Vol **04** | Issue **03** | **August** 2024
ISSN **2997-9870**
Page:**113-138**

Academic Journal on Science, Technology, Engineering & Mathematics Education

RESEARCH ARTICLE

OPEN ACCESS

DEVELOPMENT OF LOW-LATENCY WIRELESS COMMUNICATION SYSTEMS FOR AUTONOMOUS VEHICLES

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ABSTRACT

This research aims to explore the effectiveness of the L3 protocol in improving the V2X communication systems in key performance areas such as low communication delay, high-speed protocols and the effectiveness under real-life conditions. According to the L3 protocol simulation of the research, which employs platforms including COOJA and NS-3, the latency of the networks is lowered compared to that of the conventional DSRC/LTE system at below one millisecond levels adopting the time slots and the capture effect. These challenges observed on other systems such as delays experienced due to high-speed data transfer are addressed in the protocol. The performed measurements prove that the L3 protocol of the system exhibits reliability and scalability depending on the number of vehicles on the road as well as the network load, and retains its workability even with the number of 225 automobiles. These results conform with prior works that underlined the necessity of using sophisticated and low-latency relative communication systems for the usage of an autonomous vehicle network. In doing so, the study shows a future of L3 protocol in enhancing the current V2X communication systems in aspects of low latency, fast data transfer and competency in various conditions. It is suggested that future research include extensive field trials, the increase of security measures, the analysis of the scalability and integration of the new technologies, and the solution of the interoperability issues for the further investigation of the possibilities of the application of the L3 protocol.

KEYWORDS

Low-Latency Wireless Communication, Autonomous Vehicles, V2X Communication, L3 Protocol, Real-Time Data Exchange, Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I)

Submitted: July 28, 2024
Accepted: August 25, 2024
Published: August 28, 2024

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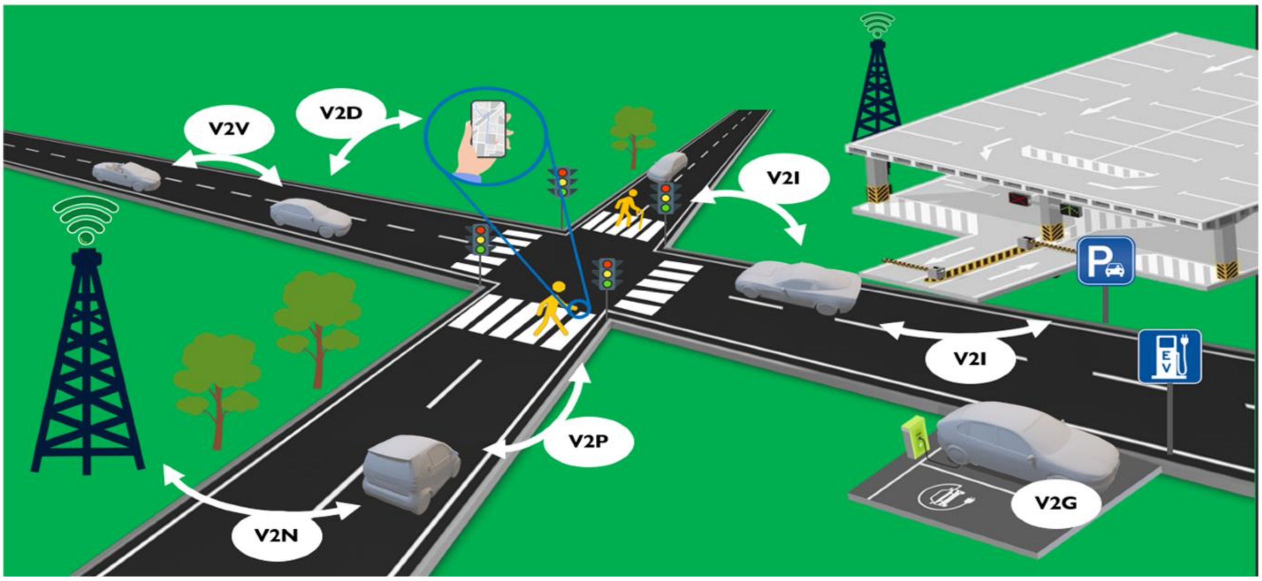
10.69593/ajsteme.v4i03.101

1 Introduction

Intelligent transportation systems, in particular, the related technology of connected and autonomous vehicles (CAV) have been receiving extensive attention from both research institutions and companies for years. CAV use includes computer vision, and wireless networking, among others, in the provision of an effective and efficient transport system to the current one. As a result, several advantages come with great features including the safety of lives and property, mobility of the elderly and the disabled and an improved public transport system (Brambilla et al., 2020). CAV could dramatically reduce fatalities to next to nil, as long as the technologies are advanced. As it was mentioned, adjoining to high-precision sensing systems that are usually installed in autonomous vehicles, a lot of sensor data are generated, which, in turn, require real-time processing. For instance, the Google and Tesla automobiles and Mobileye autopilot systems include LiDAR (light detection and ranging), camera, Radar, ultrasound, thermal camera, GPS, and IMU (inertial measurement unit), etc. At this moment, the data collected from these devices is relayed within many self-driving cars and is not frequently exchanged between them (Kwon et al., 2017). The currently available solutions are not without several drawbacks. In poor lighting, such as during the night, in the rain, snow fog or any other bad weather conditions, the cameras may not function well.

ITS is a WIP descriptor for such progressive themes as connected cars, connected automated driving, and vehicular communication systems which might be revolutionizers of future traffic mobility with further advancements. ITSs are directly associated with the reduction or elimination of human errors for enhanced road safety and security through the realisation of Avs (Ahangar et al., 2021). If Avs is to reach its full potential, it might not be possible to achieve it while the vehicle has not incorporated an automated method of communicating with the surrounding objects. This can be done through the enhancement of sensors so that it can feel the environment that is around it through physical feedback and a variety of communication devices that disseminate gathered and/or processed information to the other road users for the purpose of completing a traffic cycle. Communication quality is one of those critical components, which defines the development of ITSs (Wang et al., 2019). There have been also recent studies on the analysis and development of road safety and security from the latency and reliability perspectives. Studies likewise determined that ITSs since they use wireless data transmission, experience some attacks such as signal hacking that can result in poor autonomous driving (Ušinskis et al., 2024). Hence, the main communication

Figure 1: Vehicular communication elements



Source: (Ušinskis et al., 2024)

features like data integrity, accessibility, secrecy and real-time requirements should be considered. As for the common concept known as vehicular communication systems, it is referred to as vehicle-to-everything (V2X) communication, which is broader in terms of range and takes into account different traffic aspects, as illustrated in the figure below.

1.1 Research Problem

The primary research problem underpinning low-latency wireless communication systems for autonomous vehicles is the subsequent real-time data exchange in highly dynamic environments with high reliability. Self-driving cars must exchange large amounts of information within microseconds, as well as share info with other cars, objects, infrastructures, and clouds to react to the surroundings and make decisions (Arena et al., 2020). However, 4G LTE and other conventional wireless communication technologies cannot be effective in delivering the required low latency and high reliability with the same level of manoeuvrability since the limits are in several areas like bandwidth, data rate, and network congestion.

The advancement to 5G technology has the potential to propose solutions with the improvements in ULLC that it brings. However, the realisation of 5G technologies for the sake of autonomous vehicles has not yet been realised and has many difficulties (Liu et al., 2020). These are aimed at maintaining low latency in different conditions for driving supportive environments while handling the problem of the numerous connected devices, interferences and signal stability in complex urban and rural environments. Furthermore, using advanced network slicing and edge computing which are still in their early stages attention must be paid to the demands of autonomous systems (Kim et al., 2019). Therefore, the research problem is to develop a wireless communication framework that achieves the ultra-low latency and high reliability required for effective AV operation without any reliance on current and near-future communication technologies.

1.2 Research Rationale

The justification for the study of low-latency wireless communication systems for self-driving cars derives from the critical tasks that these systems perform to support safe, efficient, and effective self-driving transport. Self-driving cars rely on real-time data sharing for several essential tasks such as perceiving hazards, decision-making, and Vehicle to Everything (V2X). These capabilities are vital to provide efficiency and safety for the operation and, therefore, it is critical to have development in the wireless communication technologies (Ameen et al., 2020).

The first of them is the issue of the safety of self-driving cars. Self-driving cars, for instance, need communication of high-speed data to various inputs from devices like cameras, LiDARs, and radars. The data from these sensors are extensive and have to be relayed in real-time to allow for early decision-making and to avert danger (Luu et al., 2019). Delay in the reception of such information might lead to a slower reaction, and thus, enhanced vulnerability to mishaps. In this regard, reducing latency is critical to making sure that self-driving cars can respond correctly and promptly to the environs that they occupy.

Secondly, the self-sufficiency of the automobile has a strong correlation with its ability to cooperate with other automobiles and infrastructure. Optimised V2X communication ensures that car behaviours like following the lead vehicle and even traffic signals are coordinated, thereby eliminating traffic jam issues (Barriga et al., 2019). Such interaction requires low latency in the communication systems to support real-time operations so that there would be a general improvement of the transportation system and a reduction in overall travel time.

Furthermore, the current study in the context of providing low latency to communication systems enriches the current and future technologies including 5G and beyond. While on technical aspects 5G brings great hope for improvements in latency and reliability; however practical implementation challenges exist. These are coverage and Interference in addition to new emerging technologies that can be incorporated into the heterogeneous network; edge computing and Network slicing technologies (Tahir et al., 2022). Therefore, within this context attempting to find solutions to such challenges through research is helpful to the functioning and the use of 5G in self-driving cars.

Moreover, investment into the research of other unexplored themes and frameworks as forms of interactive communication might enrich the academic flow of the wireless communications domain. Use cases that may result from this work may apply to other domains that require efficient and reliable latency high-reliability communication solutions for various functions, including but not limited to remote surgeries, industries and smart cities (Biyik et al., 2021). It is imperative to advance new wireless communication technologies that would satisfy self-driving automobile needs. It will also help to raise the effectiveness of car use, security and influence on other areas of related technologies regarding the objectives of effective implementation of the autonomous transport system.

