Deggendorf Institute of Technology

Faculty of Electrical Engineering & Media Technology

Master Electrical Engineering and Information Technology

# Bewertung der Machbarkeit drahtloser Netze für das Managed Automated Driving (MAD): Ein Blick auf die Kommunikationstechnologie

# Assessing the Feasibility of Wireless Networks for Managed Automated Driving (MAD): A Spotlight on Communication Technology

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# Author's Declaration

I hereby declare that this Master's thesis is my own work, has not been submitted for any other degree at any other university, does not contain or use any sources or resources other than those referenced, and that all direct and paraphrased quotes have been duly cited as such.

Braunschweig, September 2023

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# Abstract

Driving that is automated and connected represents a significant dramatic transformation from driver to fully automated driving. Its evolution will occur in a multi-step process of successive periods of innovation. Communication between autonomous driving innovation vehicles and roadside infrastructures will grow within the next few years, in order to enhance traffic performance and road safety.

The thesis investigates the connectivity in order to establish the viability of Managed Automated Driving (MAD). Different communication methods is being adopted in the automobile industry whereas Managed Automated Driving (MAD) is a proposed concept. In MAD concept, large part of critical decision making portion is moved to the infrastructure.
This thesis focuses to implement wireless communication between the remote infrastructure and vehicle using the User Datagram Protocol (UDP), with focus on the physical, data link as well as transport layer.

The primary objective of this research is to develop a comprehensive understanding of the interplay between Signal-to-noise ratio (SNR) and Packet error rate (PER) and their implications on the overall performance of wireless communication systems.

**Keywords: MAD Urban, Remote Infrastructure Communication, Automated driving, vehicular, communication, Cooperative, connected and automated mobility (CCAM), Vehicle to Infrastructure (V2I)**

# Contents

# Chapter 1

# Introduction

## 1.1 Background

The landscape of contemporary transportation is undergoing a profound transformation, ushering in an era characterized by automation and connectivity. The transition from human-operated vehicles to fully automated driving systems represents a monumental shift in how we conceive and engage with mobility. However, this evolution is not a singular leap but rather an intricate journey comprising multiple phases of innovation. This journey promises not only to redefine our relationship with automobiles but also to enhance traffic efficiency and road safety dramatically[1].

Central to the realization of this transformative vision is the establishment of robust communication networks that seamlessly connect autonomous vehicles with the intelligent infrastructures that surround them[2]. These autonomous driving innovations are poised to interact dynamically with roadside infrastructures, laying the groundwork for a safer and more efficient transportation ecosystem. The imminent years hold the promise of substantial growth in such communication interfaces, signaling a pivotal moment in the evolution of transportation.

This thesis embarks on a comprehensive exploration of the critical facet of connectivity within the domain of Managed Automated Driving (MAD). While diverse communication methods find adoption in the automotive industry, MAD represents a novel and intriguing concept. Within the framework of MAD, a substantial portion of the decision-making process shifts from the vehicle itself to the infrastructure, resulting in a symbiotic relationship that augments the capabilities of both entities.

A core objective of this research is the implementation of wireless communication protocols that facilitate seamless interaction between remote infrastructure and vehicles. In this pursuit, we turn our attention to the User Datagram Protocol (UDP), a versatile and efficient communication protocol. Our study delves deep into the layers of communication, encompassing the physical, data link, and transport layers, to unveil the intricacies of enabling robust and efficient communication between vehicles and infrastructure.

Yet, the significance of this research extends beyond the realm of mere implementation. At its heart, this study seeks to cultivate a profound comprehension of the interplay between two paramount parameters: Signal-to-Noise Ratio (SNR) and Packet Error Rate (PER). These parameters serve as fundamental determinants in shaping the performance of wireless communication systems. Through a comprehensive examination of their dynamics, we aspire to glean insights that can propel the development of more resilient and high-performing communication systems within the context of automated and connected driving.

As we embark on this intellectual journey, it is evident that the future of transportation hinges on the fusion of automation, connectivity, and intelligent decision-making. The forthcoming chapters will provide a detailed exploration of MAD, the implementation of UDP-based communication, and the intricate relationships between SNR and PER. Together, these components constitute a holistic framework for addressing the challenges and seizing the opportunities presented by the age of autonomous and connected driving.

## 1.2 Problem Statement

The rapid evolution of automated and connected driving signifies a monumental shift in the realm of transportation, transitioning from human drivers to fully autonomous vehicles. This transformation unfolds through a multi-stage process, characterized by successive waves of innovation. At the heart of this evolution lies the communication between autonomous vehicles and roadside infrastructure, poised to experience substantial growth in the coming years. The primary goals of this communication surge are to elevate traffic efficiency and bolster road safety.

The central focus of this thesis is to delve into the intricacies of this evolving connectivity landscape, with the ultimate aim of assessing the viability of Managed Automated Driving (MAD). While the automobile industry witnesses the adoption of various communication methodologies, the concept of Managed Automated Driving (MAD) stands out as a novel proposition. In the MAD paradigm, a substantial portion of critical decision-making responsibilities is shifted from vehicles to the underlying infrastructure.

The primary research endeavor undertaken in this thesis revolves around the implementation of wireless communication protocols, particularly the utilization of the User Datagram Protocol (UDP). This implementation is carried out with a meticulous focus on the physical, data link, and transport layers, signifying the comprehensive nature of this exploration.

At the core of this research endeavor lies the primary objective, which is to cultivate a profound understanding of the intricate interplay between two fundamental parameters: Signal-to-Noise Ratio (SNR) and Packet Error Rate (PER). The examination of these parameters extends to their far-reaching implications on the holistic performance and reliability of wireless communication systems. It is through this investigation that we aim to unearth the challenges and opportunities entailed in deploying wireless communication solutions. These solutions are not only pivotal for the realization of Managed Automated Driving but also essential in shaping a future transportation ecosystem that is safer, more efficient, and technologically advanced.

## 1.3 Thesis Structure

The workflow of the thesis is organized as described below:-

- Chapter 1, deals with the introduction of this thesis
- Chapter 2, provides a literature review on the background of automated driving.
- Chapter 3, discusses the concept for the MAD.

- Chapter 4, discusses the implementation techniques used in this thesis using various functions which have been programmed using Omnet++.
- Chapter 5, will discuss the results obtained throughout the thesis.
- Chapter 6, gives the concluding remarks of the thesis and future related work.

# Chapter 2

# Theoretical Concepts

## 2.1 Automated Driving

A fully autonomous vehicle is defined as a car with the ability to perceive and navigate its surroundings without any direct human intervention. This means that it doesn't necessitate human control at any point during operation, and there's no requirement for a human passenger to be physically present within the vehicle. Essentially, an autonomous car is capable of traversing the same routes and performing tasks that a skilled human driver can, without relying on human input[3].

The benefits of utilizing autonomous driving will be as follows[3]:

- Enhanced road safety will be a prominent outcome.
- Transportation efficiency will reach unprecedented levels, boosting productivity.
- Substantial cost savings will be realized.
- Traffic congestion will see a significant reduction.
- Positive environmental impacts will be a key advantage.
- The potential for re-purposing parking areas will be unlocked for various alternative uses.

The realm of Autonomous Driving (AD) has emerged as a prominent domain of research in recent times, significantly influencing the transportation sector[4].

Notably, it assumed a crucial role amid the Covid-19 pandemic of 2020, where unmanned logistics and distribution technologies were leveraged to minimize contact in distribution processes. Nevertheless, owing to concerns related to safety, legal complexities, and regulatory considerations, the widespread adoption and implementation of AD technology have not yet materialized[4].

The prevailing standard for Autonomous Driving (AD) within the worldwide automotive sector is outlined by the International Society of Automotive Engineers (SAE), which categorizes it into six distinct levels, which includes from no automation to fully automation.

Autonomous vehicles rely on an array of components and technologies to execute their software-driven operations. This includes sensors, actuators, complex algorithms, machine learning systems, and high-powered processors. These vehicles operate by establishing and continuously updating a map of their surroundings, achieved through a diverse set of sensors placed in various vehicle locations[5].

### 2.1.1 Features of AVs

The key characteristics of AVs, which lay the groundwork for a fully autonomous transportation system, are outlined below[6]:

- Management as well as Organization: A pivotal aspect of AVs revolves around their organization and management capabilities. The primary objective is to relieve humans from the responsibility of monitoring maintenance schedules and to establish a 24/7 platform with consistent peak performance. AVs play a crucial role in adapting vehicle operations in the event of software failures and swiftly adjusting to dynamic environmental changes. They also monitor software updates and usage patterns autonomously. Additionally, AVs are designed to detect and isolate any malicious activity emanating from a specific autonomous vehicle within the network. In cases of malicious activity, AVs offer alternative solutions to passengers in minimal time.

- Optimal Configuration: Ensuring error-free configuration is essential for the seamless operation of Intelligent Transportation Systems (ITS). Given the complexity and scale of such systems, configuration tasks are prone to errors and often time-consuming. This feature expects **Avs!** (**Avs!**) to adapt to and seamlessly integrate third-party components, including transport policies, traffic control authorities, and road users' policies, to facilitate optimal system functionality.

- Optimized Resource Allocation: AVs possess the capability to fine-tune system performance and behavior based on numerous factors, as detailed in Table IV. For instance, this feature enables the system to allocate resources based on vehicle mobility, facilitating the adjustment of performance parameters to enhance efficiency.
- Self-Protection: This feature focuses on self-preservation and enhancing security measures to safeguard AVs from potential malicious attacks. It encompasses the protection of both hardware and software components from various forms of attacks. In the event of a failure, the system should possess the capability to mitigate the adverse impact and prevent the failure from affecting the entire network of systems[6].

### 2.1.2 Levels of Automation

The different levels of autonomous can be explained as follows[7]:

- **Level 0** : No Automation. In this category, the driver bears full responsibility for controlling the vehicle, including tasks like steering, braking, acceleration, and deceleration. Level 0 vehicles may include safety features such as backup cameras, blind spot warnings, and collision warnings. Even systems like automatic emergency braking, which can apply aggressive braking in imminent collision scenarios, fall under Level 0 because they do not sustain autonomous control.
- Level 1: Driver Assistance. At Level 1, automated systems begin to assume control of specific vehicle functions in certain situations, yet they do not entirely supplant human drivers. An example is adaptive cruise control, which manages acceleration and braking, usually during highway driving. Depending on system capabilities, drivers may be able to remove their feet from the pedals.

- Level 2: Partial Automation. Level 2 introduces more advanced capabilities, combining steering (lateral control) with acceleration and braking (longitudinal control) due to heightened awareness of the vehicle's surroundings.

| **SAE level** | **Level Name** | **Implementation of driving mode (either human or system)** | **Fallback performance of dynamic driving task** |
|---|---|---|---|
| Human driver observes and assesses the driving environment | | | |
| 0 | No Automation | Human | Human |
| 1 | Driver Assistance | Human and System | Human |
| 2 | No Automation | Human | Human |
| Automated driving system observes the driving environment | | | |
| 3 | Conditional Automation | System | Human |
| 4 | Highly Automation | System | System |
| 5 | Fully Automation | System | System |

**Table 2.1:** Different levels of AVs[8]

- Level 3: Conditional Automation. At this stage, drivers can fully disengage from driving, but only within specific conditions, such as particular speeds, road types, and weather conditions. Level 3 marks the entry point into autonomous driving, allowing drivers to focus on other tasks while the vehicle manages acceleration, steering, and braking. In cases like traffic jams, the vehicle alerts the driver to regain control once the traffic clears and speed increases. The system must monitor the driver′s state to ensure prompt resumption of control and be prepared to safely stop if needed.
- Level 4: High Automation. Level 4 implies that the vehicle′s autonomous system can independently monitor the driving environment and handle all driving functions under routine conditions and predefined routes. However, depending on the vehicle′s operational design domain (ODD), there may be rare situations that require human intervention, signaled by alerts. For instance, environmental conditions like heavy snow might necessitate human control[7].
- Level 5: Full Automation. Level 5 vehicles are entirely autonomous, with no requirement for a human driver behind the wheel. In fact, Level 5 vehicles may lack a steering wheel or traditional gas and brake pedals. Such vehicles might incorporate "smart cabins" where passengers can issue voice

commands for destination selection or cabin settings like temperature and entertainment options[7].

