file for the Ethernet (or fiber) configuration.

It was necessary to adapt the gateways of the Simu5G gNB modules to wireless requirements. During the modelling, it became clear that this adaptation was not possible by simply setting parameters. The Simu5G gNB modules would have had to be modified. In order to avoid this change, we chose to model the connection of the wireless interface using additional routers.

The next step in the modeling was to set up the connections between the routers in the *.ned file for the fiber configuration. This concerns both the application and control data that is transferred between the network elements. In the backhaul, this includes:

- Forwarding of data from the gNB or UE via the static routes to the core network
- Cross-cell communication between neighboring cells

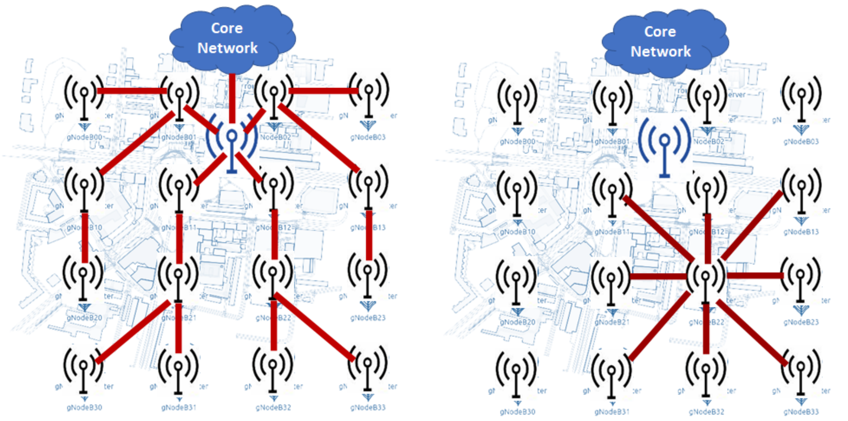


Figure 3.6: Right: Core Network Connections; Left Intercell Connections

Figure 3.6 shows an example of this.

For Wireless configurations these connections got initialized in the *.ini file.

As the IP routing tables required for communication with the base stations could not be generated automatically for the static routes used in the simulation, the routing tables had to be generated manually for each backhaul element, i.e. all gNBs and routers.

The simulation was then set up in the *.ini file. The following procedures were necessary:

- Configuration of the Veins Manager
- Configuration of the area size of the area and the locations of all base stations
- Configuration of the 5G-RAN elements
- Configuration of the wireless backhauling technology
- Definition of the physical environment
- Initialization of the applications

First, the parameters of the Veins Manager were set to assign the vehicle types to the correct UE modules. The Simu5G "cars" model was used for this. Furthermore, the TraCI interface was used to connect the Sumo configuration with the OMNeT++ configuration. A local host connection was set for TraCI. In addition, the Veins launchd.xml file had to be created to ensure that the correct SUMO configuration was executed.

Stationary mobility got assigned for gNBs, routers and the rest of RAN and backhauling infrastructure. Their specific coordnates and the playgroundsize of the whole area got assigned according to Section 3.1.

For the configuration of the 5G-RAN, mainly the standard parameters of the Simu5G-Cars example were used. These parameters provide a well-tested basis for the implemented use case. In order to adapt the simulation to the needs of this work scenario, the number of X2 applications for intercell communication and handover regulation was changed according to the current number of base stations.

The backhauling technology for the fiber configuration was set up in the *.ned file (see

| Parameter | Value |
|---|---|
| Preamble Time | 10 us |
| Header Length | 8 byte |
| Receiver Sensitivity | - 85 dBm |
| Receiver-Energy-Detection | - 85 dBm |
| Receiver-SNIR Threshold | 4 dB |
| Antenna Gain | 3 dB |
| Transmit Power | 8 W |
| Bandwidth | 90 MHz |
| Frequency for Sub6-GHz | 3.6 GHz |
| Frequency for mmWave | 60 GHz |

Table 3.3: Wireless Configuration Parameters

above). The backhauling technology for the wireless configuration was implemented in the *.ini file. It was decided to use INETs ApskScalarRadio model, for which a suitable preamble time and header length had to be defined. 10 ms was selected for the preamble time and 8 bytes for the header length. In addition we used CSMA/CA with acknowledgments. Further backhauling parameters are summarized in Table 3.3.