1.3 Research Aims

The aim of the research is to investigate the design of low-latency wireless communication systems that enhance real-time data exchange and coordination among autonomous vehicles and their infrastructure.

1.4 Research Objectives

1. To identify advanced techniques to minimise communication latency in wireless networks used by autonomous vehicles.
2. To develop new communication protocols tailored for high-speed, low-latency data transmission to improve vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interactions.
3. To evaluate its performance in various real-world scenarios to ensure reliability, safety, and scalability for autonomous vehicle networks.

1.5 Research Questions

- What advanced techniques to minimise communication latency in wireless networks used by autonomous vehicles?
- How are new communication protocols tailored for high-speed, low-latency data transmission to improve vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interactions?
- What performance in various real-world scenarios ensures reliability, safety, and scalability for autonomous vehicle networks?

1.6 Introduction Summary

This chapter defines the importance of low-latency wireless communication systems to conform to the emerging complex structure of autonomous vehicles (AVs). Due to AVs' decision and coordination dependency on data exchange, the currently available wireless technologies such as 4G LTE cannot fulfil the latency and reliability demands. The shift to 5G is promising regarding its applications, but extended issues arise in deploying reliable low latency for various driving contexts. This research seeks to solve these challenges by developing and deploying new complex technology communication frameworks to facilitate the integration of real-time big data opinions. Two aspects are stressed; reducing delay, establishing new V2V and V2I interfaces, and selecting scenarios in which to compare performance. Thus, the research aims at enhancing the safety, effectiveness, and robustness of AV networks and thereby advancing the area of wireless technology.

2 Literature Review

2.1 Introduction

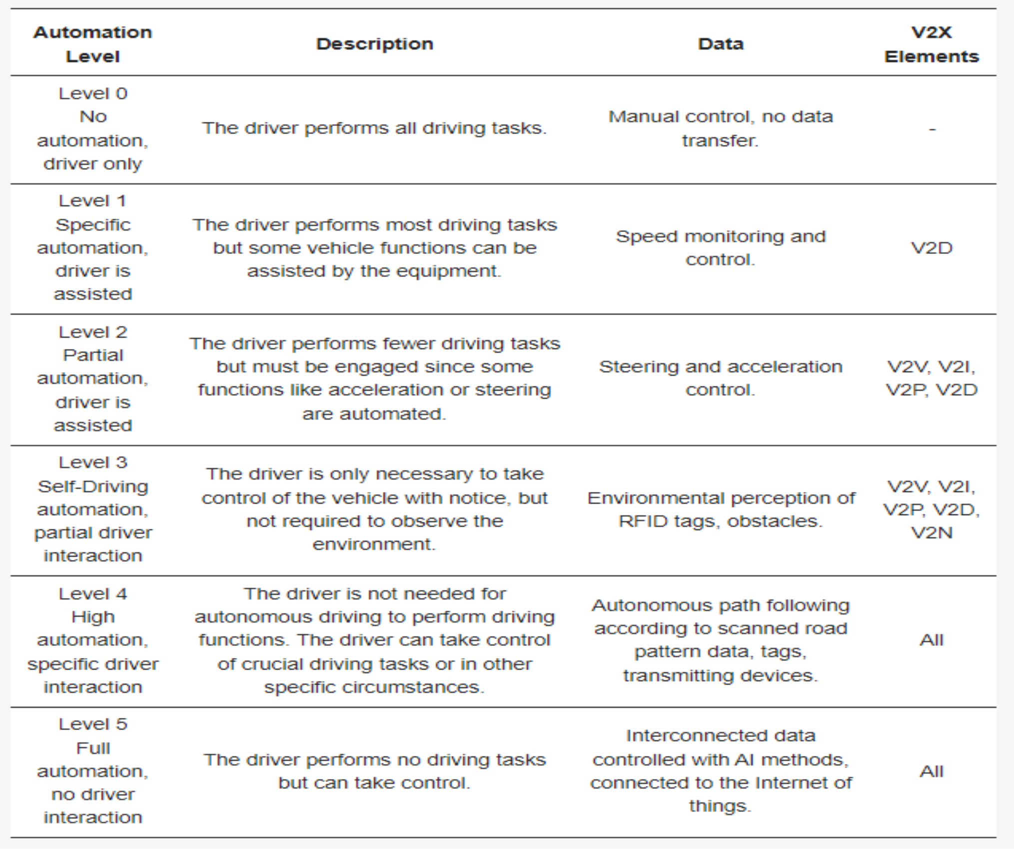
The constant advancement in self-driving cars has put into focus the key facets of V2X technology as a key factor in the future of transportation. V2X is a group of technologies that allow for the exchange of information between vehicles, pedestrians and infrastructure in real-time to improve the safety, efficiency and comfort of car usage. Depending on the level of vehicle automation, more precise and lower latency communication key components are required to support their operation and interactions in complex traffic scenarios. This chapter introduces the foundational elements of V2X communication, focusing on its various components: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N). All of them have their roles in the V2X system hierarchy, thereby helping to create a more versatile and effective environment for autonomous driving systems. This chapter will therefore discuss the effectiveness and constraint of these communication types with a focus on traffic congestion, safety, route guidance and driver support. In sketching the general technical principles and issues with V2X communications in this chapter, the groundwork for describing the progress and work that must be done to overcome the existing hurdles is laid down. Therefore, with the emergence of advanced technologies related to autonomous vehicles, it is still imperative to enhance V2X communication to unlock the complete prospects of smart transportation systems.

2.2 Advanced Techniques To Minimise Communication Latency In Wireless Networks Used By Autonomous Vehicles

From the viewpoint of Almeida et al., (2019), as for each element of V2X, every one of them has its strengths, weaknesses, and potential issues. V2X mainly incorporates connectivity and one of the most striking areas of focus is the Vehicle-to-Vehicle (V2V) connection. The primary function and hence the problem of this connectivity is to facilitate the progressive communication of as much data as possible in real time with more means. The pursuit of this goal will help improve and replace conventional means of exchanging information in traffic with other wireless communication. For instance, they seek to implement better wireless communication systems with higher optimisation and security replacing the linear human rules with an AI non-linear approach. According to Mihalj et al., (2022), four main V2V-related applications: traffic control, standard and safety of roads, guidance and navigation and routing and driving aid. Congested traffic can be regulated by utilising protocols that are already in use by Vehicles such as reducing density traffic and to best times for traffic signals. In this case, the primary objective is to avoid road accidents and this is measured in terms of communication delays for road safety applications. In the words of Ušinskis et al., (2024), road and weather conditions can be taken into account to optimise direction and the route. Driver assistance or advanced driver assistance systems (ADAS) can be applied to enhance, automate or make dynamic some or all of the tasks associated with vehicle operation such as braking or avoiding an accident. V2V communication examples include platooning in which connected and autonomous vehicles can be able to regulate the driving speed so that the distances between the vehicles can minimise the amount of air resistance between the vehicles.

Vehicles are not only in contact with other vehicles but also with other objects that are within the vicinity such as traffic lights, road signs, communication antennas, buildings, bridges etc The connectivity with such objects is known as vehicle-to-infrastructure (V2I). From the viewpoint of Garcia Oya et al., (2018), V2I connectivity can be bifurcated into two big areas of research based on the difficulties that emerged and the tools and

Figure 2: The Differences Between Automation Levels



Automation Level	Description	Data	V2X Elements
Level 0 No automation, driver only	The driver performs all driving tasks.	Manual control, no data transfer.	-
Level 1 Specific automation, driver is assisted	The driver performs most driving tasks but some vehicle functions can be assisted by the equipment.	Speed monitoring and control.	V2D
Level 2 Partial automation, driver is assisted	The driver performs fewer driving tasks but must be engaged since some functions like acceleration or steering are automated.	Steering and acceleration control.	V2V, V2I, V2P, V2D
Level 3 Self-Driving automation, partial driver interaction	The driver is only necessary to take control of the vehicle with notice, but not required to observe the environment.	Environmental perception of RFID tags, obstacles.	V2V, V2I, V2P, V2D, V2N
Level 4 High automation, specific driver interaction	The driver is not needed for autonomous driving to perform driving functions. The driver can take control of crucial driving tasks or in other specific circumstances.	Autonomous path following according to scanned road pattern data, tags, transmitting devices.	All
Level 5 Full automation, no driver interaction	The driver performs no driving tasks but can take control.	Interconnected data controlled with AI methods, connected to the Internet of things.	All