### 2.1.3 Autonomous Vehicle Ecosystem

Autonomous vehicles, often referred to as self-driving cars or driverless cars, are equipped with a plethora of sensors, cameras, lidar, radar, and advanced AI algorithms. These vehicles can navigate, make decisions, and operate safely without human intervention. The key components of the autonomous vehicle ecosystem include:

- Sensors: Autonomous vehicles rely on various sensors to perceive their surroundings. These sensors provide data on nearby objects, road conditions, traffic signals, and pedestrians. Radar sensors play a pivotal role in monitoring the positions of nearby vehicles. Video cameras contribute to tasks such as identifying traffic signals, reading road signs, tracking surrounding vehicles, and recognizing pedestrians. Lidar (light detection and ranging) sensors utilize light pulses to gauge distances, identify lane boundaries, and detect road contours. Ultrasonic sensors positioned in the vehicle's wheels prove invaluable for detecting obstacles, like curbs and other vehicles, particularly during parking maneuvers[9]. The next stage involves the sophisticated processing of this wealth of sensory data. Specialized software takes charge, analyzing the input from these sensors, charting a course, and issuing commands to the vehicle's actuators. These actuators are responsible for managing acceleration, braking, and steering, ensuring that the vehicle adheres to its designated path. The software leverages a combination of hard-coded rules, obstacle avoidance algorithms, predictive models, and object recognition techniques to facilitate compliance with traffic regulations and the safe navigation of obstacles.

- Control Systems: Advanced control systems process sensor data and make real-time decisions to control the vehicle's speed, direction, and braking.

- Communication: Autonomous vehicles require seamless communication with other vehicles, roadside infrastructure, and central traffic management systems.

- Connectivity: High-speed, low-latency connectivity is essential for transmitting data between vehicles and infrastructure. This connectivity is crucial for achieving safe and efficient autonomous driving.

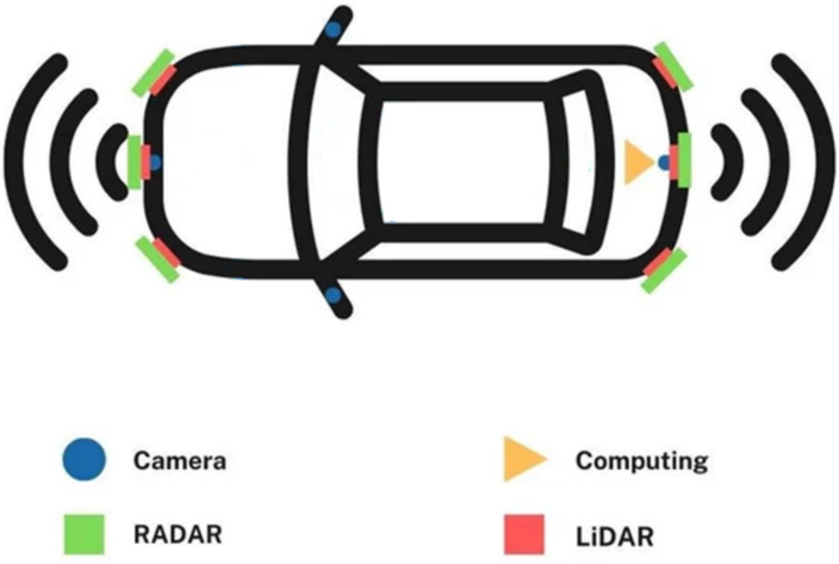

**Figure 2.1:** Vehicle with different sensors [10]

### 2.1.4 Communication Requirements

The communication requirements for autonomous vehicles are distinct and demanding. Some of the key communication needs include:

- Vehicle-to-Vehicle (V2V) Communication: Autonomous vehicles must communicate with nearby vehicles to exchange information about their positions, speeds, and intentions. This real-time V2V communication is essential for collision avoidance and cooperative driving.

- Vehicle-to-Infrastructure (V2I) Communication: Autonomous vehicles need to communicate with roadside infrastructure, such as traffic lights, signs, and control systems. V2I communication enables vehicles to receive traffic updates, traffic signal information, and lane closures.

- Sensor Data Transmission: The sensor data generated by autonomous vehicles, including lidar, radar, and camera feeds, must be transmitted to onboard computers for processing. Low-latency, high-throughput communication is critical for this data exchange.

- Real-Time Control Commands: Control commands from the vehicle's AI system must be transmitted rapidly to actuators such as brakes, accelerators, and steering systems. Any delay in these commands can impact vehicle safety.

### 2.1.5 Challenges of Automated Driving

Fully autonomous vehicles (Level 5) are currently in the testing phase in various regions worldwide; however, they have yet to become accessible to the general public. The widespread availability of such vehicles remains several years away, as they confront a multitude of challenges spanning technological, legislative, environmental, and philosophical dimensions. Here are some of the uncertainties and questions that persist[11]:

- **Light Detection and Ranging (LIDAR) and Radar**: LIDAR technology presents cost-related challenges and seeks to strike a delicate balance between its range and resolution. When multiple autonomous cars share the same road, might their signals interfere with one another, is one of the issues in automated driving.

- **Weather Conditions** : Operating in adverse weather conditions poses a significant challenge for autonomous cars. Heavy precipitation, for instance, raises concerns. In the presence of snow on the road, lane dividers may become obscured. How well the vehicle's cameras and sensors effectively track lane markings when they are hindered by water, oil, ice, or debris.

- **Traffic Conditions and Laws**: Autonomous cars must navigate various traffic scenarios and adhere to relevant laws.

- **State vs. Federal Regulation** : The regulatory landscape in the United States has shifted toward state-level mandates for autonomous vehicles, away from federal guidance. Some states are considering implementing per-mile taxes on autonomous vehicles to prevent the proliferation of "zombie cars" operating without passengers. Proposed legislation even includes mandates for autonomous cars to be zero-emission vehicles and to feature panic buttons.

- **Accident Liability** : Determining liability in accidents involving autonomous cars presents a complex challenge. Is the manufacturer liable, or is it the human passenger, is an other major issue. The current concept of Level 5 autonomous vehicles suggests the absence of a dashboard or a steering wheel, leaving passengers without the option to take control of the vehicle during emergencies.

- **Artificial vs. Emotional Intelligence** : Human drivers rely on nuanced cues and non-verbal communication, such as making eye contact with pedestrians or interpreting the facial expressions and body language of fellow drivers, to make quick judgments and anticipate behaviors. Can autonomous cars replicate this level of connection? Will they possess the same life-saving instincts as human drivers[11]?

### 2.1.6 Benefits of Autonomous Driving

The following benefits can be acheived using AVs [12]:

- Mitigate traffic congestion by a significant reduction in the number of vehicles on the road.
- Achieve substantial cost savings of across transportation aspects, encompassing vehicles, fuel, and infrastructure.
- Enhance the pedestrian-friendly nature and overall quality of urban living.
- Re-purpose parking lots for alternative community uses, such as schools, parks, or community centers.
- Significantly curtail global urban Carbon-di-oxide emissions.

## 2.2 Wireless Network

### 2.2.1 Wi-Fi Basics

Recent Wi-Fi standards leverage various techniques to enhance data rates, including OFDM modulation, MIMO technology, and modulation schemes, which we discuss in the following sections.

#### 2.2.1.1 OFDM

OFDM serves as a multicarrier modulation scheme designed for efficient data transmission within a channel. It achieves this by partitioning the channel into multiple subcarriers or tones, enabling parallel data transmission across these subcarriers. The separation between subcarrier frequencies, such as 312.5 kHz in Wi-Fi 5, is carefully chosen to ensure orthogonality among them, minimizing interference. Consequently, each subcarrier can be independently modulated[13].

In OFDM, the information from a high-bitrate stream is typically distributed across $2^n$ subcarriers. To achieve this, m-bit groups are allocated to each subcarrier and translated into a constellation point using quadrature amplitude modulation (QAM) modulation. The collective set of all these constellations points forms an OFDM symbol. This OFDM symbol is then converted into an electromagnetic wave, resulting in an OFDM signal. An OFDM signal can transmit one or more concatenated OFDM symbols[13].

#### 2.2.1.2 Modulation

Modulation techniques are employed to optimize the quantity of transmitted bits per subcarrier. In the case of Wi-Fi 5, it accommodates up to 256 QAM, a modulation scheme that encodes 8 bits of information within each subcarrier. QAM modulation is responsible for encoding data across individual subcarriers. The utilization of more bits per OFDM symbol results in increased throughput, provided that the Signal-to-Noise Ratio (SNR) meets the necessary criteria. It's important to note that higher-order modulations are anticipated to be most effective when specific conditions are met, such as clear environments and shorter transmission distances[14].

MIMO technology offers three distinct approaches to data transmission within a given channel[15]:

- Spatial Multiplexing: In this method, each antenna has the capability to independently transmit unique data signals to the receiver. These individual data signals are referred to as spatial streams . One noteworthy advantage of Spatial Multiplexing is that it enables a linear increase in throughput with the addition of more antennas[16].
- Spatial Diversity: Spatial Diversity capitalizes on the multipath effect by concurrently transmitting identical data across multiple antennas. This approach leverages the fact that each antenna on the receiving end may receive duplicate data from other streams, thereby introducing redundancy into the system. To reconstruct the complete data chunk, a Digital Signal Processing (DSP) module combines the received spatial streams[16].
- Beamforming: This technique involves dynamic adjustment of the radiation pattern produced by a group of antennas. Essentially, it is akin to steering the signal in a specific direction, concentrating the signal's strength in that

direction rather than dispersing energy uniformly in all directions. The result is the generation of narrower beams that yield stronger signals while concurrently mitigating interference[15].

### 2.2.2 Introduction to Wi-Fi 6E

Wireless communication endeavors to establish pervasive connectivity across diverse applications and scenarios, encompassing industrial contexts. As we draw closer to the era of Industry 4.0, the imperative of ensuring robust communication quality within factories becomes increasingly pronounced. This imperative stems from the desire to achieve heightened levels of automation and intelligence in future factory operations. Industry 4.0 represents the forthcoming industrial revolution, characterized by the concept of intelligent interconnected factories. This vision extends beyond the interconnection of stationary machinery, sensors, and devices, encompassing mobile entities such as drones, mobile robots, and human workers. The deployment of wireless connections in factory settings alleviates the constraints imposed by physical cables, facilitating more adaptable configurations and enhanced automation. In this context, the radio access technology utilized assumes critical importance, as both latency and reliability emerge as pivotal factors for the feasibility of such interconnected applications[14].

Recently, the Wi-Fi Alliance introduced Wi-Fi 6E, an evolution of Wi-Fi 6. Wi-Fi 6E inherits all the capabilities of Wi-Fi 6 while further enhancing support for a larger number of users, increased throughput, and reduced latency when compared to its predecessor, Wi-Fi 5. An additional notable feature of Wi-Fi 6E is its access to newly expanded unlicensed spectrum within the 6 GHz bands. With its comprehensive feature set and access to abundant wireless resources, Wi-Fi 6E is poised to surpass the performance of legacy Wi-Fi technologies[14].

Task Group AX (TGax) within the IEEE 802.11 working group developed the IEEE 802.11ax standard with the aim of enhancing system throughput-per-area, especially in high-density scenarios involving Access Points (APs) and Stations (STAs). This standard, also known as Wi-Fi 6, introduces a range of new features spanning the Physical Layer (PHY) protocol and power management, as depicted in Table 2.1. Notably, 802.11ax's updated Physical Layer (PHY) protocol enables Wi-Fi 6 to achieve a nominal data rate of up to 9.6 Gbps, surpassing the 6.9 Gbps of Wi-Fi 5 (802.11ac)[14].