The building data imported from OSM for Magdeburg University Square was used to simulate the physical environment. The OSM data include floor plans and coordinates of the buildings in the area under consideration and were used to supplement the simulation with real building information. This data was parsed and rewritten into an OMNeT++ compliant *.xml file, with brick walls set as the material. For all buildings a height of 15m was specified. The building information is then incorporated in the OMNeT++ simualtion by using the IdealObstacleloss model. Also the flat ground model was assumed.

Various applications can be modeled in 5G communication networks. Classic application types that Simu5G offers are

- Burst (as a function for classic internet surfing)
- VoIP
- Video on Demand

In this simulation, VoIP was used as an example. All UEs and the server, which is connected to the core network, were modeled as transmitter and receiver. The data collection only included end-to-end network traffic at application level.

Figure 3.7 shows the final product of the implementation. On the right side is the implementation of the fiber configuration and the wireless configuration is on the left.

Figure 3.7: OMNeT++ Configurations

## CHAPTER 4

# Thesis Outcome

Simulations were performed for both developed models, i.e. the fiber configuration and the wireless configuration. The simulation was carried out for the three concepts fiber (Figure 3.7 right), sub-6GHz (Figure 3.7, left, 3.6GHz) and mmWave (Figure 3.7, left, 60GHz) with the parameters described in Chapter 3 and a simulation time of 1800s (half an hour). The following section presents the performance parameters used to evaluate the simulation results and explains how the result data generated by OMNeT++ was processed and analyzed.

## 4.1 Evaluation criteria

The three concepts Sub-6GHz, mmWave and fiber are evaluated with performance criteria. These are briefly explained below.

### 4.1.1 End-to-end packet latency

Packet latency is measured at application level and includes the time that elapses between the sending of a packet and the receiption of the same packet[26]. The following formula shows the calculation formula for the latency at application level:

$$Del_i = A_i - T_i$$

Here, $Del_i$ is the calculated latency value in seconds for the $i$-th packet arriving at the recipient, $A_i$ is the arrival time of packet $i$ and $T_i$ is the transmission time of packet $i$.

### 4.1.2 Jitter

Jitter represents the time differences between two consecutive packet latencies. Due to different network utilization, there can be large differences in packet latency. The respective application must be able to cope with these varying latencies. A value of 0 represents the ideal case and stands for a fluctuation-free latency of incoming packets, which is particularly desirable for real-time applications[26]. The jitter is calculated with the following formula:

$$Jit_i = |Del_{i-1} - Del_i|$$

$Jit_i$ is the jitter value in seconds calculated for the $i$-th arriving packet, $Del_{i-1}$ is the latency value in seconds of the packet that arrived before the packet $i$, while $Del_i$ is is the latency seconds of packet $i$.

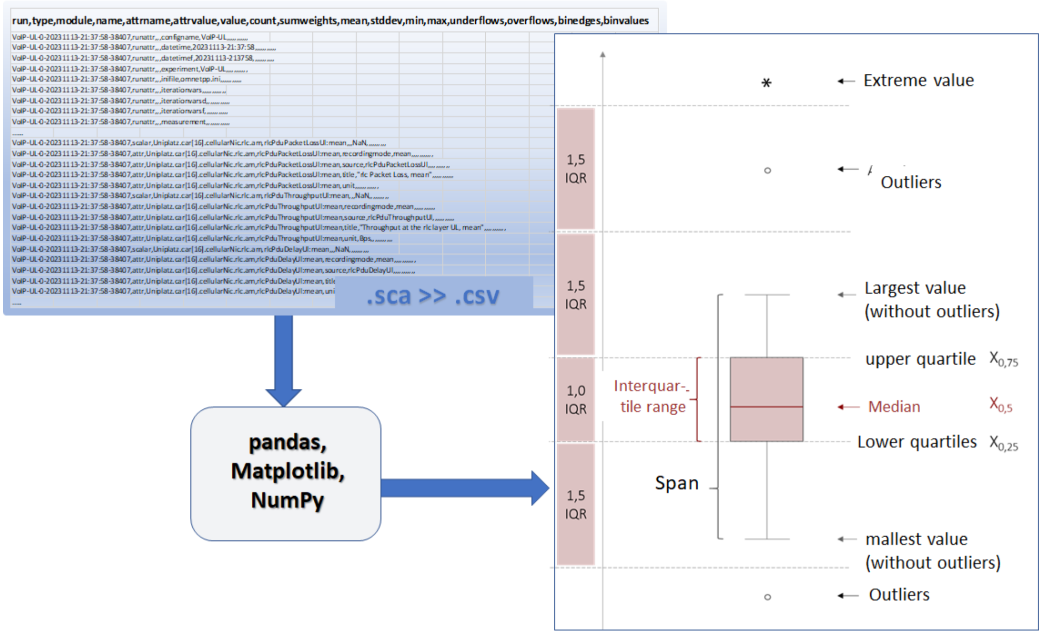
### 4.1.3 Frame Loss Rate

As define in RFC 1242 [27] the Frame Loss Rate is the Percentage of frames that should have been forwarded by a network device under constant load that were not forwarded due to lack of resources.