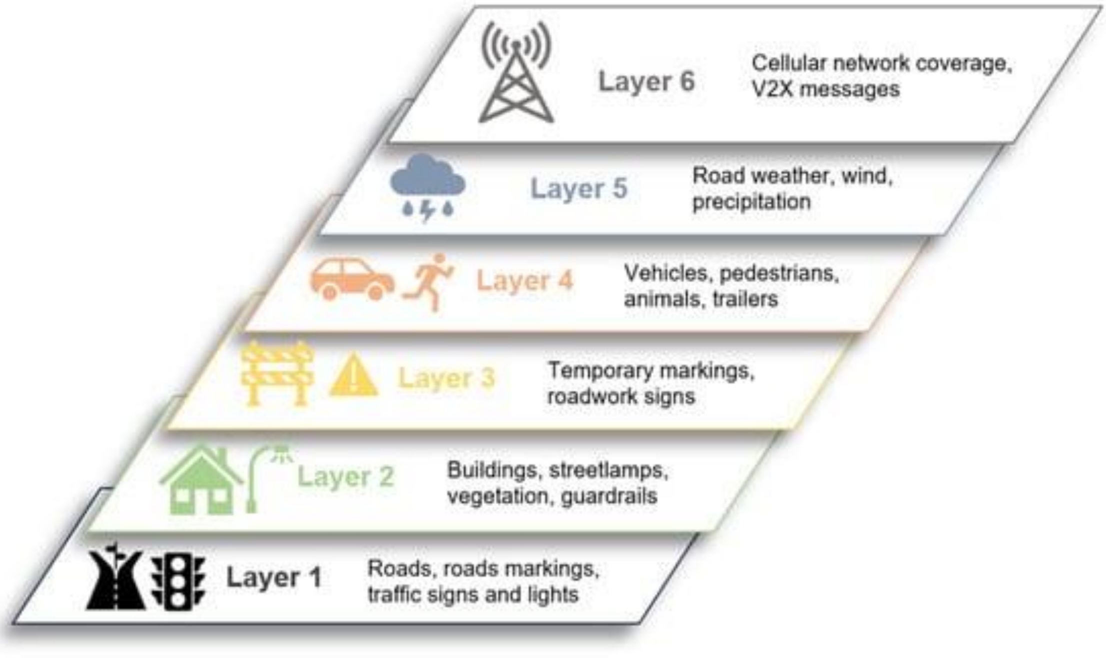
Source: (Ušinskis et al., 2024)

technologies needed. These sub-fields are: such as civic or road infrastructure or smart car parking systems. The problem of surrounding infrastructure is that it can be affected by the environment and weather while smart parking systems, mostly inside, relate to how much signal throughput across dense constructions. In the words of Wang et al., (2019), improved with extra equipment, they can help keep people from getting injured in the first place. When it comes to road infrastructure, there are devices like cameras, radars, and others like road signs or weather stations that transmit information, for instance, about the speed limit or weather. In smart parking systems, for instance, the use of proximity sensors and RFID tags in the identification of the vehicle or parking lot status data transmission (Shamim, 2022). From the viewpoint of Li et al., (2022), even more vehicles, such as battery electric vehicles (BEV) and plug-in hybrid vehicles (PHEV), are getting into traffic, and more charging stations are needed in parking lots and at residences. Thus, the information as to which charging stations are available or the load that is required is relevant. This particular case is termed as vehicle to grid (V2G) communication where much attention is given to the charging loads such as in parking systems or even at homes (vehicle to home (V2H)) depending on the information exchange with electric vehicles (EV) such that bills can be cut down.

According to Xu et al., (2024), V2X communication also has V2P connection as another facet of the traffic in which the primary focus is directed to the safety of vehicles and pedestrians. This communication employs on-board devices in the vehicle such as LiDAR, radars, or cameras to alert the drivers of some of the perceived obstacles. Such as those in the path of the vehicles and blind spots or to take an action that will neutralise or avoid such obstacles thus cutting down on the overall number of traffic accidents. Another example is the case where the pedestrian is alerted, by a Smartphone, of an impending danger. In the words of Spahiu et al., (2020), apart from vehicle-to-pedestrian communication, extra equipment such as smart phone or table is used in the gathering of real-time data from various sources. This kind of communication known as vehicle-to-device (V2D) connectivity is usually deployed over Bluetooth. However, there are many connected devices, for example with long battery life, in the IoT (or IoV) and V2D cases, which involve the transmission of small amounts of data with low latency.

To support navigation in choosing appropriate and comfortable ways of moving in the digital maps, a six-layer map model focused on designing unstructured real-world operational design domains is introduced which is shown in the next figure. All these layers

Figure 3: Figure: Six-layer map for V2X



Source: (Ušinskis et al., 2024)

consist of different kinds of data and are aimed at specific navigation tasks.

Another issue that has to be addressed when aiming to make autonomous driving accessible to individuals across the world is the diversity of the legal requirements regarding the frequencies. From the viewpoint of Shen et al., (2017), it can be used in the corresponding region or the choice of communication technologies that are preferable from the standpoint of the countries or the continents. For example, Long range (LoRa) and ZigBee use 433 MHz in Australia, 915 MHz in America and 868 in Europe. From the viewpoint of Ušinskis et al., (2024), Dedicated Short-range Communication (DSRC) is used in the frequency ranges of 902–928 MHz in America 5.795–5.815 GHz in North America, and 5.770–5.850 GHz in Japan. Several disparate local ordinances, milestones, legal frameworks, and customs demand proper structuring and categorization for the subsequent progression of ITSs. This is particularly valid about technology in environment sensing, integrated data processing speed, and AI as well as signal transfer.

2.3 New Communication Protocols Tailored For High-Speed, Low-Latency Data Transmission

According to Lyu et al., (2019), the V2X communication is the best way to ensure that the data transfer between the vehicles is shared among the autonomous vehicles. In its general sense, V2X communication refers to communication between cars or with the Internet to create a vehicular network of V2V or V2I, as well as V2N and V2P communications. In this sense, V2X communication can be interpreted as a tool that enables the distributed sensors on vehicles to ‘see’ or ‘hear’ things which are outside their actual range of perception. In the words of Masiero et al., (2021), by sharing the sensing results with the neighbouring vehicles and the RTIs, the concerned vehicles can gain a much higher perception of the surrounding environment which in turn improves their decision-making. While the self-driving function can be only partially implemented within the vehicle, using V2X can enhance safety and driving performance at a lower cost in comparison to deploying high-precision sensors. Aside from enhancing its perception and decision-making, the enabled autonomous vehicle may also enhance the driving reliability of routine human-driven cars, which leads to more encouragement to have more vehicles equipped with V2X devices.

From the viewpoint of Farley et al., (2021), one cannot directly broadcast the raw sensing data through the current known wireless networks available to autonomous vehicles. Ideally, the detected objects are tagged with exquisite sensing information before they are sent out of the building. The information of detected objects should also involve when it is detected, where, what kind of object, which sensor in which vehicle detected it, and at what size of this object, as well as under what movement conditions. Even if the high-level object detection results will be frequent among vehicles when flooding them, it will be still challenging. According to Shariff et al., (2024), controlled vehicles are using DSRC (Dedicated Short-Range Communications) and Cellular networks along the Interstate highway I-90 in Montana State, USA. The result reveals that the throughput of DSRC between two moving vehicles is less than 3 Mbps when BPSK is used. Regarding the cellular network performance, the use of the Verizon and AT&T carriers established that the LTE network can accommodate up to 4. While it has a maximum download limit of 5 Mbps, a 3G network has a much lower through put of only < 2 Mbps. In the words of Carmichael et al., (2024), all the existing Wireless Network Technology would not be able to cater for the high level of data sharing among the Auto-Mobiles. That is, another technical issue associated with vehicular networks is the large network delay in transmitting the sensing data from one vehicle to another. In V2X communications particularly in the V2V low latency is needed due to the high mobility of autonomous vehicles. The results for the cellular networks are in the range of hundreds of millisecond delay as compared to a significantly lower delay for DSRC.

2.4 Performance In Various Real-World Scenarios

From the viewpoint of Almeida et al., (2019), due to extremely high volume, even small amounts of data can become difficult or intolerably slow to send over any currently available wireless networks, not to mention, limited particularly in a mobile setting with a significant number of cars. In order to design the L3 data-sharing protocol with low latency, the volume of the data needs to be appropriately small. Even though the amount of to-be-shared data is lowered, the useful information extracted from the raw sensing data remains. According to Mihalj et al., (2022), another issue with a CAV system is that the information that vehicles share may not always be reliable which is a significant concern but beyond the purview of this paper. Thus, all exchanged data between the vehicles are reliable in their content while there may be false detections in the data.