Orthogonal Frequency Division Multiple Access (OFDMA), a key feature of Wi-Fi 6, significantly enhances its ability to manage multiple simultaneous channel accesses, alleviating the contention overhead. Additionally, Wi-Fi 6 incorporates improvements in Overlapping Basic Service Set (OBSS) management and power management, enhancing its performance in scenarios with overlapping networks and reducing device power consumption[14].

The advent of Wi-Fi 6E further elevates the competitiveness of Wi-Fi technology. While both Wi-Fi 6 and Wi-Fi 6E share the same features as 802.11ax, it's important to note that Wi-Fi 6 operates exclusively within the unlicensed legacy spectrum, encompassing 2.4 GHz and 5 GHz bands, which are already densely populated with potentially interfering devices. In contrast, Wi-Fi 6E extends the available spectrum into the 6 GHz band. Following the Federal Communications Commission (FCC) regulations, the band from 5.925 GHz to 7.125 GHz has been designated for Wi-Fi 6E use. In practical terms, this means a 1.2 GHz band with reduced interference is available for channel planning[14].

In summary, Wi-Fi 6E, with its incorporation of new 802.11ax features and access to the newly approved unlicensed spectrum, is poised to be a compelling indoor wireless network solution for industrial settings, offering enhanced performance and reduced interference.

Wi-Fi 6E introduces extended capabilities that offer significant advantages to connected vehicles[17]:

- Tri-band Capability: The inclusion of the 6 GHz band, which provides double the spectrum compared to the combined 2.4 GHz and 5 GHz bands, brings notable enhancements. It offers 14 additional 80 megahertz (MHz) channels and seven extra 160 MHz channels, effectively addressing congestion issues prevalent in today's Wi-Fi networks. Connected vehicles can establish robust connections with home or business networks and electric vehicle (EV) charging stations, ensuring optimal connectivity. This facilitates high-speed data uploads and downloads, including terabytes of telematics data or firmware updates, without suffering from interference or network congestion.

- 160 MHz Wide Channel: Wi-Fi 6E's 160 MHz capability, a substantial advancement from Wi-Fi 5's 80 MHz, achieves speeds of up to 2.4 gigabytes per second (Gbps) in a 2x2 MIMO configuration. This is 2.5 times faster when connecting to external Wi-Fi 6E networks. Even a single-stream network operating in 160 MHz can provide ample capacity, exceeding 1.2 Gbps, making it ideal for serving multiple passenger devices, rear seat displays, wireless cameras, and more. This simplifies the wireless subsystem's complexity and cost structure while catering to next-generation requirements.

- Higher Speed with Advanced Quadrature Amplitude Modulation (QAM): Wi-Fi 6 and Wi-Fi 6E introduce higher modulation across all three bands—2.4 GHz, 5 GHz, and 6 GHz. As mentioned earlier, speeds in the 5 GHz and 6 GHz bands are 2.5 times faster than Wi-Fi 5. Additionally, Wi-Fi 6 enhances speed and capacity in the 2.4 GHz band by approximately two times through advanced QAM. Higher speeds translate to reduced airtime for data transfers, leading to lower power consumption.
- Extended Range: Wi-Fi 6 and Wi-Fi 6E incorporate range enhancement capabilities, featuring a more robust packet structure as part of Wi-Fi CERTIFIED 6™ Release 2. This enhancement results in an extended range across all modulation and coding scheme (MCS) rates. As connected vehicles increasingly rely on external Wi-Fi infrastructure for data uploads, this uplink extended range feature enhances connectivity performance, benefiting carmakers.
- Low Latency: Wi-Fi 6E devices exclusively access the 6 GHz band, effectively creating a greenfield opportunity with an efficient protocol tailored for low-latency and time-sensitive applications. Carmakers implementing Wi-Fi 6E in infotainment systems can offer significantly improved user experiences for multimedia, gaming services, and phone connectivity, such as Carplay[17].

### 2.2.3 Orthogonal Frequency Division Multiple Access (OFDMA)

Orthogonal Frequency Division Multiple Access (OFDMA) is a pivotal technology in the context of wireless communication. In traditional Orthogonal Frequency Division Multiplexing (OFDM), data transmissions are distributed across a broad spectrum, necessitating the utilization of the entire available bandwidth. In scenarios characterized by densely populated networks, a multitude of stations vies for access to the communication medium, thereby escalating the likelihood of collisions. These collisions, in turn, lead to a reduction in overall throughput[15].

To address this challenge, Wi-Fi 6 incorporates the innovative OFDMA technology. OFDMA introduces a paradigm shift in the way data is transmitted. Unlike conventional OFDM, which mandates the allocation of the entire spectrum to a single transmission, OFDMA enables a single transmission to utilize only specific portions of the spectrum. This breakthrough allows for the concurrent occurrence of multiple transmissions within the same spectrum, significantly mitigating contention and associated overheads at the Medium Access Control (MAC) layer. Consequently, this reduction in contention and overhead leads to a marked reduction in latency and a notable improvement in throughput, particularly in densely populated network environments[15].

It's worth noting that while OFDMA has previously been employed in Long Term Evolution (LTE) networks for downlink multi-user transmissions, Wi-Fi 6 extends its support to encompass both uplink and downlink transmissions in multi-user mode. However, to ensure backward compatibility with the existing 802.11a/g/n/ac standards, Wi-Fi 6 hardware retains support for conventional OFDM as well. This approach allows for a seamless transition and coexistence of legacy devices with the latest Wi-Fi 6 technology[15].

### 2.2.4 Target Wake Time (TWT)

Target Wake Time (TWT) is a crucial feature within the IEEE 802.11 standard, primarily designed to optimize the battery life of Wi-Fi stations. This feature addresses a common issue found in Wi-Fi networks, where stations with data to send or receive tend to contend for network access immediately following the reception of a beacon frame. This contention often leads to undesirable traffic peaks and collisions, negatively impacting network performance [2].

Furthermore, in the existing Power Save Mode (PSM), a station remains in an active state until all its pending packets have been either received or transmitted. This approach results in prolonged periods of activity for Power Save Mode (PSM)-enabled devices, even when they have only minimal data to exchange. This extended active state can significantly drain the battery of these devices [2].

To ameliorate these challenges and enhance the efficiency of power management, Wi-Fi 6 builds upon and extends the concept of TWT, which was originally introduced in the IEEE 802.11ah standard. TWT allows for the proactive scheduling of wake times for stations, ensuring that these wake times do not overlap. By carefully coordinating these wake times, the standard optimizes the periods during which stations are in a sleep state. This, in turn, leads to a substantial reduction in power consumption, significantly prolonging the battery life of Wi-Fi devices[2].

### 2.2.5 Crowded Environments

In environments characterized by high population density, numerous access points coexist within a confined space, resulting in overlapping Basic Service Sets (BSSs). Wi-Fi 6 is tailored to accommodate such densely populated indoor and outdoor settings, including apartments, stadiums, university campuses, airports, and industrial facilities, among others[15].

One of the key advantages of Wi-Fi 6 in these scenarios is the utilization of Spatial Reuse (SR), which enhances the efficiency of concurrent transmissions within neighboring BSSs that share the same channel. Additionally, Orthogonal Frequency Division Multiple Access (OFDMA) plays a crucial role in reducing collision rates stemming from the large number of users typically present in densely populated areas. Moreover, Multi-User Multiple Input Multiple Output (MU-MIMO) technology further bolsters the network's overall capacity, which is essential for accommodating the high demand for connectivity in such environments[15].

### 2.2.6 Internet of Things (IoT)

The rapid growth of the Internet is primarily driven by Machine-Type Communications (MTC), with an estimated manifold increase in global Internet traffic over the next few years. This surge is largely attributed to the proliferation of Internet of Things (IoT) devices, with the average user expected to have around 3.6 IoT devices connected simultaneously. These IoT devices find applications in various domains, including home automation, industrial automation, autonomous vehicles, healthcare, and more. Due to their reliance on battery power, IoT devices require energy-efficient communication solutions, a requirement well-addressed by TWT support. Furthermore, OFDMA technology plays a pivotal role in optimizing medium access, particularly when dealing with a massive volume of small data packets generated by IoT devices[18].

### 2.2.7 Multimedia Applications

The past decade has witnessed a surge in multimedia applications characterized by high-throughput and low-latency demands, especially on mobile devices. Examples of such applications include 4K/8K video and audio streaming, online gaming, virtual reality, augmented reality, and more. These bandwidth-intensive applications often exceed the capacity constraints of legacy Wi-Fi access points [15].

Wi-Fi 6 addresses this challenge by enhancing the capacity of access points through several mechanisms. Firstly, it leverages higher-order modulation schemes to increase data rates. Secondly, the implementation of OFDMA technology optimizes spectrum utilization, enabling efficient handling of the diverse traffic generated by multimedia applications. Lastly, the integration of Multi-User Multiple Input Multiple Output (MU-MIMO) technology further improves network performance, ultimately resulting in an enhanced user experience when using multimedia applications[15].

## 2.3 User Datagram Protocol (UDP)

The UDP is a core communication protocol used in computer networks. It operates at the transport layer of the OSI model and provides a connectionless, lightweight, and fast method of data transmission. Unlike its counterpart, the Transmission Control Protocol (TCP), UDP does not establish a connection or guarantee the delivery of data. Instead, it focuses on delivering data packets as quickly as possible, making it suitable for applications where speed is crucial.

### 2.3.1 UDP vs. TCP

To understand the role of UDP in autonomous vehicles, it's essential to compare it to TCP, another widely used transport layer protocol:

- Connectionless vs. Connection-Oriented: UDP is connectionless, meaning it doesn't establish a connection before sending data. TCP, on the other hand, is connection-oriented, establishing a connection, and ensuring reliable data delivery through acknowledgments.

- Reliability: TCP guarantees the reliable delivery of data. It retransmits lost or corrupted packets and orders received data packets. UDP does not provide such guarantees, making it faster but less reliable.
- Overhead: TCP has more overhead due to connection establishment, acknowledgment packets, and retransmissions. UDP has minimal overhead, making it suitable for applications that prioritize speed.
- Latency: UDP introduces lower latency compared to TCP since it doesn't wait for acknowledgments or perform retransmissions. In applications where low latency is critical, UDP is preferred.

### 2.3.2 Advantages of UDP

UDP offers several advantages that make it well-suited for specific use cases, including those in the autonomous vehicle domain[19]:

- Low Latency: UDP minimizes communication delays, making it ideal for real-time applications. In autonomous vehicles, low latency is crucial for quick decision-making and response to changing road conditions.
- Speed: UDP is faster than TCP due to its reduced overhead. This speed is valuable for applications where rapid data transmission is essential, such as sensor data sharing and control command transmission.
- Simplicity: UDP's simplicity is an advantage in scenarios where complex error recovery mechanisms are unnecessary. In autonomous vehicles, simplicity can lead to more efficient communication.

### 2.3.3 Challenges of UDP

While UDP offers speed and low latency, it also comes with challenges that must be addressed in the context of autonomous vehicles:

- Lack of Reliability: UDP does not guarantee the delivery of data. Lost or corrupted packets may go unnoticed, which can be problematic for critical safety-related messages.
- Ordering: UDP does not maintain the order of transmitted packets. In cases where maintaining packet order is essential, additional mechanisms must be implemented.

- Error Handling: UDP provides limited error handling. Error detection and correction mechanisms must be integrated at higher layers of the protocol stack or in the application itself.

- Congestion Control: UDP does not perform congestion control, which can lead to network congestion in scenarios with high data rates. Effective congestion management mechanisms are essential.

### 2.3.4 UDP in Wi-Fi Networks

#### 2.3.4.1 Wi-Fi as the Communication Backbone

Wi-Fi networks have become the backbone of wireless communication, connecting an array of devices, including smartphones, laptops, smart home devices, and, significantly, autonomous vehicles. Wi-Fi offers high data rates, scalability, and ease of deployment, making it an attractive choice for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in autonomous driving scenarios [20].