## 4.2 Post Processing

The simulation results of OMNeT++ are stored in a self-defined output folder. By default OMNeT++ choose a "result" folder with the same path as the omnetpp.ini. This was unfavorable in the used development environment, so a separate folder was selected. Saved files are a file for all vectors (*.vec file), a file for all scalars (*.sca file) and an additional file (*.vci file) to support indexing, processing and accessing the vector file. Here vectors are statistical data over a certain period of time. Both files *.vec and *.sca contain several thousand to several million data entries, even after limiting the recorded result data. Of these are the specific end-to-end throughput, delay, jitter and frameloss data at application level the most important to us. In order to evaluate this huge amount of collected data post-processing had to carried out. For each performance parameter and each simulation run, the data was filtered and processed using the Python libraries pandas, NumPy and Matplotlib to generate the boxplot diagrams for analysis. Matplotlib[28] is a versatile low-level graph plotting Python library, crafted for generating static, animated, and interactive visualizations and simplifying the creation of plots. With Matplotlib, users can create high-quality plots suitable for publication. As an open-source tool, Matplotlib is freely available and proves instrumental for visualization tasks. Pandas[29] is a Python library specifically designed for handling and analyzing data sets. Pandas povides many functions for data analysis, cleaning, exploration, and manipulation. It is a powerful library enabling users to analyze extensive data sets and draw conclusions based on statistical theories. NumPy[30] is a Python library that makes scientific computing efficient and high-performance. It offers a strong framework for a variety of mathematical and statistical operations in Python. Figure 4.1 shows typical OMNeT++ output data, which was converted from the *.sca format into a *.csv file, as well as a boxplot representation into which the data was transferred. The boxplot diagram is often used to visualise the distribution form of a metrically scaled variable. The center line shows the distributions median. The box shows the interquartile range, containing the middle 50% of the values. All values that are more than

1.5 interquartile ranges away from the box are defined as Outliers.[31] In this work, all performance parameters are therefore presented as a boxplot, created from results of the simulation.



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VoIP-UL-0-20231113-21:37:58-38407,runattr,,,datetime,20231113-21:37:58,,,,,,,,,,,
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Figure 4.1: Post Processing

## 4.3 Evaluation

In the following, the simulation results for all three concepts, i.e. fiber, sub-6GHz and mmWave, are evaluated in terms of latency, jitter and frameloss (as an indicator of reliability).

### 4.3.1 Latency

Firstly, the three concepts are compared in terms of latency. According to the ITUs IMT Vision[1], a latency of one ms is required as a performance parameter for the URLLC usage scenario 5G networks are aiming at. Figure 4.2 shows the results of the three simulations in boxplots for the mean delay of each vehicle.

The simulation results in the fiber configuration shows a latency a the median of around 8.5 ms, with almost no deviation and few outliers. The few existing outliers arrange themself in the range from 8ms to 9ms. The simulation of the two wireless scenarios (sub-6GHz and mmWave) produces roughly the same results with a median of about 10ms and an interquartile range from 9.3ms to 10.2ms. The results show a slight edge for mmWave over sub6GHz, though the difference is generally lower 100$\mu$s.

While fiber clearly provides a more reliable latency compared to our wireless configurations, overall its latency is only marginally better. In our network configuration none of the three technologies could achive the aspired latency of 1ms, though this was not to be expected.