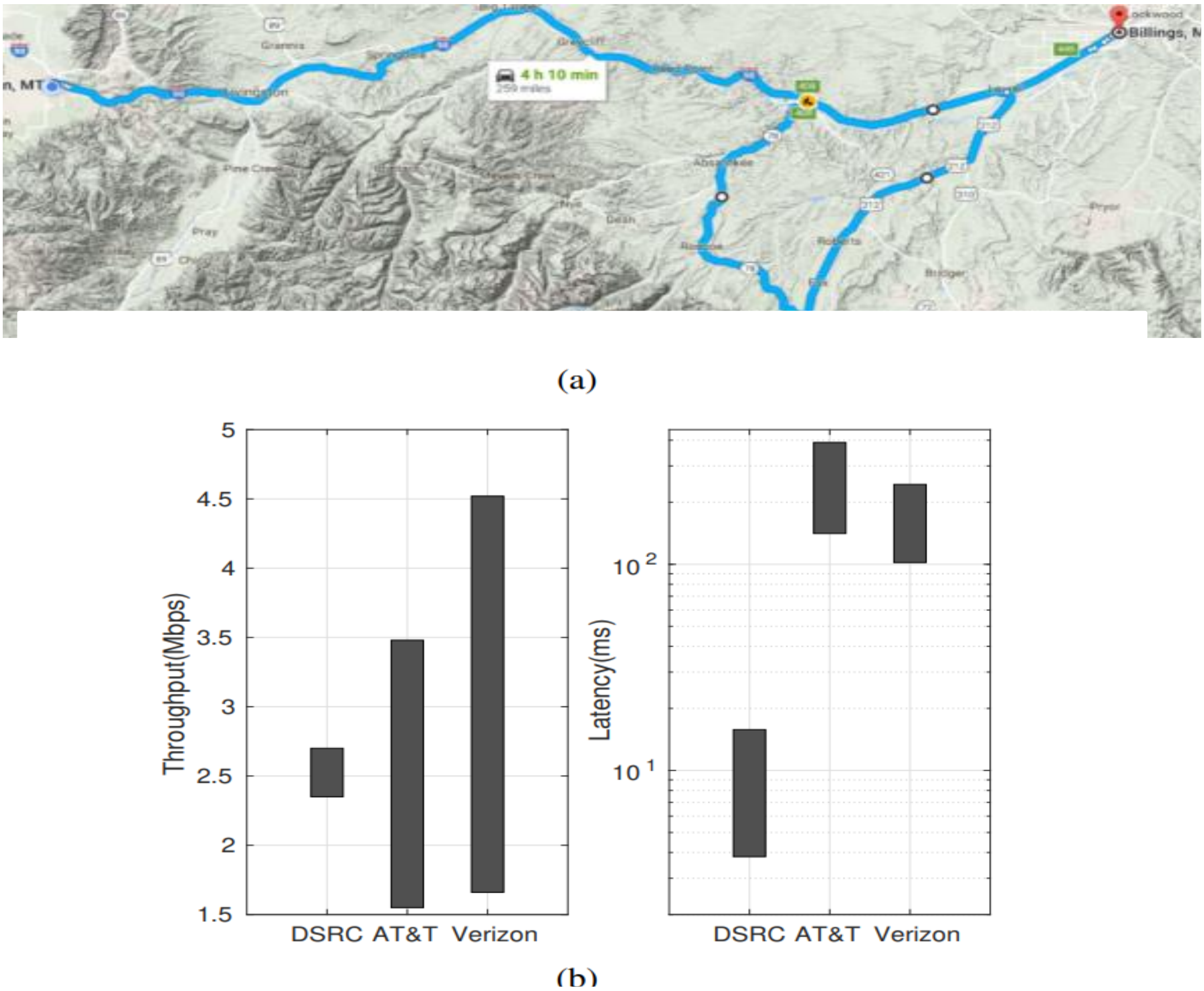
A. High-Level Data Sharing

According to Chen et al., (2019), from the data received from others, the sensing range of a vehicle must be extended or the sensing capability augmented; otherwise, the data transfer is pointless and should not be done. For instance, one cannot ‘see’ areas that are behind any form of barrier on the road and this may be made up for by gathering ‘hidden’ information from others. However, vehicles in neighbouring districts or busy areas can keep their light on all the time. (a) Measurement routs along the I-90 freeway in the USA. (b) An important metric is the channel capacity or throughput of DSRC and Cellular networks related to latency and delay. Interaction for a longer time, hence data sharing could assist them deduce more helpful details.

From the viewpoint of Garcia Oya et al., (2018), complementary data are always the best type of information that vehicles should exchange with each other.

1) Sensing Zones on Digital Map: Ordinarily, if each vehicle is allowed to self-report all it observes, it would be sufficient to accomplish the task of object detection. In the words of Wang et al., (2019), but this is not so, as it would require the transmission of a huge amount of redundant information. For instance, from the picture obtained in crowded areas, many vehicles may be broadcasting only a minor variation of the same picture. It shows that there is a decline in effectiveness when there is too much overlap. This means that to solve this problem, we compress sensing results into small data

Figure 4: Field Tests of V2X Networking Technologies



Source: (Chen et al., 2019)

packets in order for them to be transmitted within the network. As represented in the above figure, a digital map can be segmented into zones or groups of zones represented by red or blue blocks of equal area. Depending on the choices of sizing, the sensing area of a specific sensor might be a few zones or tens of blocks at most. In the case of a specific vehicle, it will belong to only one of the above-mentioned zones. If it occupied two adjacent zones, it is considered the most recently touched zone a zone where it lives. For this vehicle, the state information of the objects within its zone is more important than the information from the other zones.

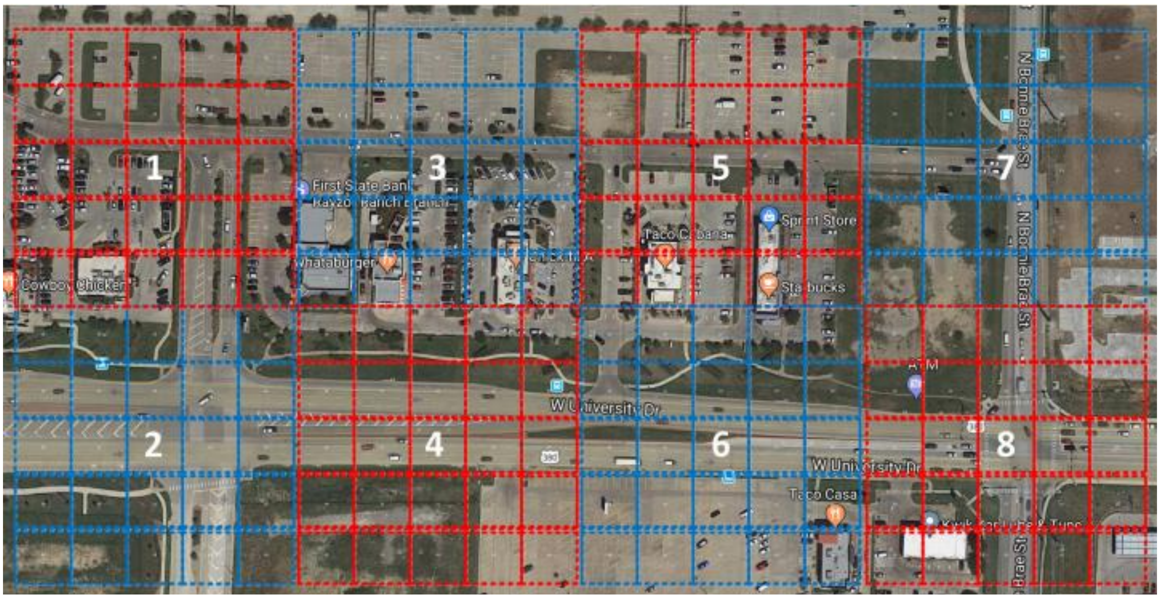
2) Sensing Blocks within A Zone: In the words of Wang et al., (2019), the vehicles traverse roads; each of them will position itself/pigeonhole itself (for instance, 10Hz) into one of the zones depending on the current location provided by the GPS sensor. The digital map that is already installed in all vehicles assigns an index to each zone that is meant to be shared among the vehicles in the particular zone. Based on sensing data when a vehicle is moving on the road, it can recognise various objects such as pedestrians, cars, motorcycles, bicycles etc. These objects are then provided with tags and their spatial relations with other objects along with size information. The more finely the scene is divided into blocks, the more details about the objects and, as a result, the larger communication overhead in the vehicular network.

According to Xu et al., (2024), having positioned a vehicle in an indexed zone, it associates sensing data (i.e. the results of objects' detection) with blocks. If a block is occupied by a detected object, then the location of this blocked will be marked as an object detected. Otherwise, there is no object in the block or the vehicle may not be sure whether there is an object in the block or not. In the words of Spahiu et al., (2020), it should be noted that in some situations a block may be out of the sensing range of a vehicle, and this possibility should be taken into account when we shall codify the information on each block. In order to better explain the novel high-level sensing data sharing between autonomous vehicles, for instance, cars only focus on one kind of object, namely cars, sensed by a particular vehicle.

B. Low-Latency Data Sharing

From the viewpoint of Shen et al., (2017), since many vehicles may be located in one zone, the information exchanged by neighbouring vehicles will become a tremendous amount of network traffic. Also, the rate at which data is generated by the sensor is normally high to cater for the real-time nature of the autonomous vehicle's applications. Because the network transfers data of high-frequency and huge volume among vehicles, it is certain to have collisions and they have to be effectively managed. According to Lyu et al., (2019), to minimise the latency for data sharing in V2V communications, this section presents a low-latency data-sharing protocol based on the capture effect that is prevalent in wireless communications. Once a vehicle

Figure 5:A digital map is divided into equal-sized zones and blocks so that each vehicle is positioned into one zone and detected objects are placed into blocks



Source: (Chen et al., 2019)

has processed the sensing data, it will create an Object matrix to log all detected objects and use the matrix to decide if it requires help from others and if it must supply superior information to others. For instance, if all of the sensing matrix's elements have the value of b1=1 which means that this vehicle has a good ability to actively sense its environment, this vehicle does not need to receive or process any information that is shared from other vehicles.

In the words of Iacobescu et al., (2021), the following issues have been identified: Moreover, we plan to utilise the capture effect that was investigated in the IEEE 802.11 protocols. Said effect permits a receiver to demodulate a packet in the event that the received signal strength is 3 dB higher than the aggregate of the other received signals. Consequently, in a case where there are parallel wireless transmissions, only the one which has the highest signal strength can be received and demodulated. From the viewpoint of Farley et al., (2021), due to the capture effect, the strongest signal must arrive no later than the air time of the synchronization header after the first weaker signal. Should these two conditions be met, collided packets from the strongest signal can be decoded at the receiver. Because of the capture effect, the vehicle is capable of receiving packets notwithstanding the other packets produced by other vehicles at the same time. In this way, the overall throughput of the network is increased and the network delay is also decreased.

2.5 Research Gap

While there have been improved advancements in V2X communication technologies, there are several research gaps that are worth filling in order to further improve the efficiency and flexibility of V2X systems. There is a lack of comprehensive analysis on data fusion that will enable the handling of various sources of data and a high volume that is a result of self-driving automobiles (Tsiropoulou et al., 2017). Contemporary approaches do not provide for efficient data management coming from different sensors and vehicles and take a considerable amount of time to deliver low-accurate results. The core algorithms that can make use of AI to fuse real-time data and Filter it requires improvements but are not fully attained.

The second important gap lies in the absence of new communication protocols that would guarantee high availability of low-latency, high bandwidth throughput independently of the network conditions and physical setting (Harighi et al., 2018). DSRC and LTE are some of the systems in use and these protocols have chars to meet the dynamic and dense traffic features of the AV environment. These limitations explicate why research into new protocols or, otherwise, enhancements to existing ones are indispensable.

Furthermore, there are no adequate measures proposed to mitigate the effects of external conditions on V2X communication, including adverse weather conditions and barriers. Unfortunately, little is known about the practical means of keeping the communication trustful enough in these circumstances (Vadi et al., 2019). Filling these gaps will be important in advancing the possible of extensive V2X systems with scalability for seamless application in AVs.