#### 2.3.4.2 UDP and Wi-Fi Compatibility

UDP is inherently compatible with Wi-Fi networks. Wi-Fi's high data rates and low latency align well with UDP's strengths. When configured properly, Wi-Fi can provide the low-latency, high-throughput environment that UDP requires to function effectively.

#### 2.3.4.3 Performance Considerations

When implementing UDP in Wi-Fi networks for autonomous vehicles, several performance considerations come into play:

- Quality of Service (QoS): To ensure that critical data packets receive priority treatment, Quality of Service mechanisms should be in place. This guarantees that safety-critical messages, such as collision warnings or emergency braking commands, are transmitted with minimal delay.

- Network Design: The design of the Wi-Fi network, including the placement of access points, channel allocation, and interference management, can significantly impact UDP performance. Optimizing the network for low latency and high throughput is essential.

- Redundancy: To address UDP's lack of reliability, redundancy can be introduced at higher layers of the protocol stack or within the application. This redundancy helps mitigate the risk of data loss or corruption.

#### 2.3.4.4 Applications of UDP in Autonomous Vehicles

Following are the applications of UDP in Autonomous Vehicles[21]:

- Vehicle-to-Vehicle (V2V) Communication: One of the primary applications of UDP in autonomous vehicles is vehicle-to-vehicle (V2V) communication. Vehicles exchange information about their positions, speeds, and intentions using UDP packets. This real-time V2V communication is critical for enabling cooperative driving, collision avoidance, and traffic coordination. Low-latency and high-throughput UDP transmissions are vital for the success of these applications.

- Vehicle-to-Infrastructure (V2I) Communication: In addition to V2V communication, autonomous vehicles rely on vehicle-to-infrastructure (V2I) communication to interact with roadside infrastructure. This includes traffic lights, signs, control systems, and even cloud-based traffic management platforms. UDP facilitates the rapid exchange of data, ensuring that vehicles receive timely information about traffic conditions, road closures, and other critical updates.

- Sensor Data Transmission: Autonomous vehicles generate vast amounts of sensor data, including LIDAR, radar, and camera feeds. This sensor data is crucial for the vehicle's perception and decision-making systems. UDP's ability to transmit data quickly and efficiently makes it well-suited for the transmission of sensor data between onboard sensors and the vehicle's control systems.

- Real-Time Control Commands:Autonomous vehicles rely on real-time control commands to execute actions such as braking, accelerating, and steering. These commands are generated by the vehicle's AI systems and must be transmitted to actuators with minimal delay. UDP's low latency ensures that control commands are executed promptly, contributing to vehicle safety.

#### 2.3.4.5 Low-Latency Communication with UDP

Low latency is a critical requirement for autonomous vehicles. In situations where split-second decisions are necessary to avoid accidents or respond to changing road conditions, high latency in communication can be detrimental. UDP's low-latency nature ensures that messages are delivered promptly, enabling rapid responses.

#### 2.3.4.6 Bandwidth Requirements

Autonomous vehicles generate and consume vast amounts of data, particularly sensor data. High-throughput communication is necessary to transmit this data efficiently. UDP, with its low overhead, is well-suited for high-throughput applications.

#### 2.3.4.7 Techniques for Achieving Low Latency

Achieving low latency with UDP in Wi-Fi networks involves several techniques:

- Quality of Service (QoS): Prioritizing UDP packets with QoS mechanisms ensures that safety-critical messages receive preferential treatment in the network.
- Edge Computing: Offloading processing tasks to edge computing nodes near the vehicles can reduce latency by minimizing the distance data must travel.
- Network Optimization: Careful network design, channel allocation, and interference management can reduce latency in Wi-Fi networks.

### 2.3.5 Challenges and Trade-Offs

While low latency is crucial, it's essential to recognize that achieving extremely low latency can introduce challenges and trade-offs. For example, aggressively prioritizing UDP packets may lead to congestion in the network. Balancing the need for low latency with overall network performance is a complex task that requires careful consideration.

## 2.4 Packet Error Rate PER

Wireless communication is an integral part of modern life, with Wi-Fi networks serving as a ubiquitous means of data transfer. One of the critical performance metrics in Wi-Fi networks is the PER. This metric quantifies the likelihood of packets being lost or corrupted during transmission, significantly impacting network reliability and quality of service. This thesis aims to provide a comprehensive understanding of PER in Wi-Fi networks, covering its significance, measurement techniques, influencing factors, mitigation strategies, and its role in optimizing network performance.

### 2.4.1 Significance of PER

PER holds paramount significance in Wi-Fi networks for several reasons:

- Quality of Service (QoS): High PER can degrade the QoS, leading to issues in real-time applications like VoIP and video streaming.
- Network Reliability: PER directly impacts network reliability. Understanding and managing it are essential for ensuring consistent connectivity.
- Protocol Optimization: Network designers and engineers rely on PER data to optimize communication protocols for better performance.

### 2.4.2 Calculation of PER

PER is expressed as a percentage or decimal fraction. It is calculated by dividing the number of lost or erroneous packets by the total number of transmitted packets[22]:

$$\text{PER} = \left( \frac{Number \quad of \quad Lost \quad or \quad Erroneous \quad Packets}{Total \quad Transmitted \quad Packets} \right) * 100$$

### 2.4.3 Factors Affecting PER

Several factors influence PER:

- Signal-to-Noise Ratio (SNR): Lower SNR leads to higher PER as weak signals are more prone to errors.
- Interference: External signals, noise, or collisions can introduce errors.

- Channel Conditions: Multipath fading, shadowing, and reflection affect signal quality.
- Modulation Scheme: Different modulation schemes have varying error susceptibility.

### 2.4.4 Mitigation Strategies

Here are some discussed strategies to mitigate high PER:

- Forward Error Correction (FEC): Adding redundant data for error recovery.
- Automatic Repeat reQuest (ARQ): Resending packets upon detection of errors.
- Channel Coding: Employing error-correcting codes.
- Adaptive Modulation and Coding (AMC): Adjusting modulation and coding schemes based on channel conditions.

## 2.5 Singal-to-noise ratio SNR

Signal-to-Noise Ratio SNR is a fundamental parameter in wireless communication systems that measures the ratio of the strength of the received signal to the strength of background noise or interference. It quantifies the quality of the signal by indicating how much cleaner the signal is compared to the noise present in the environment.

Mathematically, SNR is expressed as[23]:

$$\text{SNR} = \left( \frac{S}{N} \right)$$

where:

- S represents the power or strength of the signal
- N represents the power or strength of the noise.

In Wi-Fi networks, SNR is typically measured in decibels (dB), which provides a logarithmic representation of the ratio. A higher SNR value indicates a stronger signal relative to the noise, resulting in better signal quality.

### 2.5.1 Importance of SNR in Wi-Fi

SNR is of paramount importance in Wi-Fi networks due to the following key reasons:

- Data Reliability : In Wi-Fi communication, data is transmitted wirelessly as radio waves. A high SNR ensures that the received data packets are less likely to be corrupted by noise or interference during transmission. This reliability is critical for applications that demand error-free data transfer, such as video streaming, online gaming, and VoIP (Voice over Internet Protocol) calls.

- Network Throughput : SNR directly affects the achievable data rates in Wi-Fi networks. Higher SNR levels allow for the use of advanced modulation and coding schemes, enabling faster data transmission. Conversely, a low SNR forces the use of more robust (but slower) schemes to maintain reliable communication.

- Coverage Range : Wi-Fi signals with higher SNR values can travel over longer distances while maintaining acceptable performance. An increased SNR extends the coverage range of access points, providing connectivity to devices that are farther away from the source.

- Quality of Service (QoS) : QoS is crucial for applications like video conferencing and online gaming, where low latency and minimal packet loss are essential. A higher SNR contributes to better QoS by reducing latency and packet loss.

- Spectral Efficiency : Wi-Fi networks often operate in shared frequency bands. A higher SNR allows for more efficient use of available spectrum since it reduces the likelihood of signal collisions and retransmissions. This, in turn, increases overall network capacity.

### 2.5.2 Measuring SNR

#### 2.5.2.1 Decibel Scale

SNR is typically expressed in decibels (dB) due to the wide range of values encountered in wireless communication. The dB scale provides a logarithmic representation of the SNR ratio, making it easier to work with both small and large values.

The dB value of SNR is calculated as[24]:

$$\text{SNR}_{dB} = 10 * \log \text{SNR}$$

This formula allows for convenient representation, comparison, and analysis of SNR values in Wi-Fi networks.

#### 2.5.2.2 Signal Strength and Noise Measurement

To measure SNR in a Wi-Fi network, two primary parameters must be determined: the received signal strength (RSSI) and the noise level. RSSI represents the power of the received signal, while the noise level measures the background interference.

The SNR can then be calculated as [25]:

$$\text{SNR}_{dB} = RSSI_{dB} - Noise_{dB}$$

This calculation yields the SNR value in decibels (dB), providing insight into the signal quality.

### 2.5.3 Factors Affecting SNR

Several factors influence the SNR in Wi-Fi networks. Understanding these factors is essential for optimizing network performance.

- Signal Strength : Signal strength, often represented as RSSI (Received Signal Strength Indicator), measures the power of the Wi-Fi signal at the receiver. A higher signal strength results in a higher SNR and better signal quality. Factors affecting signal strength include the transmission power of the access point, distance from the transmitter, and obstacles in the signal path.
- Noise Level : Noise in a Wi-Fi network includes all unwanted radio signals and interference that degrade the quality of the received signal. Common sources of noise include electronic devices, neighboring networks, and non-Wi-Fi interference. Reducing noise levels is crucial for improving SNR.

- Interference : Interference occurs when multiple wireless devices or networks operate in the same frequency band. Co-channel interference, where two or more networks use the same channel, can significantly impact SNR. Interference mitigation techniques, such as channel selection and interference avoidance, help combat this issue.
- Distance : The distance between the Wi-Fi transmitter (access point or router) and the receiver (client device) affects signal strength and, consequently, SNR. As distance increases, signal strength decreases, leading to lower SNR values. Signal boosters and repeaters can extend coverage range in such cases.
- Antenna Gain : Antenna gain plays a role in both signal strength and noise. High-gain antennas can amplify the Wi-Fi signal, improving SNR. However, they can also capture more noise, so antenna selection should consider the balance between signal amplification and noise sensitivity.
- Modulation and Coding Scheme (MCS) : Modern Wi-Fi standards support various modulation and coding schemes (MCS) that determine how data is encoded and transmitted. Higher MCS levels offer higher data rates but require a higher SNR for reliable communication. In adverse SNR conditions, devices may downshift to lower MCS levels to maintain connectivity.

### 2.5.4 SNR Thresholds

SNR thresholds are predefined values used to determine the quality of a wireless connection. These thresholds are often used to classify the connection as "good," "fair," or "poor." Different applications and devices may have varying SNR requirements, but some common thresholds include[26]:

- Good SNR: Typically considered to be above 25 dB. A good SNR supports high-speed data transmission and low error rates.
- Fair SNR: Falls in the range of 10 to 25 dB. A fair SNR allows for basic internet browsing and email communication but may not support high-bandwidth.

# Chapter 3

# Concept of MAD

## 3.1 Concept

The U-Shift electric vehicle concept represents a driverless innovation that introduces a unique form of modularity. This modularity is achieved by decoupling the driving module from the transport capsule, thereby opening doors to novel intermodal solutions, diverse product offerings, and innovative business models. The versatile drive module can be seamlessly integrated with different types of capsules, catering to a wide range of transportation needs, including the movement of passengers and goods. Some noteworthy applications of this concept encompass autonomous and electric night deliveries, efficient intra-logistics operations, and inclusive passenger transport that eliminates barriers to accessibility[27].

## 3.2 About MAD

To address the security challenges associated with vehicle-based automation, the Institute of Vehicle Concepts at the German Aerospace Center (DLR) introduces the concept of MAD. In this innovative approach, a significant portion of the automation process, spanning from perception to decision-making, is relocated to the infrastructure itself. By leveraging sensors integrated into the infrastructure, continuous surveillance of the entire operational area becomes achievable. This eliminates constraints stemming from the limited perspective and range of sensors in vehicle-based automation and enables the provision of a highly accurate and reliable comprehensive view of the environment by the MAD system[27].