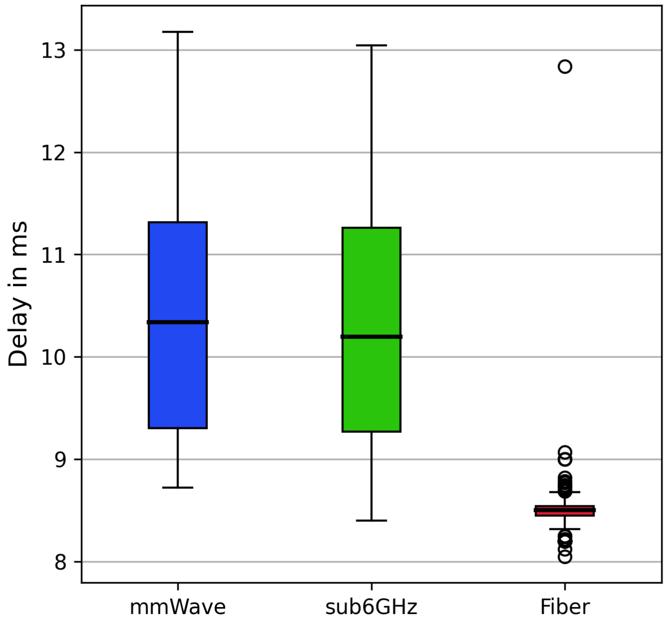

Figure 4.2: Mean Delay per Vehicle

### 4.3.2 Jitter

The findings for jitter values can be seen in Figure 4.3. They show the results of the previous section in more detail. Though the fiber configuration has some values and outliers in or about the interquartile range of the wireless configurations, it generally fluctuates with a margin of 3 to 10 times less. The Median for the fiber configuration lies at 0.01ms while the median for wired configurations can be found at approximately 0.8ms. We could not find an expected or proven real-world value for the jitter to compare our values again, however it is easy to see that a Jitter value of up to more than one ms would be quite unreliable, if a delay value of one ms is aimed at.

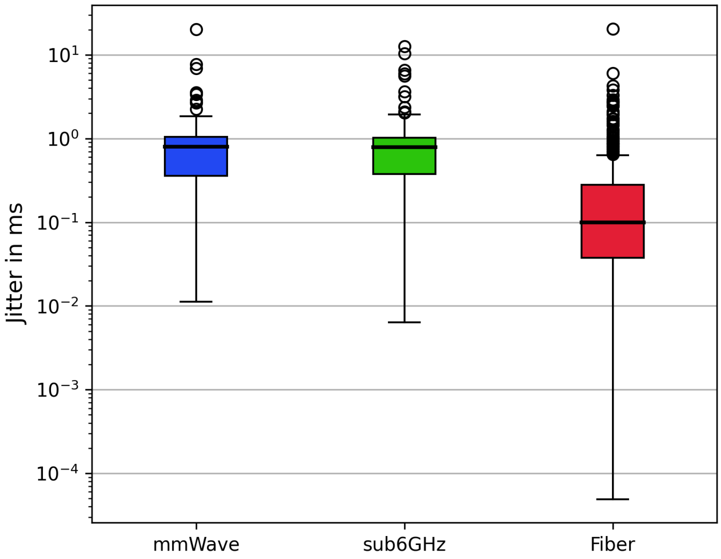

Figure 4.3: Mean Jitter per Vehicle

### 4.3.3 Frame Loss

The Frame Loss diagrams in Figure 4.4 are showing underwhelming results for the wireless configuration. While the fiber configuration is able to achieve the 99.999% reliability that 5G is aiming for [1], the wireless configurations mostly range from 0 to 10% frame loss ratio. Sub6GHz achieves slightly better results than mmWave, which has up to 60% frame loss for at least one application. It is obviously expected that the fiber configuration outclasses any wireless configuration in terms of frame loss ratio but, even while the wireless configuration could be far worse, a lower frame loss ration would be desireable. This could be achieved by implementing better wireless connection, which are closer to modern specifications, than the ones we could use in this work.