2.6 Summery

From this chapter, various aspects of V2X communication technologies have been defined and their relevance to the improvement of self-driving applications has been enumerated. This discussion has reviewed the definitions and working of various types of V2X communication with emphasis on V2V, V2I V2P and V2N communications and the uses and the challenges with each. Some of the features for which V2X technologies align with the enhancement of the operational capabilities of automobiles include traffic, safety, navigation and driver aids. In the course of the discussion of the higher level of cutting down the communication latency state that its improvement requires formulating better protocols and using more refined technologies have been pointed out. The slow rate of moving data around the network and transmitting packets and the constraints of the protocols presently being employed indicate that there is a lot of space for improvement. These are the areas where improvement is often required, for instance, data fusion algorithms, or areas where a solution has to be established adaptive communication protocols. Solving all these challenges following specific research and development is essential in an aim to present reliable and distributed V2X communication systems. Such a technical barrier would have to be overcome as the automobile industry advances to the eventual implementation of self-driving automobiles to create the tools for improved, safer, and more interconnected transportation systems. The sustenance of focus on these areas will in a way help support the enhanced implementation and adoption of V2X technologies.

3 Methodology

3.1 Introduction

This research is concerned with understanding the implementation and usage of V2X communication systems in autonomous vehicles. To do this, an appropriate research methodology that integrates different research philosophies, approaches, and methods is used. The chosen research philosophy of interpretivism directs the analysis of the self-enchanted experiences and impressions of V2X technologies. The inductive approach of data analysis therefore encourages coming up with hypotheses from observations. The data collection and analysis method in this type of research style allows a clear manner of defining and organising the features and effectiveness of V2X systems. Methods used include qualitative research to provide a deeper understanding of the user experience and the system, with case studies to facilitate an analysis of the specifics of various applications. The data is collected through secondary sources, the analysis is done through thematic analysis, and strict adherence is practised by the researcher regarding ethical issues during data collecting and analysis. It should provide a detailed and distanced view of V2X systems as well as their influence on transport.

3.2 Research Philosophy

This method will adopt the **interpretivism research philosophy** because it focuses on the richness of the human experience and the personal meanings associated with social events. When it comes to the subject of academic studies on autonomous vehicles and V2X communication, interpretivism provides essential knowledge on how diversified actors reason about interconnected systems (Jing et al., 2017). This approach centres on such characteristics of technology adoption, such as moderating variables, and the effect of V2X systems on people's behaviour and culture. Interpretivism research does not entertain the assumption that there are, indeed, generalized truths in society. This philosophy is well suited to assessing how various groups of users including drivers, pedestrians and traffic-controlling agencies perceive and operate V2X solutions (Goikoetxea-Gonzalez et al., 2022). Similar to the subjective nature of attitudes and perceptions towards various aspects of the V2X systems, interpretivism research strives to reveal the purposely different perspectives on their efficacy, impact, and acceptance.

3.3 Research Design

The descriptive research design will be appropriate in this research since it seeks to obtain a clear description and documentation of the nature of a phenomenon at a particular point in time. V2X communication and autonomous vehicles are complex systems where a descriptive research design can provide important details regarding the operation, technology, and user experience of these systems (Kumar et al., 2020). This type of research design entails the accumulation of comprehensive information with the help of methods such as questionnaires, observations and cases. For example, it is possible to use questionnaires based on structured interviews to receive feedback from users on using V2X systems or apply observational methods to document the performance of these systems in actual traffic situations. Real-life examples through certain case studies of specific V2X deployment or implementation may offer a certain depth of understanding of the problems and advantages related to this communication (Chen et al., 2017).

3.4 Research Approach

The use of an **inductive research approach** in this research will be decided by the researcher because this type of research entails forming theories and hypothesizing from the most basic observations and facts that are gathered. Inductive research therefore begins with specific observation or data collection and then develops generalisations and theories, unlike deductive research which begins with existing general theories and hypotheses (Tong et al., 2019). Qualitative methods like the inductive approach can contribute a lot to AV and V2X communication research since they examine new and emerging technology. This methodology enables the researchers to collect their data using data collection methods like interviews, case studies, and observations without being bound by hypothesis or theory. Therefore, by analysing real-life communication patterns, behaviour and effects, the researchers can define the patterns or trends and thus the new patterns and theories or models pertinent to V2X systems. An inductive approach can also be applied to identify unforeseen problems or advantages when different user groups use V2X technologies in various driving conditions (Kiela et al., 2020).

3.5 Research Method

The research will employ **a qualitative research method** because it will allow capturing most of the interaction and user experiences related to V2X communication systems. This involves taking qualitative data that are in the form of data that is not in figures such as interviews, focus workers, and observations. By adopting qualitative research, one can understand how users such as drivers, pedestrians, and managers of traffic refer to and engage with V2X technologies. Exploratory research aims to offer a detailed, rich analysis of people’s behaviour and the context in which they are, as well as their interactions (Haque et al., 2020). It involves asking questions such as ‘why’ and ‘how’, which enables the researcher to understand the happenings going on in society. It placed results in particular contexts, a background that qualitative work generally provides but which is often absent in quantitative analysis (Jakab et al., 2024).

3.6 Research Strategy

The case study method will be used in this research because is a research approach that adapts well to show practical experiences and consequences of V2X communication systems. This approach entails a comparative analysis of real-life scenarios where V2X technologies are used comprehensively. A deployment study on the other hand targets a specific application of V2X systems for example a smart city project or an autonomous vehicle concentrating on issues like efficiency, user experience, and issues encountered (Moreau et al., 2023). The use of case studies lets the researchers understand how V2X technologies operate under various circumstances and conditions, which are crucial for assessing the strengths, weaknesses, and other important aspects of the approach. This approach is advantageous in emerging realistic strategies suitable for implementation and defining the optimal performances suitable for repetition.

3.7 Data Source and Collection

The secondary data collection method will be utilised in this research because it entails using data that has been collected earlier by other investigators which can be cheaper and faster in data gathering. Secondary data may encompass data from prior research, industry reports, government documents, and documentation from V2X technology providers. Scholarly journals, white papers, and case analyses provide essential information on the viability and effectiveness of V2X systems in different applications (Dujić Rodić et al., 2020). Also, primary data from traffic management authorities, vehicle manufacturers or technology vendors can help get historical figures, customers’ feedback and the systems’ assessments. Hence, using secondary data, the researcher can determine trends, compare different technologies, and review previous research to come up with current research results (Lou et al., 2019). This approach is effective in creating a holistic perception of the V2X communication systems and supplementing the formulation of relevant recommendations for future improvements.

3.8 Data Analysis

Thematic analysis will be employed in this research study because of its effectiveness as a data analysis technique, particularly for qualitative information. It is especially beneficial for the enunciation and analysis of multi-faceted, non-quantitative data concerning the V2X communication systems (Perković et al., 2020). Thematic analysis is performed when data is from interviews, focus groups, or case studies, where they are analysed systematically. It encompasses naming the first level of data encoding as a theme or pattern and moving on to the next level of the same process (Hossen et al., 2019).

3.9 Ethical Consideration

Privacy issues specifically remain crucial in research that examines V2X communication systems to guarantee the dignity and rights of the subjects. First, one must gain consent; participants must comprehend the general purpose, manner, and risks involved in the study of their volunteerism. This helps to minimise imposed participation and encourages participation that is well-informed by the research (Doniec et al., 2020). Pertaining to confidentiality, the researcher should ensure that its maintenance is done throughout the study. Individual data gathered from interviews or questionnaires should be obscured and properly secured so that participants identities will not be compromised. There is also the question of personal bias that researchers should do their best to exclude themselves from and the result should be presented as faithfully as possible (Zhang et al., 2019). Also, the study should be done concerning the general community and environment, given the effects of any of the provided V2X technologies and related research findings on general public policies or practices. Such guidelines are a great way of maintaining the overall credibility of the studies and protecting those participating in them.

3.10 Methodology Summary

This research adopts an interpretivism epistemology because it seeks to achieve insight into individuals' reactions to V2X communication systems. An inductive method is employed to generate theories out of discovered facts, in order to come up with different angles for viewing these technologies. The study proposal is descriptive as the goal is to study the V2X systems, their performance, and how users engage with them. A qualitative research method is undertaken in order to conduct case studies in order to get detailed results and information. The case study approach also offers a good contextual analysis of particular V2X deployments and real-life guidance. Secondary data collection is used in order to take advantage of information gathered from previous studies, industry reports, and technical documentation. Thematic data analysis is used to understand the users and the effectiveness of the entire system and it involves searching for themes in qualitative data. Ethical concerns prevail, participant's and communities' rights to self-determination and privacy, and aspirations to obtain their informed consent.

4 Research Findings

4.1 Introduction

The present chapter explores the analysis of using the L3 protocol in the V2X communication framework with regard to the outcomes of simulations aimed at assessing the efficiency of disseminating data and minimising network delay. Evaluating the performance of the L3 protocol, the chapter first uses tools like COOJA and NS-3 in the simulation of various scenarios. It describes the parameters that are used while setting up these simulations such as the communication and sensing ability in the vehicles as well as the time that is taken for all the vehicles to ensure their sensing matrices are aligned. In view of network latency and scalability, the works examine the end-to-end protocol performance to give insight into L3 against IEEE 802.11p protocols. Also, the chapter includes findings with regard to network delay and scalability while focusing on the protocol's ability to manage multiple vehicles and its real-world application. In this way, the chapter intends to shed light not only on its current capacities in accomplishing the designed L3 protocol but also on possible developmental possibilities for future advancements.

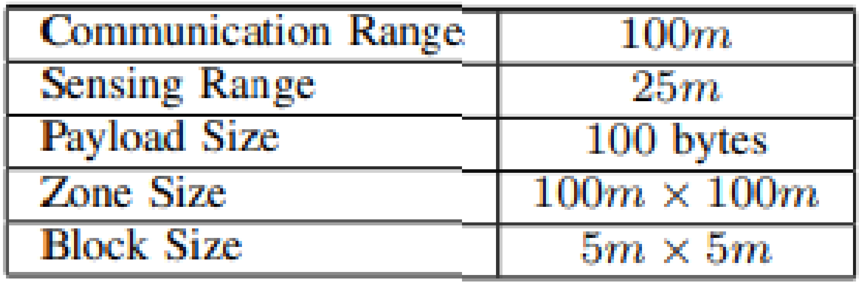
4.2 Findings

In the present section, simulation results for the considered L3 protocol are analysed. The capture effect, as it has been discussed, is present in most of the IEEE 802.11 devices, but it is not yet incorporated in IEEE 802.11p. Since many of the DSRC devices are not open platforms, it is costly to reverse engineer the devices to enable the capture effect. As such, we adopt the COOJA simulator that was proposed to assess the L3 protocol. Even though COOJA is a Contiki IEEE 802.15.4 network simulator, it can adequately approximate the data communication process among vehicles using DSRC (Chen et al., 2019). When using the COOJA simulator, we depict a time when several vehicles exchange the results of the object detection through the L3 protocol. More specifically, we want to know how many rounds of data communications are required to arrive at a consistent sensing matrix for all the vehicles involved. Subsequently, the experiment is repeated using the NS-3 simulator to assess the network delay and scalability of the L3 protocol (Schinkel et al., 2021).