One distinctive aspect of MAD is that vehicles under its control are not mandated to have an onboard driver or conventional input mechanisms like steering wheels. Instead, the MAD concept incorporates the option of remotely operating these vehicles from a central workstation. Initially, remote driving serves as a backup with safety responsibilities akin to those of safety drivers in vehicle-based automation approaches. The ultimate objective is to gradually reduce the reliance on remote driving assistance as the automation software matures, with the eventual goal of utilizing remote driving only for rare edge cases in which the automation software encounters challenges that it cannot independently resolve[27].

# Chapter 4

# Implementation

In this chapter, we would like to introduce the methodologies adopted in order to evaluate Wi-Fi 6E's performance for autonomous vehicles. Initially, Section 4.1 provides a concise outline of the methodologies employed, aligning with our established research procedures. Subsequently, in Sections 4.2 and 4.3, we delve into the specifics of our experimental simulation design and the corresponding analytical approaches used in our study[13].

## 4.1 Research Process

In this section, we elucidate the research methodology adopted in this project. Initially, we conducted a comprehensive literature review focusing on Wi-Fi 6E systems and wireless networks that align with the requirements of our autonomous vehicle project. This literature study serves as a foundational step, enhancing our understanding of the project's context. Subsequently, we devise a series of Wi-Fi performance simulations informed by the insights from the literature review. These simulations are meticulously designed and executed to culminate in the ultimate assessment and analysis of Wi-Fi 6E performance[13].

### 4.1.1 Wi-Fi Performance Simulation

Our approach encompasses the design and execution of experimental simulations that span a spectrum from straightforward scenarios to intricate ones. In the simpler scenarios, we evaluate relatively uncomplicated traffic patterns. As we progress to the comprehensive cases, we incorporate complex traffic models, considering a broader range of variables and intricacies. We will evaluate the performance of wifi based on Packet Error Rate as well as Signal-to-noise ratio.

## 4.2 System Design and Measurements

In this section, To commence our investigation, we present the Wi-Fi system model as the foundational framework. Subsequently, we undertake a diverse set of simulations aimed at assessing Wi-Fi performance under varying scenarios.

### 4.2.1 Simulation Tools and Environmental Setting

In this thesis, all the simulations are based on OMNET++ network simulator, as well as Python are used to plot figures.

#### 4.2.1.1 OMNET++

OMNeT++ (Objective Modular Network Testbed in C++) stands as a highly utilized discrete event simulation framework and network simulator, holding a significant role in the realm of research and development pertaining to communication networks, distributed systems, and multifaceted systems. This versatile tool offers a robust simulation environment, effectively tailored for the modeling and simulation of intricate systems, with a particular emphasis on network simulations encompassing both wired and wireless communication networks, IoT systems, and vehicular networks[28].

A notable attribute of OMNeT++ lies in its modular and component-based architecture, which empowers users to seamlessly generate and incorporate custom models. This modularity framework facilitates the representation of a wide spectrum of system components and interactions, rendering OMNeT++ suitable for a diverse array of research topics[28].

Additionally, OMNeT++ is rooted in discrete event simulation, wherein events unfold at clearly defined points in time. This methodology proves invaluable when modeling and scrutinizing systems where event timing holds paramount significance, as is the case in network protocols and communication systems[28].

This versatile and powerful framework serves as an invaluable asset in the arsenal of researchers and developers, offering a comprehensive platform to explore and innovate across various domains.

### 4.2.2 Design process summary

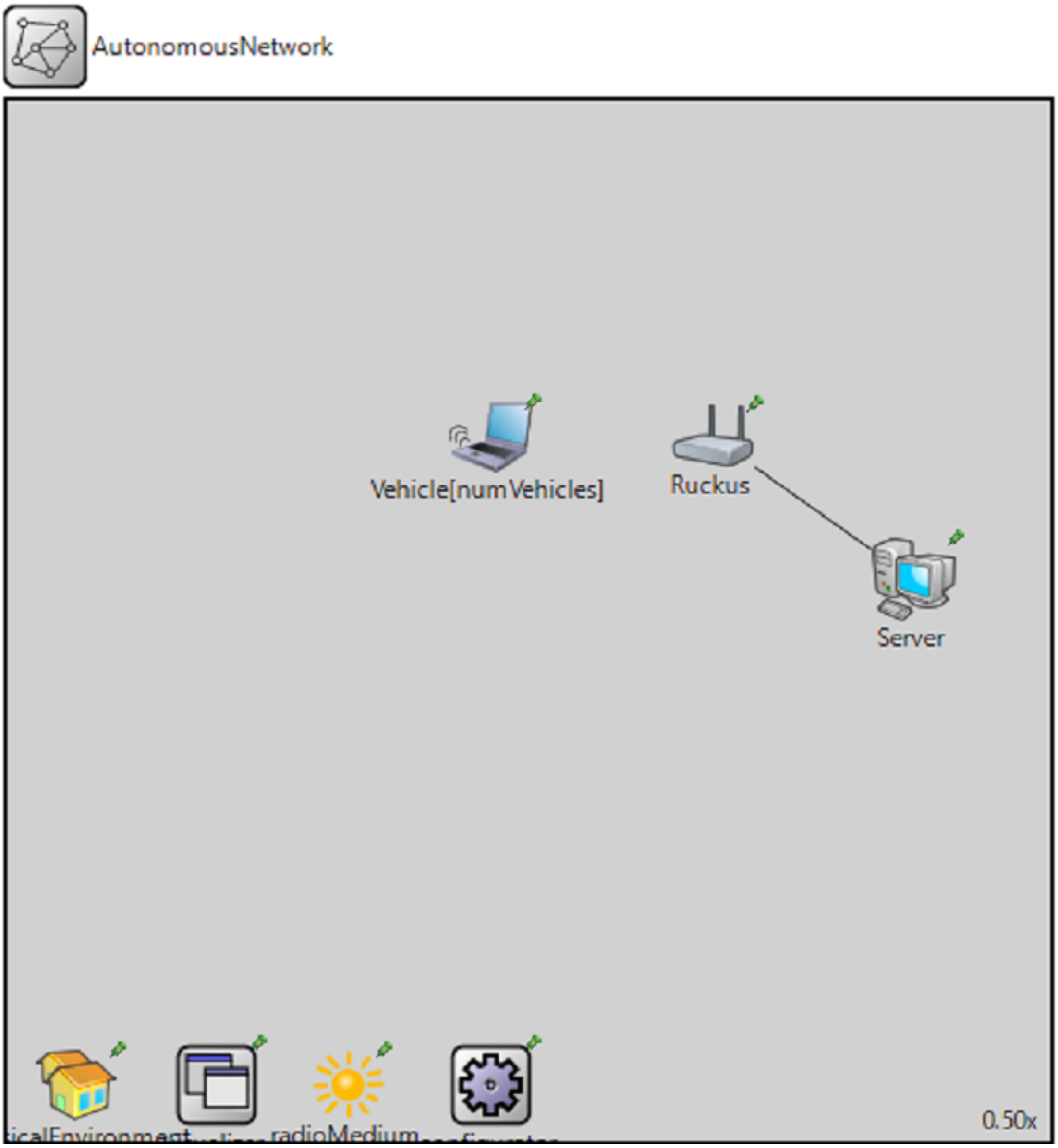

**Figure 4.1:** Network of Autonomous Network

In this section, we will discuss the design process summary which are as follows:

- Our server is connected to the Access Point Ruckus T750 and Ruckus T811-cm.
- Our vehicle is wirelessly connected to Access Point.
- For simpler traffic, we use only one Vehicle. Whereas for comprehensive cases, we use multiple vehicles.

### 4.2.3 Imports

These import statements are essential for including various modules and components from OMNeT++'s library and other packages to be used in your simulation:

```
import inet.networklayer.configurator.ipv4.
   Ipv4NetworkConfigurator;
import inet.node.ethernet.Eth10M;
import inet.node.inet.StandardHost;
import inet.node.inet.WirelessHost;
import inet.node.wireless.AccessPoint;
import inet.visualizer.canvas.integrated.
   IntegratedCanvasVisualizer;
import inet.visualizer.common.IntegratedMultiVisualizer;
import inet.visualizer.common.IntegratedVisualizer;
import inet.physicallayer.wireless.ieee80211.packetlevel.
   Ieee80211ScalarRadioMedium;
import inet.physicallayer.wireless.ieee80211.packetlevel.
   Ieee80211DimensionalRadioMedium;
import inet.node.ethernet.EthernetLink;
import inet.physicallayer.wireless.noise.NoiseSource;
import inet.environment.common.PhysicalEnvironment;
import inet.physicallayer.wireless.common.pathloss.
   TwoRayInterference;
import inet.physicallayer.wireless.apsk.packetlevel.
   ApskScalarRadio;
```

- import inet.networklayer.configurator.ipv4.Ipv4NetworkConfigurator: This import statement includes the Ipv4NetworkConfigurator module, which is used to configure IPv4-related settings in network simulations. It allows you to set up IP addresses and routing configurations for nodes in the network.

- import inet.node.ethernet.Eth10M - This Eth10M import statement brings in the Eth10M module, which represents a standard Ethernet interface with a speed of 10 Mbps. It can be used to model Ethernet connections and nodes in the simulation.

- import inet.node.inet.StandardHost - This StandardHost import statement imports the StandardHost module, which represents a standard internet host in the simulation. It typically includes features like IP stack, transport protocols, and application layers for communication.

- import inet.node.inet.WirelessHost - This WirelessHost import statement includes the WirelessHost module, which represents a wireless host in the simulation. Wireless hosts differ from standard hosts as they are equipped with wireless network interfaces, and their communication characteristics are different.
- import inet.node.wireless.AccessPoint - This import statement imports the AccessPoint module, which is used to model wireless access points in the simulation. Access points are critical components in wireless networks, as they provide connectivity to wireless hosts.
- import inet.visualizer.canvas.integrated.IntegratedCanvasVisualizer - This import statement brings in the IntegratedCanvasVisualizer module, which is a visualizer component used to display network simulations on a canvas. It helps in visualizing the network topology and various simulation parameters.
- import inet.visualizer.common.IntegratedMultiVisualizer - This import statement includes the IntegratedMultiVisualizer module, which is used for creating integrated visualizations of multiple aspects of the simulation. It allows for a comprehensive view of the simulation results.
- import inet.visualizer.common.IntegratedVisualizer - This import statement imports the IntegratedVisualizer module, which is another component used for visualization in network simulations. It may provide different visualization options or focus on specific aspects of the simulation.
- import inet.physicallayer.wireless.ieee80211.packetlevel.Ieee80211 ScalarRadioMedium - This import statement includes the Ieee80211 ScalarRadioMedium module, which is used to model the physical layer of wireless communication systems following the IEEE 802.11 standard. It helps simulate wireless communication characteristics such as signal propagation and interference.
- import inet.physicallayer.wireless.ieee80211.packetlevel.Ieee80211 DimensionalRadioMedium - This import statement imports the Ieee80211 DimensionalRadioMedium module, which is another module for modeling the physical layer of IEEE 802.11 wireless systems. It may provide additional features or capabilities compared to the scalar version.

- import inet.node.ethernet.EthernetLink - This import statement includes the EthernetLink module, which may represent the physical link between Ethernet nodes in the simulation. It can be used to configure parameters related to Ethernet connections.
- import inet.physicallayer.wireless.noise.NoiseSource - This import statement imports the NoiseSource module, which can be used to model noise sources in wireless communication. Noise is an essential factor in determining signal quality and network performance.
- import inet.environment.common.PhysicalEnvironment- This import statement brings in the PhysicalEnvironment module, which represents the physical environment in which the network operates. It may include characteristics like terrain, obstacles, and weather conditions that affect network behavior.
- import inet.physicallayer.wireless.common.pathloss.TwoRayInterference - This import statement includes the TwoRayInterference module, which is used to model a common path loss model for wireless communication. It helps simulate how signal strength attenuates with distance.