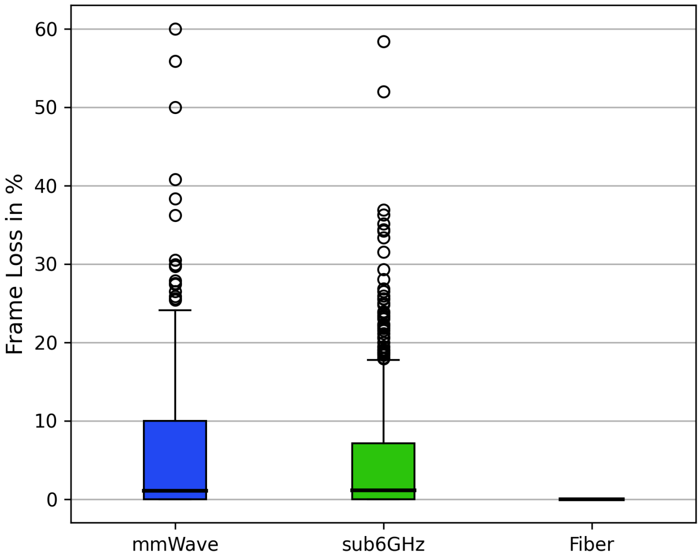

Figure 4.4: Mean Frame Loss per Vehicle

## CHAPTER 5

# Conclusion

## 5.1 Summary

Simulations for three 5G backhaul concepts were developed as part of this work. Magdeburg University Square was selected as the test environment. The communication of road users via VoIP was simulated. For this purpose, both the traffic network and the 5G communication network had to be set up and parameterized in the simulation model. The simulation environment used was SUMO for the traffic simulation and OMNeT++ with the Simu5G library and Veins as interface to SUMO for the 5G network simulation. Two models were implemented, one for a fiber configuration and one for two wireless configurations. The underlying traffic simulation is the same for all models. For the traffic simulation, OpenStreetMap data was imported as the basis for the road and building structure. The traffic flow data was compiled from the statistical reports of the city of Magdeburg and the public transport timetables. Random movement patterns were assigned to pedestrians. The transfer of the traffic data from the sources into data structures suitable for simulation required various independently developed calculation steps and definitions for the simulation of the scenario. It was not possible to create an error-free environment for the traffic simulation with the help of OpenStreetMap data. This data formed roughly a 80% basis, but still required corrections regarding intersections, road layouts and traffic light circuits, which were made with netedit. In addition, the route information had to be created and adapted. It was also difficult to control the behavior of the vehicles in the same way as real road users generally behave. This applies, for example, to changing lanes, which could not be adequately taken into account in the simulation. These and similar small inaccuracies sometimes lead to unnatural behavior of road users in the traffic simulation and thus to larger traffic jams after a longer simulation time. It was not possible to clarify what influence these inaccuracies have on the simulation results of the 5G network simulation.

The implementation of the 5G backhaul simulation with OMNeT++ proved difficult in the following regard. The Simu5G library does not have a gNB model with a suitable wireless interface for backhaul traffic. Accordingly, a separate solution had to be found in order to be able to send and receive via wireless. Additional routers were used here. As a result of changing the usual Simu5G setup, the routes for all backhaul elements could not be generated automatically. Routing tables had to be created manually for every possible connection, which took a lot of time. The high susceptibility to errors without automatic checking options led to additional work. The 5G channels required for backhaul communication are not available in the Simu5G library. In INET, a solution approximating the conditions was created. The simulation results are output by OMNeT++ in the form of vector and scalar value files. An evaluation is only possible with the help of comprehensive data preparation. The decision was made in favor of creating boxplot diagrams with Python and Matplotlib

The three concepts were evaluated according to the performance criteria of latency, jitter and frameloss, with the frameloss parameter being used in particular to assess the reliability of communication in the 5G network. The simulation of the real world example showed that wireless backhaul networks could be useful in at least some usage scenarios, while still being outperformed by fiber networks. The latency values of the implemented wireless configurations (10ms) are only marginally worse compared to fiber (8.5ms). In contrast the findings for jitter and frame loss values for the wireless configuration, were significantly worse than those of the wired configuration. This was to be expected though. Overall the wireless configuration did not perform devastatingly worse and remains a possible alternative where wired setups are not viable. This holds especially true with the further development of these technologies. While it remains clear that wired configuration outperform wireless configurations, neither wired nor wireless configurations cloud reach the requirements of ITU Vision[1] fully.

## 5.2 Future Work

In this work it was shown that the simulation environment in the combination of SUMO for traffic simulation and OMNeT++ with the Simu5G library and Veins as an interface to SUMO is in principle well suited for the simulation of 5G backhaul networks. However, some gaps and difficulties also became apparent, which were solved in the context of this work using manual inputs or approximations. In particular, the modeling of wireless gateways proved to be difficult, as the Simu5G library did not have suitable tools. In further work, the already valuable work of Simu5G could be adapted in order to better fit the implementation of wireless backhaul networks. For further simulations, consideration should also be given to the required accuracy of the traffic simulation needed to obtain exact results for the 5G backhaul network assessment. Based on the experience gained from this work, strict adherence to realism is neither necessary nor feasible. Instead, a higher focus should be placed on user applications and the resulting experiments, including various experiment variations. A scenario was implemented in this work with a focus on the VoIP application. Additional applications such as VoD, burst traffic and more could be integrated in further works. The development of various analyses with comparative scenarios appears to be viable. Further research and analyses should also be carried out in order to validate the simulation results with current applications. Also Variation the the network topology could be examined, this could include a different density of base stations as well as a different amount of hops counts. All these experiments improvements seem viable choices for assessing 5G backhaul networks further and achieving improvements towards a better more reliable 5G infrastructure.

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