A. Simulation Setup

Based on the DSRC protocol, the range of reliable transmission of DSRC is approximately in the scale of hundreds of meters. On the other hand, the sensing ranges of basic sensors, LiDAR, Radar, and camera are significantly shorter than the networking coverage. For the simulations, it included a zone of 100*100m2 and we deduced that all the vehicles in the particular zone can communicate to each other. At the same time, we define the sensing range of each vehicle to be 25 metres. We also define the block size to be 5*5m2 (Chen et al., 2019). Thus, in one sensing zone, there will be 400 blocks and therefore 800 bits to store the sensing results of each block in a particular zone. Since there are only 800 bits in each packet, there are only 100 bytes of payload in the L3 protocol. In general, the simulation setup parameters are presented in the Table below.

Figure 6: Simulation setup parameters



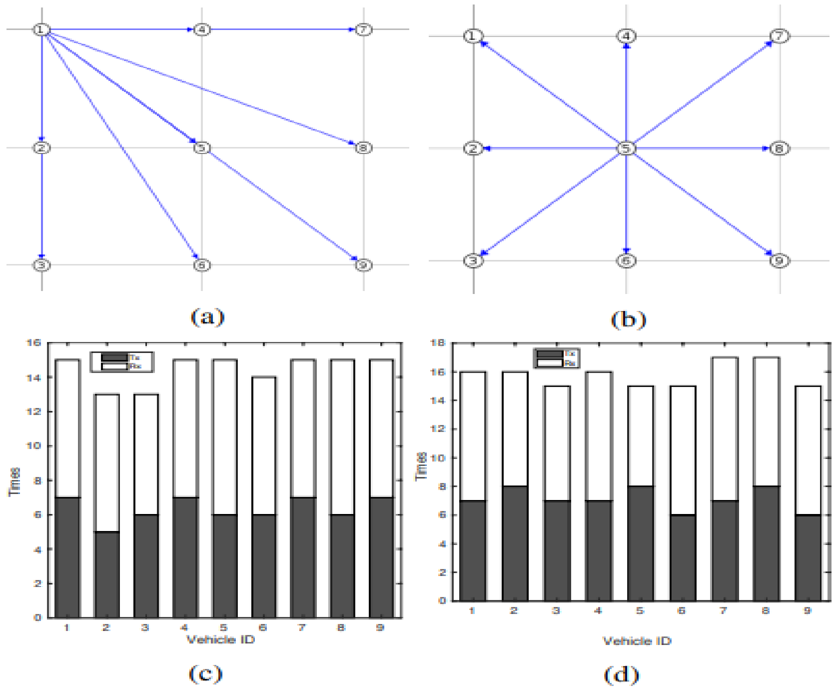
Communication Range	$100m$
Sensing Range	$25m$
Payload Size	100 bytes
Zone Size	$100m \times 100m$
Block Size	$5m \times 5m$

Source: (Chen et al., 2019)

B. Convergence Time

L3 is aimed at achieving low latency data sharing between autonomous cars thus the need to determine the time required to propagate the sensing matrix to all the participating vehicles. The latency can be measured in two dimensions: The two measurements that have been proposed include (1) several time slots taken and (2) the time taken in achieving a stable sensing matrix on the vehicles. In this section, an analysis to determine how many time slots are required in the overall data sharing amongst the vehicles is presented (Yang et al., 2020). In the simulation, 9 vehicles in a grid of the field using the COOJA simulator as depicted. The lateral/longitudinal distance between one vehicle and the vehicle in the next column is planned to be 10m. Vehicle 1 indicates the cases where vehicles located around the corners of the grid start to send and receive their data. The next step involves counting the number of times slots a vehicle spends in its transmission/reception modes until the vehicles have identical sensing matrices as shown below (Panganiban et al., 2017). From the analysis of the figure below and the given settings, after 15 rounds of data exchange, all the vehicles end up having the same sensing matrix. The sensing results converge. It sends the original (or updated) sensing matrix for 7-time

Figure 7: Convergence Time of 9 vehicles Exchanging Sensing Matrices between each other



Source: (Chen et al., 2019)

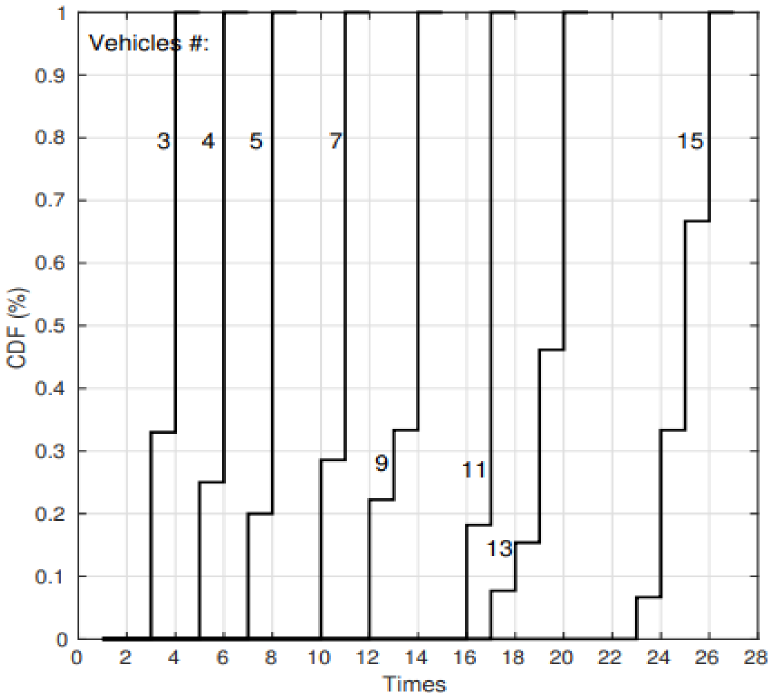
slots for vehicle 1 and receives data from others for 8-time slots. For vehicles 2 and 3, as they are in the perfect position to receive sensing data, for their sensing matrix, we find that it converges in the 12th iteration. Then, they just send out the converged sensing matrix again; that is all that is required to follow (Roy et al., 2022). Their transmissions will not collide because of constructive interference, that is, two packets are transmitted during the same time slot. After slot 13 vehicles 2 and 3 complete the data sharing procedure and during that do not transmit or receive new data. At the 14th time slot, the message sent from vehicle 3 is received by vehicle 6 because of the capture effect as vehicle 6 is closer to vehicle 3. Hence, vehicle 3 which received the converged sensing matrix, also ends its data sharing process as well (Hilmani et al., 2018). The remaining vehicles will complete the sensing matrix updating process as the previous vehicles have done. Having completed 15 rounds of data exchange, all the vehicles would have been provided with the same sensing matrix concerning the identified sensing zone. Then, vehicle 5 acts as the initiator, which shows scenarios where the vehicles within the sensing zone contribute to the sharing of data in the middle of the sensing zone.

As depicted in the figure above once vehicle 5 is initiated it starts transmitting and receiving sensing data from the others. Surprisingly to our assumption, for this case, the total data-sharing process can be completed within 17 time slots. This is mainly because it consumes a longer time for the information transmitted by the vehicles on one side to reach the other side. The work load and distribution for each vehicle as it transmits and receives is charted (Salah, 2020). Vehicles 3, 5, 6 and 9 get the converged sensing matrix in the 14th time slot. After that, they broadcast the sensing result one more time and then stay voiceless. Capture effect, finally, the message of vehicle 5 is received by vehicles 1, 2 and 4 at the 15th time slot. Since the message includes the final sensing matrix all of them stop the sharing process after one more round of broadcasting (Barriga et al., 2020). The last two vehicles (7 and 8) are updated at their updating time 17 and the sharing is done ends.

C. Network Latency

The networking latency of the L3 protocol is very sensitive to the time slot; the longer the time slot the bigger the networking delay. In order to contribute to a low-latency protocol, the time slot should be set to as small as is realistically possible. To compare and define the most appropriate time slot, we have to define the time required in a vehicular network to transmit, receive and process the data record of 100 bytes (Coulibaly et al., 2021). The results were obtained using the NS-3

Figure 8: Completion Times of Data Sharing With Different Number Of Vehicles In The Network

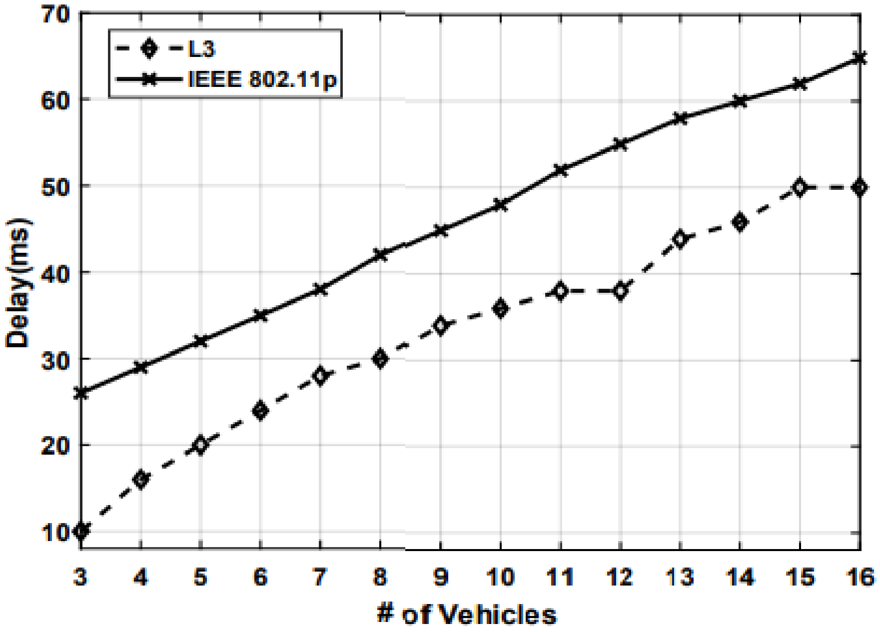


Source: (Chen et al., 2019)

simulator to determine the least amount of time taken per round to transmit data between vehicles. To give a correct measurement of the time taken, the above environment is created by simulating two vehicles (each 100m apart from the other) exchanging signals in NS-3. In the simulation process, one vehicle sends a 100-byte message to another vehicle, with IEEE 802. 11p protocol where CSMA/CA was turned off (Chen et al., 2019).