### 4.2.4 Modules used in OMNET++

The different modules used in OMNET++ are as follows:

```
visualizer: IntegratedMultiVisualizer {
    @display("p=200.79999,945.76794");
    }
configurator: Ipv4NetworkConfigurator {
    @display("p=463.848,945.76794");
    }
Server: StandardHost {
    @display("p=869.464,459.832");
    }
Ruckus: AccessPoint {
    @display("p=676.696,321.28");
    }
Vehicle[numVehicles]: WirelessHost {
    @display("p=463.848,323.288");
```

```
    }
radioMedium: Ieee80211ScalarRadioMedium {
    @display("p=327.304,943.75995");
    }
physicalEnvironment: PhysicalEnvironment {
    @display("p=66.264,945.76794");
    }

    connections:
        Server.ethg++ <--> Eth10M <--> Ruckus.ethg++;
```

- Visualizer: IntegratedMultiVisualizer - This module is responsible for visualization aspects within the simulation. It may include features for rendering the simulation results in a graphical form, providing a visual representation of how the network and its components behave during the simulation. In this case, it's configured to be an integrated multi-visualizer.

- Configurator: Ipv4NetworkConfigurator - The Ipv4NetworkConfigurator module typically handles the configuration of IPv4 network parameters within the simulation. It is responsible for setting up the network addressing, routing, and related configuration settings. This module helps ensure that the simulated network functions correctly regarding IP communication.

- Server:StandardHost.This represents a standard host node within the simulation. Hosts are devices capable of running applications and communicating over the network. The "Server" node is positioned at coordinates (869.464, 459.832) in the simulation space.

- Ruckus: AccessPoint - This module represents an access point, which is a device that connects wireless devices (such as the "Vehicle" nodes) to a wired network. Access points are crucial components in wireless network simulations, and here, "Ruckus" is positioned at coordinates (676.696, 321.28).

- Vehicle[numVehicles]: WirelessHost - This part represents multiple wireless host nodes denoted as "Vehicle." The number of vehicles is indicated by "numVehicles." These nodes likely represent mobile devices or vehicles within the simulation, and they are wireless hosts capable of communicating over the wireless medium. They are located at coordinates (463.848, 323.288) in the simulation space.

- radioMedium: Ieee80211ScalarRadioMedium - The "radioMedium" module represents the medium through which wireless communication takes place. It's configured as an IEEE 802.11 scalar radio medium, which is a common choice for simulating wireless communication in network simulations. This module defines how wireless signals propagate, interfere with each other, and affect communication between wireless devices.
- physicalEnvironment: PhysicalEnvironment -The "physicalEnvironment" module represents the physical environment in which the simulation takes place. It may include characteristics such as terrain, obstacles, or other environmental factors that can influence communication in the simulated network.

### 4.2.5 Configuration script

The provided code appears to be a configuration script for an OMNeT++ simulation. he script contains various parameters and settings that define the simulation environment, network components, and their behavior. Here is an explanation of the key sections and directives in the code:

```
**.radio.packetErrorRate.result-recording-modes = +vector
**.radio.bitErrorRate.result-recording-modes = +vector
**.radio.minSnir.result-recording-modes = +vector

*.*Host.ipv4.arp.typename = "GlobalArp"

*.physicalEnvironment.ground.typename = "FlatGround"
*.physicalEnvironment.ground.elevation = 0m
**.pathLoss.typename = "TwoRayInterference"
```

- General Configuration:
  - network = AutonomousNetwork: Specifies the name of the network being simulated, which is likely a custom network model tailored for autonomous systems.
  - sim-time-limit = 8s: Sets the simulation time limit to 8 seconds, meaning that the simulation will run for this duration
- Result Recording Modes:

  - **.radio.packetErrorRate.result-recording-modes = +vector: Configures result recording modes for packet error rate statistics using a vector.
  - **.radio.bitErrorRate.result-recording-modes = +vector: Configures result recording modes for bit error rate statistics using a vector.
  - **.radio.minSnir.result-recording-modes = +vector: Configures result recording modes for minimum Signal-to-Noise and Interference Ratio (SNIR) statistics using a vector.

- ARP Configuration: *.*Host.ipv4.arp.typename = "GlobalArp": Configures the Address Resolution Protocol (ARP) as "GlobalArp" for all hosts.
- Physical Environment and Path Loss:
  - *.physicalEnvironment.ground.typename = "FlatGround": Defines the ground type as flat.
  - *.physicalEnvironment.ground.elevation = 0m: Sets the ground elevation to 0 meters.
  - **.pathLoss.typename = "TwoRayInterference": Specifies the path loss model as TwoRayInterference, which is used to estimate signal attenuation.

```
**.wlan[*].radio.centerFrequency = 6GHz
*.Ruckus.wlan[*].radio.tranmitter.power = 28dBm
*.Ruckus.wlan[*].radio.antennaGain = 3dBi
**.wlan[*].radio.transmitter.power = 100mW
**.wlan[*].radio.transmitter.headerLength = 192b
*.Ruckus.radio.tranmitter.analogModel.communicationRange = 300
   m
*.host*.wlan[0].radio.receiver.snirThreshold = 3dB
**.wlan[*].radio.receiver.sensitivity = -86dBm
**.wlan[*].bitrate = ${bitrate=12,18,24,36,54}Mbps
```

- Wireless Network Configuration:
  - **.wlan[*].radio.receiver.sensitivity = -86dBm: Sets the receiver sensitivity for all wireless LAN nodes to -86 dBm.
  - **.wlan[*].radio.centerFrequency = 6GHz: Sets the center frequency for all WLAN radios to 6 GHz.

  - *.Ruckus.wlan[*].radio.tranmitter.power = 28dBm: Sets the transmitter power for Ruckus wireless LAN nodes to 28 dBm.
  - *.Ruckus.wlan[*].radio.antennaGain = 3dBi: Specifies the antenna gain for Ruckus WLAN radios.
  - **.wlan[*].radio.transmitter.power = 100mW: Sets the transmitter power for all WLAN nodes to 100 mW.
  - **.wlan[*].radio.transmitter.headerLength = 192b: Defines the header length for WLAN transmitters.
  - *.Ruckus.app[0].typename ="PingApp": Specifies that the Ruckus application type is "PingApp."
  - *.Ruckus.radio.tranmitter.analogModel.communicationRange = 300m: Sets the communication range for Ruckus radios to 300 meters.
  - *.host*.wlan[0].radio.receiver.snirThreshold = 3dB: Configures the SNIR threshold for WLAN receivers.

```
*.Vehicle[*].mobility.typename = "MassMobility"
*.Vehicle[*].mobility.changeInterval = 1s
*.Vehicle[*].mobility.angleDelta = uniform(-10deg,10deg)
*.Vehicle[*].mobility.rotationAxisAngle = uniform(-10deg,10deg)
*.Vehicle*.mobility.speed = 50mps
*.Vehicle*.mobility.initialX = 0m
*.Vehicle*.mobility.initialY = 0m
*.Vehicle*.mobility.initialZ = 0m
**.constraintAreaMaxX = 1000m
**.constraintAreaMaxY = 1000m
```

- Vehicle Configuration:
  - **.numVehicles = 5: Specifies that there are 5 vehicles in the simulation.
  - Configuration for vehicle applications, such as UDP communication, message length, and destination addresses.
  - Mobility settings for vehicles, including speed, initial position, and mobility model.
  - Constraint area dimensions for vehicles' mobility.

```
**.numVehicles = 50
*.Vehicle.app[*].typename = "UdpBasicApp"
*.Vehicle.app[*].destAddresses = "Server"
*.Vehicle.app[*].packetName = "UDPData"
*.Vehicle.app[*].destPort = 5000
*.Vehicle.app[*].messageLength = 100B
*.Vehicle.physicalLayer.radioMediumModule = RadioMedium
```

- Server Configuration:
  - **.wlan[*].bitrate = bitrate=6,18,54Mbps: Sets the WLAN bitrates for different nodes, which appear to be configurable as 6, 18, or 54 Mbps.
  - **.backgroundNoise.power = -86dBm: Defines the background noise power as -86 dBm.

```
*.visualizer.mobilityVisualizer.displayMovementTrails
   = true
**.displayCommunicationRange = true
*.visualizer.*.statisticVisualizer[0].signalName = "
   packetSentToUpper"
*.visualizer.*.statisticVisualizer[0].
   statisticExpression = "packetErrorRate"
*.visualizer.*.statisticVisualizer[0].sourceFilter =
   "*.Ruckus.wlan[*].radio"
*.visualizer.*.statisticVisualizer[0].format = "
   packetErrorRate: %v"
*.visualizer.*.statisticVisualizer[3].signalName = "
   packetSentToUpper"
*.visualizer.*.statisticVisualizer[3].
   statisticExpression = "Snir"
*.visualizer.*.statisticVisualizer[3].sourceFilter =
   "*.Vehicle[*].radio"
*.visualizer.*.statisticVisualizer[3].format = "SNIR:
   %v"
*.visualizer.*.statisticVisualizer[3].placementHint =
   "topLeft"
```

  - Visualizer Configuration: Various visualizer settings for displaying simulation results, including mobility trails, communication range, statistics, packet drops, and other information.

In summary, this code snippet defines a simulation environment for modeling an autonomous network. It configures various aspects of the network, such as radio characteristics, mobility, and visualization parameters, to conduct simulations and gather results related to packet error rates, bit error rates, and SNIR.

# Chapter 5

# Result and Discussion

## 5.1 Simulation using 5 Vehicles

In this simulation, we have 5 Vehicle moving in different directions from a common starting point.

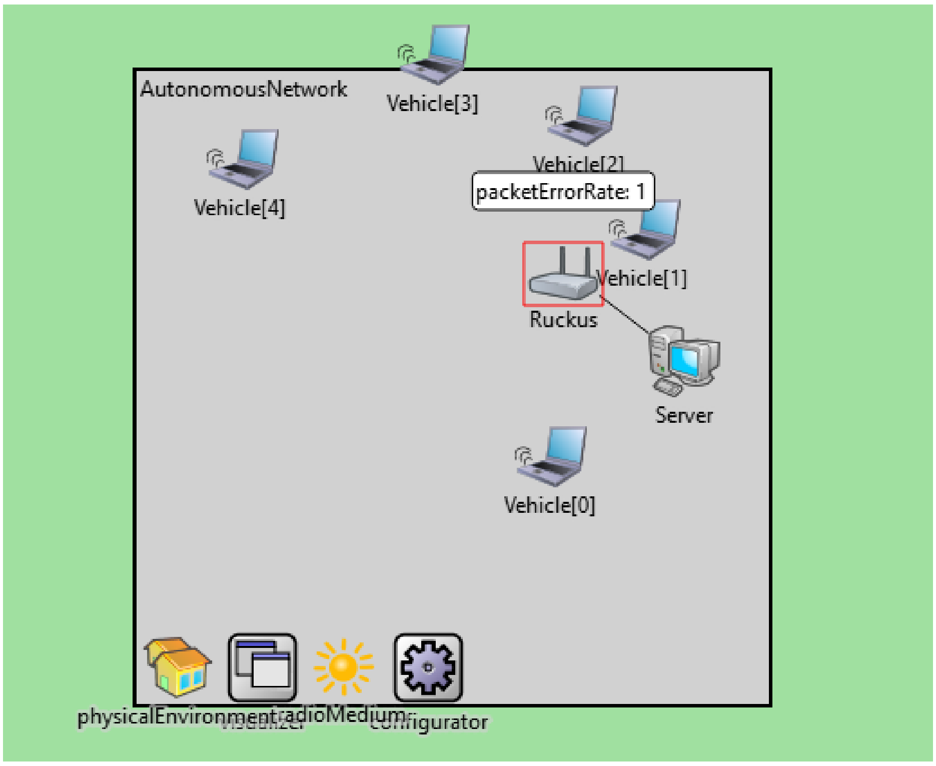

**Figure 5.1:** Network having 5 vehicle

Here are the results of SNR as follows:

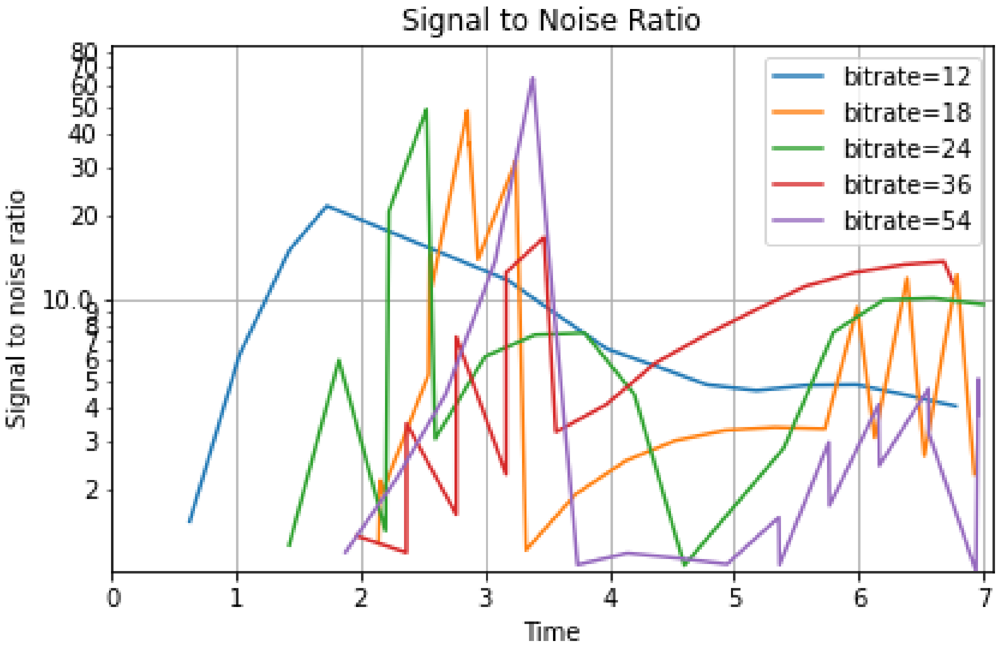

**Figure 5.2:** Signal to noise ratio in logarithm value

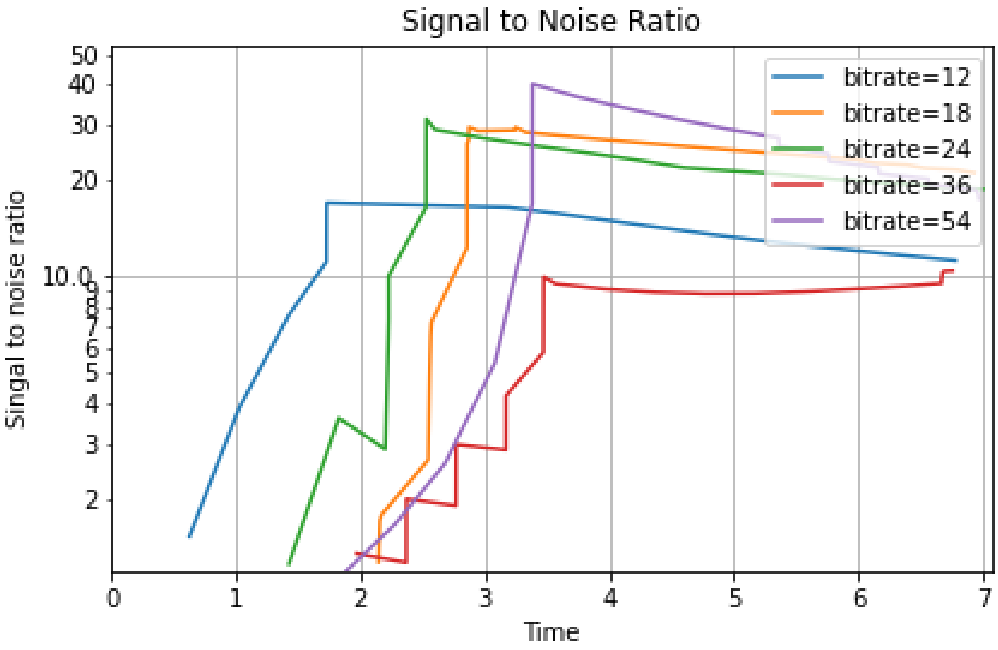

**Figure 5.3:** Mean value of Signal to noise ratio

Here we can find the result for PER as below:

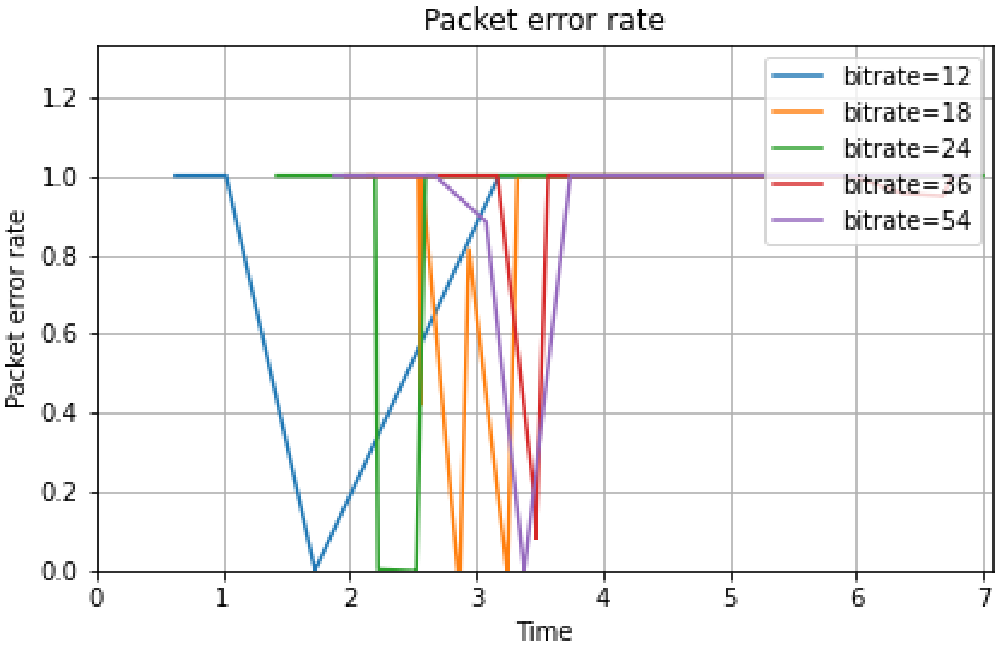

**Figure 5.4:** Packet error rate

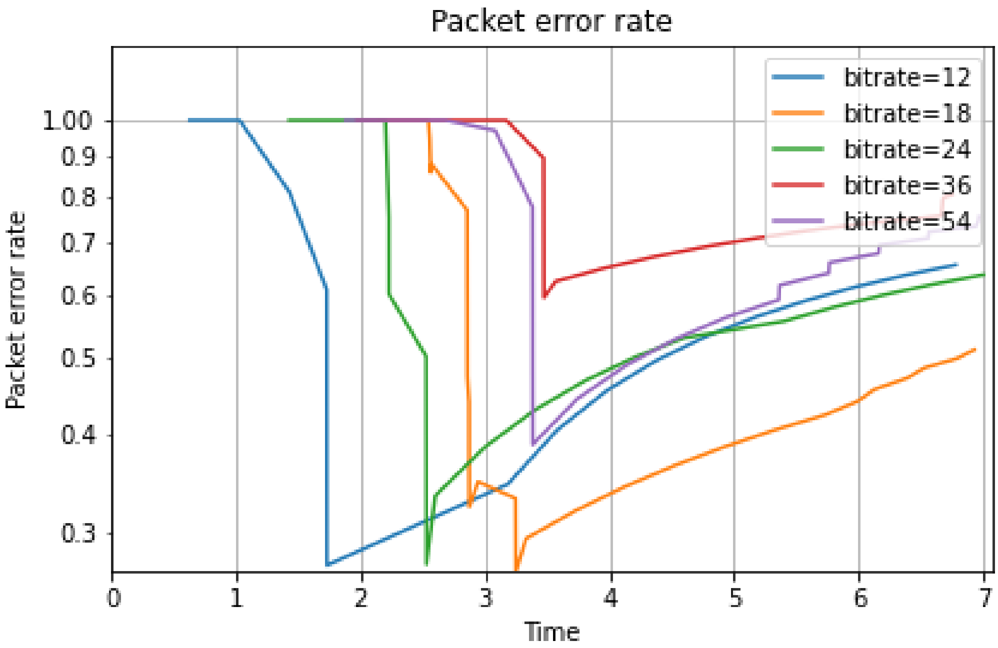

**Figure 5.5:** Mean value Packet error rate

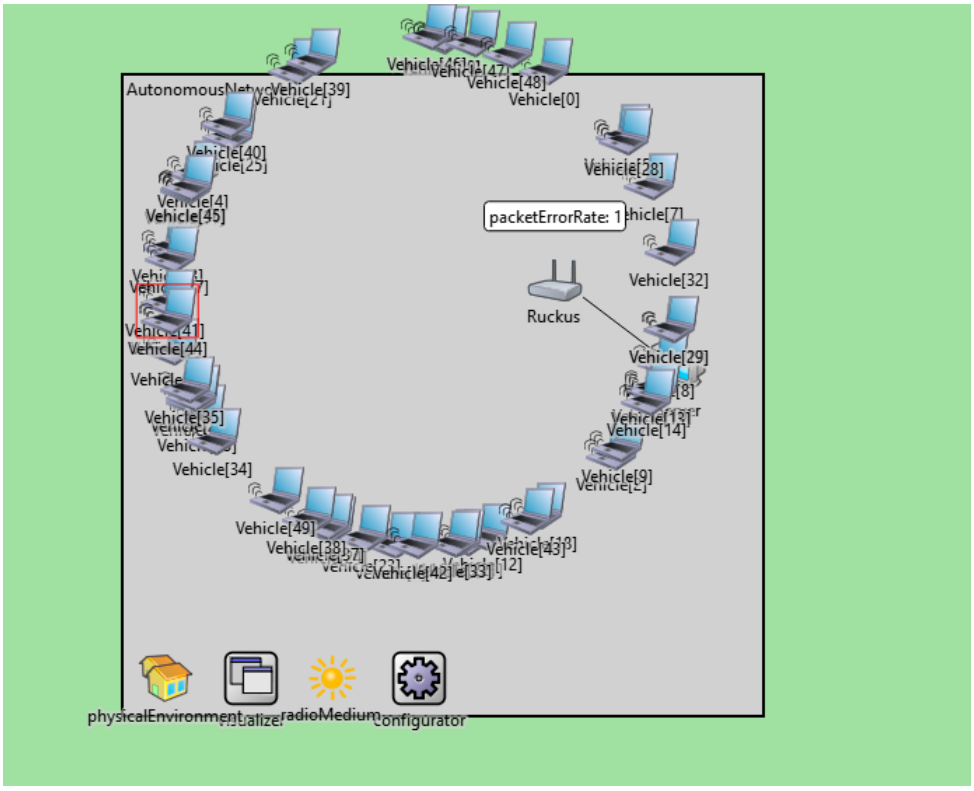

**Figure 5.6:** Network having 50 vehicle

## 5.2 Simulation having 50 vehicles

In the figure 5.6, we can see multiple vehicle moving in random direction from the access point. While having multiple devices in close proximity leads to noise creation. Hence, influencing the SNR.
Here are the results of SNR as follows:

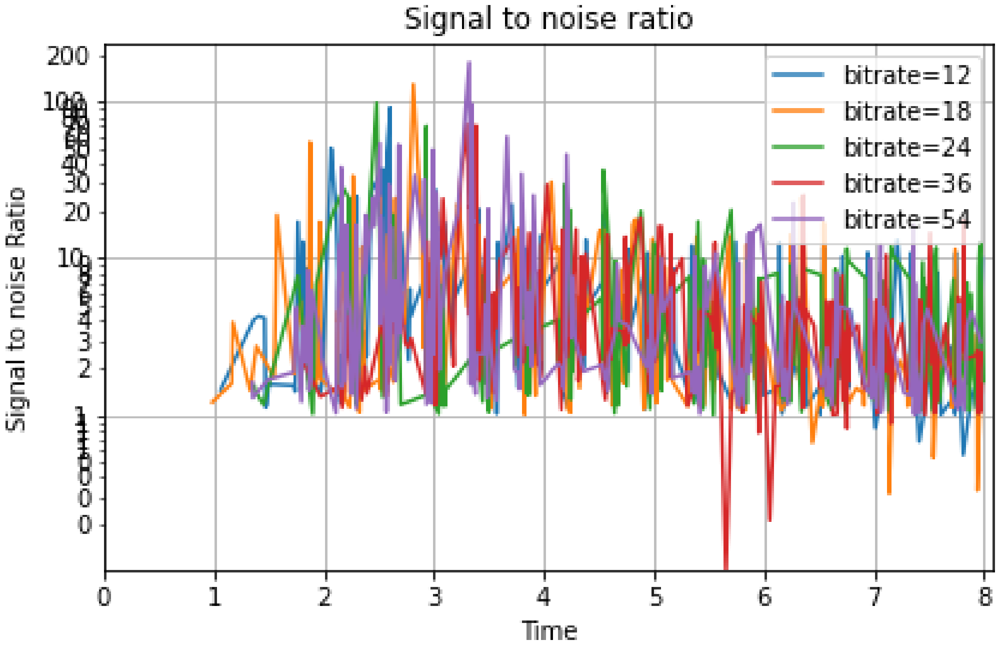

**Figure 5.7:** Signal to noise ratio in logarithm value

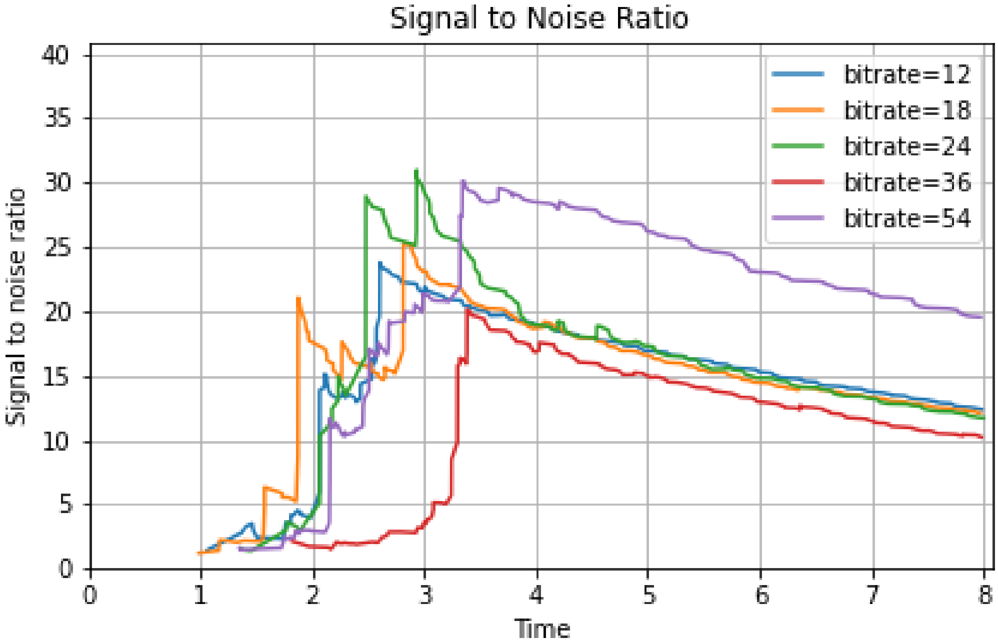

**Figure 5.8:** Mean value of Signal to noise ratio

Here we can find the result for PER as below:

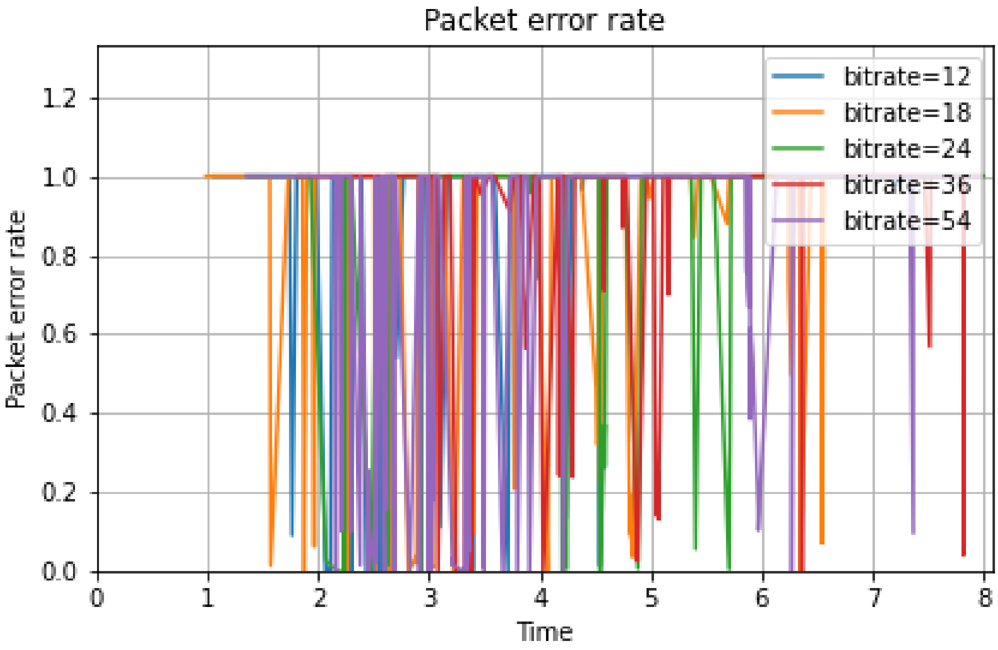

**Figure 5.9:** Packet error rate

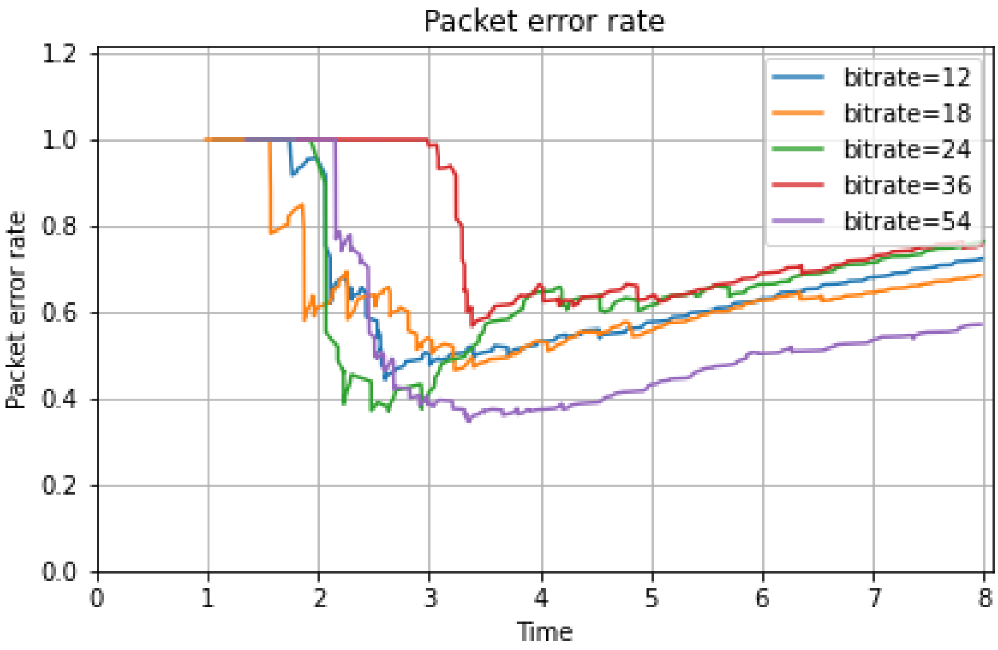

**Figure 5.10:** Mean value Packet error rate

## 5.3 Discussion

As we can see in Figure 5.1 and Figure 5.6, we are having 5 vehicle and 50 vehicles respectively connected to our access point. Using massmobility configuration, enables the mobile host's movement follows a specific pattern. It proceeds along a straight path for a certain duration before altering its course. The duration of this continuous movement is determined by a random variable, specifically following a normal distribution with an average of 1 second. When it executes a change in direction, the new angle at which it will travel is determined by another normally distributed random variable. This angle has an average equal to the previous direction and a standard deviation of 10 degrees.

From Figure 5.2 and figure 5.7, the value of SNR decreases with more number of vehicles connected to the access point. This indicates that the signal gets weaker with more number of devices connected as well as indicate the noise is occurring from the nearby wireless devices.

As the count of lost packets rises and the throughput experiences a decline, the transition to a lower bitrate mode becomes a more pragmatic course of action.

# Chapter 6

# Conclusion and Future Work

This chapter is divided into two sections. In the first section, the conclusion to this thesis is discussed. In the second and last section, ideas and suggestions for future works that evolved from this work are discussed.

## 6.1 Conclusion

In this thesis, we have conducted a comprehensive assessment of Signal-to-Noise Ratio (SNR) and Packet Error Rate (PER) within the Wi-Fi 6E framework, focusing on their critical significance in the context of autonomous vehicle communication. As the automotive industry progresses towards autonomous driving solutions, reliable and low-latency wireless connectivity plays a pivotal role in ensuring the safety and efficiency of autonomous vehicles.

Our research has yielded the following key findings:

- Wi-Fi 6E Advancements: Wi-Fi 6E, with its utilization of the 6 GHz frequency band, demonstrates substantial enhancements in SNR and PER performance. These improvements hold the promise of enabling real-time, high-data-rate communication for autonomous vehicles.

- SNR-PER Dynamics: As SNR increases, PER decreases, underlining the direct impact of signal quality on data packet reliability.

- Challenges and Mitigations: While Wi-Fi 6E holds immense potential, challenges such as interference management, security, and network optimization in dynamic vehicle environments must be addressed to ensure robust and secure communication.

## 6.2 Future Work

Looking ahead, the study of SNR and PER in Wi-Fi 6E for autonomous vehicles presents a rich field for further exploration:

- Advanced Antenna Technologies: Investigate advanced antenna systems, such as beamforming and MIMO, to enhance SNR and mitigate interference in vehicular environments.
- Edge Computing Integration: Explore the integration of edge computing solutions to process data locally, reducing the burden on wireless networks and potentially enhancing latency-sensitive applications.
- Field Trials and Prototyping: Conduct extensive field trials and prototyping in real-world autonomous vehicle scenarios to validate the performance of Wi-Fi 6E under varying conditions and evaluate its practicality in vehicular communication.

# List of Abbreviations

| | |
|---|---|
| **MAD** | Managed Automated Driving |
| **V2X** | Vehicle to Everything |
| **UDP** | User Datagram Protocol |
| **CCAM** | Cooperative, connected and automated mobility |
| **V2I** | Vehicle to Infrastructure |
| **SNR** | Signal-to-noise ratio |
| **PER** | Packet error rate |
| **AVs** | autonomous vehicles |
| **LIDAR** | Light Detection and Ranging |
| **OFDM** | Orthogonal Frequency Division Multiplexing |
| **QAM** | quadrature amplitude modulation |
| **OFDMA** | Orthogonal Frequency Division Multiple Access |
| **TWT** | Target Wake Time |
| **IoT** | Internet of Things |
| **UDP** | User Datagram Protocol |
| **TCP** | Transmission Control Protocol |
| **PHY** | Physical Layer |

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