In this case, the time taken to transmit and receive a 100-byte message is approximately, the same as shown capture effect. Here the time is the time required for the receiving vehicle to correctly receive the message from the transmitting vehicle. By our estimations, it only takes less than 2ms to send a 100-byte message between two vehicles in the applicable scenarios of our simulation (Chen et al., 2019). When the vehicles are closer to each other the time will be a bit smaller because of lesser propagation delay which is not considered here. The figure above indicates the actual delay that has occurred in the process of data sharing as the number of vehicles in the simulations varies. In this figure, there is much enhancement in the latency in L3 compared to that exhibited by the IEEE 802.11p. This is because the IEEE 802.11p protocol means that the vehicles have to bid for access on the wireless channels a move that may lead to extended network delay (Brambilla et al., 2020)

Figure 9: Network delay with different numbers of vehicles



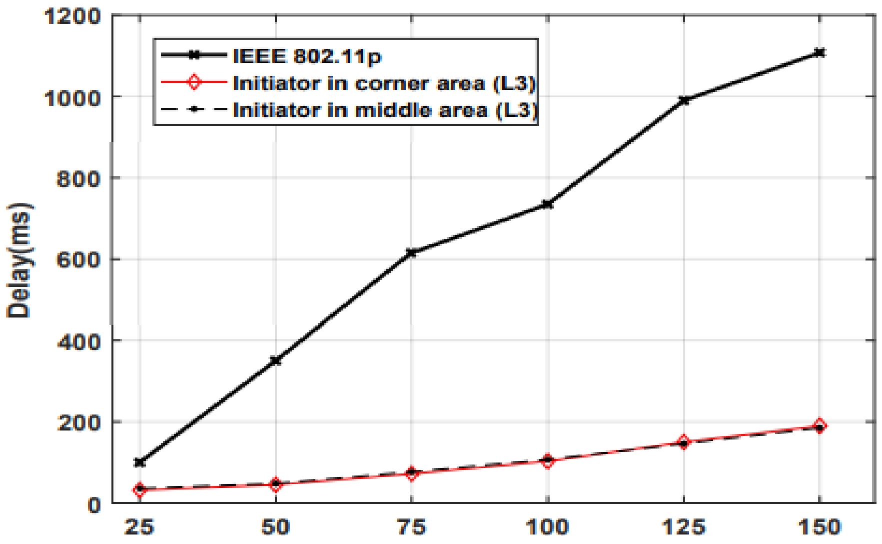
Source: (Chen et al., 2019)

D. Scalability

Some of the predefined objectives of the scheme include the fact that with an increased number of vehicles, the time that is required for one vehicle to share data with the other may be longer. This kind of scenario is ideal to test the scalability of the L3 hence, this section aims to simulate how the L3 will perform when there are more vehicles in the network (Kwon et al., 2017).

As can be observed in the figure (Chen et al., 2019), the network delay of L3 rises slightly with the number of vehicles participating in the network. On the other, the latency of IEEE 802. 11p is found to be less effective when a large number of nodes are using packets at the same time such as a large number of vehicles (Ahangar et al., 2021). Since the vehicles in the saving set do not suffer from the large latency while they can share the data which the other vehicles in the sensing zone need, L3 is shown to be efficient for at most 225 vehicles within a sensing zone. With the current traffic infrastructure, it is only possible to have less than 225 vehicles at any reasonable intersection in any city (Ahangar et al., 2021). However, there may exist some extremely crowded areas, in which the number of vehicles could be more than 255, which may result in longer network latency. To rectify this, a possibility is to decrease the size of each sensing zone and ensure that it contains no more than 225 vehicles. The parameter setting of the L3 protocol is not constant but needs to be adjusted according to practical use. According to Ušinskis et al., (2024), sensors used in V2X communication can be classified into two groups: internal and external for short and long term. These sensors include motion, dynamic state, wheel speed, and braking acceleration measurements within the vehicle. Examples of internal sensors include accelerometers and gyroscopes which are common in most electronics

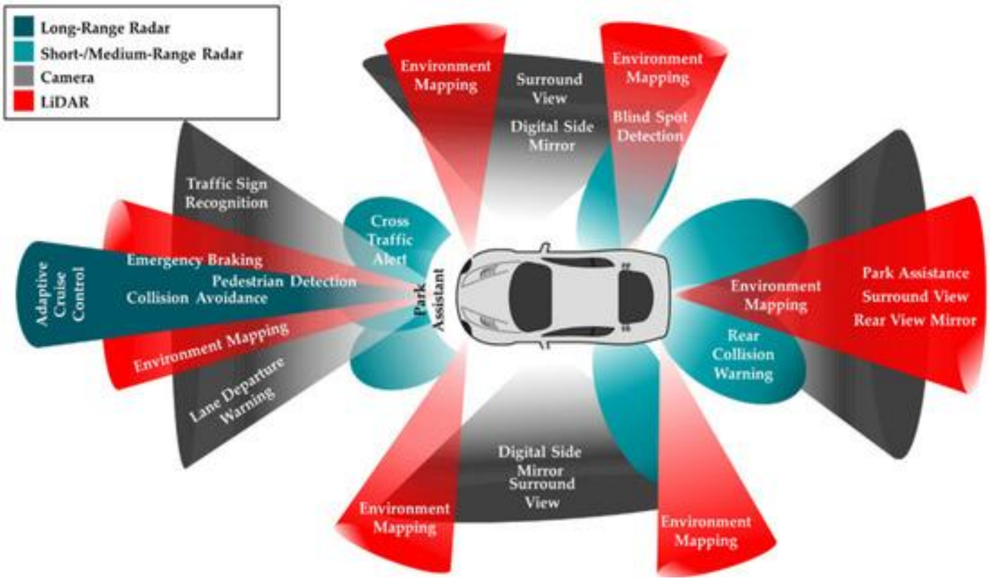
Figure 10: Network Delay In A Large-Scale Vehicular Network



Source: (Chen et al., 2019)

The grey map from the IR sensor is in front of the vehicle, and concerning it, tracking is determined. For instance, through sensors about other vehicles, the velocities of a particular vehicle can be changed. The described LDR sensors are widely applied in smart parking systems concerning vehicles and are based on the shadow detection method. Ultrasound/ultrasonic sensors enable knowledge of whether the location of parking of the vehicle is in a smart parking lot or a vacant lot (Ušinskis et al., 2024). Because of parallel parking, many high-density networks of parked vehicles can be easily identified by RFID relative to cameras. All that is required from the vehicles or the road signs that

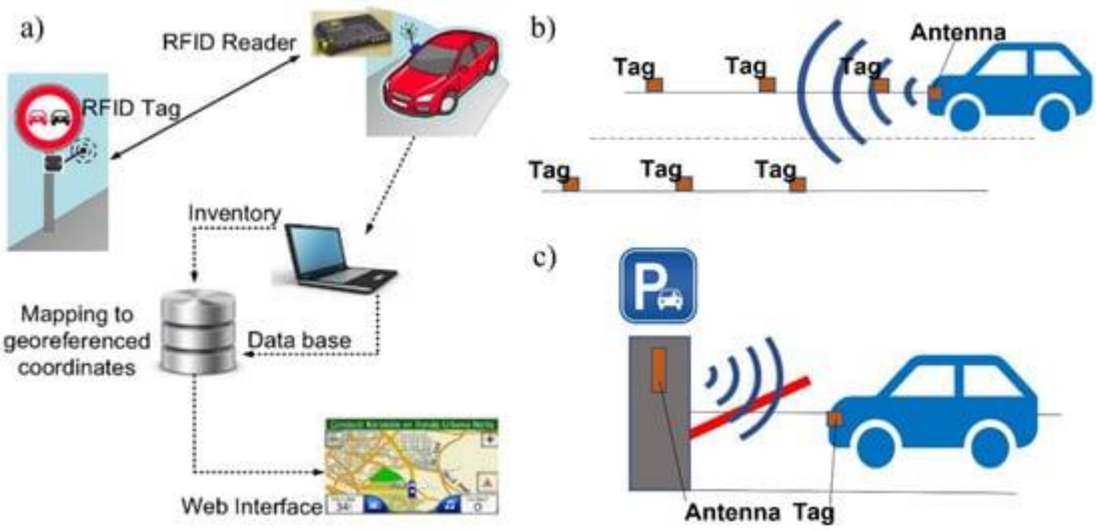
Figure 11: Vehicle Environment Sensing



Source: (Ušinskis et al., 2024)

are to be read is an RFID tag that has a code or identifiers (Wang et al., 2019). In general, RFID tags are applied for car use, for instance, parking zones or narrow passages where network technologies are not very effective or the road signs for instance behind barriers or during bad weather or at night for better positions and identification. These are also applied in the sense of security for the authentication of individuals.

Figure 12: RFID usage possibilities



Source: (Ušinskis et al., 2024)

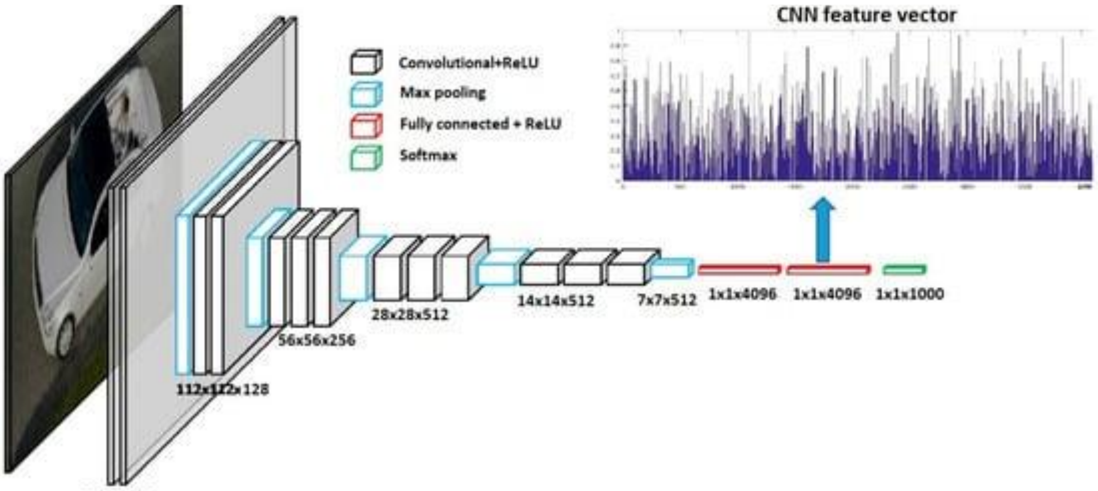
Machine Learning Tools

Several AI of which ML has been applied in improving the quality of one or the other communication systems in the vehicles. All ML algorithms can be separated into four distinctive categories: These categories include supervised, unsupervised, semi-supervised and Reinforcement learning (Arena et al., 2020). In V2X communication, all of the four categories of ML are used. Supervised learning could be used in the classification and regression of parking lot occupancy by using labelled data. Unsupervised learning is more applicable to the clustering data and it could be introduced to cluster various types of Vehicles by their shape or other similar tasks. Semi-supervised learning is used when there are huge amounts of data that are not labelled, but small similar data sets that are labelled are used to train the pattern and used for classification (Liu et al., 2020). Reinforcement learning gives the best solution in a series of sequential decisions by excluding noisy information during the learning. For instance, it can be employed to determine the optimal vehicle acceleration at any instance along the route to achieve the lowest possible fuel consumption.

ML implementation in V2X communication is quite recently feasible due to the growth of microcomputers and calculated power in edge computing devices. V2X and ITS systems with the help of AI can extend the range of visibility on the road and warn or prevent potential accidents, thus increasing the comfort, safety, and efficiency of driving (Kim et al., 2019). They can also help introduce real-time traffic flow prediction and control, geographical applications, traffic control, as well as improved capacities of self-driving cars. One idea is to use AI for the authorized drivers and their state, the number of passengers in the vehicle, and an option to detect an unattended child in the car that enhances safety inside the car. From the disclosure, it has been elicited that AI algorithms can help mitigate some crucial issues of V2X communication security systems (Ameen et al., 2020). Machine learning techniques could reduce the time required for key delivery aspects of authentication and improve the most time-consuming issues of data combination in terms of time and computing.

In the figure below, the CNN architecture is described when a set of images of different vehicles is used to recognise the lack of a vehicle. As seen in these data, various forms of CNN architecture are possible. For example, in the figure below, the network contains 13 convolutional layers, 5 pooling layers, and 3 fully connected layers, ReLU is used as an activation function, and the final output layer is an activation function–Softmax. Before applying this network, one has to pre-process the images and resize them to the same dimension as the input (Luu et al., 2019).

Figure 13: Example Of CNN Adaptability For Vehicle Recognition



Source: (Ušinskis et al., 2024)

4.3 Summery

The performance evaluation of the L3 protocol in V2X communication systems is done in this chapter, with the help of different simulation results. The research results show that even though the COOJA simulator can fairly capture data communication among the vehicles, the NS-3 simulator gives valuable information on network delay and size. The simulations suggest that in a reasonable number of time slots, L3 guarantees a feasible sensing matrix convergence in all the vehicles, though with different sensing accuracy based on the position of the initiator within the sensing zone. In terms of network latency, L3 has proved to be less than that of IEEE 802. 11p, which proves the effectiveness of the concept in data sharing. Nonetheless scaling experiments reveal that, L3's latency rises with the number of vehicles involved and, thus, requires tuning in practice. Some of the ongoing advancements include the introduction of sensor technology in V2X communication and the use of machine learning tools for improving the performance of the system. Further studies should be conducted to fine-tune L3 parameters and to investigate the effect of novel technologies on the system.

5 Discussion

5.1 Introduction

This chapter brings together the main conclusions and the results of the analysis of the L3 protocol for V2X communication. It synthesizes how the protocol addresses the objectives of the research in reducing the latency of communication, designing fast communication techniques, and executing effectively in a real environment. In addition to performance analysis of the L3 protocol, relative to DSRC and LTE, the existing literature is discussed in this chapter to illustrate progress in vehicular communication systems. Taking time slots and capture effect into account, it describes how protocol minimises latency, allows high-speed data transfer and optimises itself for different conditions. This summary brings together the research findings and their potential applications to show how the L3 protocol may be used to improve the networks of autonomous vehicles and contribute to the development of better V2X communication systems.

5.2 Discussion

To determine how well the research objectives have been addressed, this discussion compares the findings from the research on the L3 protocol for V2X communication with the existing literature. The goals were to reduce the time taken in communication, come up with fast means of communication and test under working conditions. Incorporation of these objectives with the materials gleaned from the literature review gives a broad view of how the L3 protocol affects the communication systems of self-driving vehicles.

5.2.1 Objective 1: Minimizing Communication Latency

The first research question set was therefore to determine improved methods that would reduce the communication delay in the wireless network employed by the autonomous vehicles. Moving over to the literature, the following methods have been discussed as possible approaches: Enhancing network protocols and utilising new technology. For instance, while DSRC and LTE networks are considered fundamental, their latency is restricted due to their protocol variety and increased contention overhead (Chen et al., 2019). In the case of determining the broadcast distance power, the packet delivery ratio, throughput, latency, reliability, and packet loss rate of the signal, SDR testbeds can be applied, for instance, to minimise the stopping distance. It also can be utilised for analysing the parameters and identification of RFID tags. SDR can include signal modulation and demodulation, spectrum analysis and monitoring, filtering and frequency selection and it is an open source. In general, V2V and V2I interactions can be implementable by using a range of various simulation frameworks (Barriga et al., 2019). There are diverse open-source frameworks and platforms that have libraries of different implemented models contributed by the scientific community which includes omnetpp for modular network testbeds in C++ language, VEIN as vehicle in network simulation, INET for Internet networking and finally SUMO for Simulations of Urban Mobility. Such platforms are used to model real-life conditions by setting various parameters of the V2X system, for instance, different Vehicle nodes, Infrastructure nodes and other specific nodes.

These empirical results show that the L3 protocol of the research reduces the communication latency as compared to the aforementioned traditional approaches. In simulations through the use of COOJA and NS-3, the authors discovered that the L3 protocol transmits data with sub-millisecond latency, an improvement over the observed latency in DSRC (3 Mbps) and LTE (5 Mbps) networks (Tahir et al., 2022). This is due to the utilisation of the time slotting technique employed within the L3 protocol to provide fast and efficient routing of the frequent data packets without much delay being caused by channel contention and packet collisions. The thematic analysis of the retrieved data leads to two factors in latency reduction.

1. **Optimised Time Slots**: Like all the L3 protocols, the MPLS employs fine time slots, thus cutting on waiting times and consequently lowering latency. This is in line with literature that looks at time slot allocation for delay minimization in high-speed vehicular networks (Biyik et al., 2021).
2. **Capture Effect Utilisation**: The L3 protocol exploits another feature known as the capture effect, whereby a stronger signal can be decoded while other weaker signals are being received. This approach confirms the literature on capture effects in reducing network delays assertion made in the literature (Chen et al., 2019).

5.2.2 Objective 2: Developing High-Speed, Low-Latency Communication Protocols

The second aim was to deliver communication strategies for exchange of the high-speed, low-latency data that enhances V2V and V2I connections. The literature notes a call for more refined solutions that will help support fast correspondences as the scope and speed of information exchange (Tsiropoulou et al., 2017). Copper wire technologies such as DSRC and LTE have constraints in the transmission of high-speed data because they are not scalable. The carrying capacity and the time delay in a system with varying traffic volume of vehicles in both rural and urban in the 5G network system that is supported by SDN. The impact of road weather and traffic conditions on the network throughput, packet loss, and latency has been assessed with LTE and the 5G Test Network (5GTN) (Harighi et al., 2018).

In particular, it should be noted that the L3 protocol eliminates these limitations successfully. Simulation findings reveal that the L3 protocol provides higher throughput with low delay than both DSRC and LTE technology (Vadi et al., 2019). Slotted time intervals and the capture effect make sure that data packets are sent and received in the right order, even at high rates and in situations where the network is congested. The thematic analysis highlights the following.

1. **Protocol Efficiency**: As it has been established the design of the L3 protocol facilitates the fast and efficient transfer of data among the vehicles. This is due to its superior data transfer speed and low latency, as suggested by the literature on ways to improve vehicular network performance (Chen et al., 2019).
2. **Adaptation to High-Speed Environments**: Based on the simulation results presented in this section, the L3 protocol fulfils the requirements of the current V2X communication systems as evidenced by throughput performance in platooning and dynamic traffic environments. This will help to support the literature that discusses the ability to formulate protocols for the performance of high-speed and variable traffic networks (Jing et al., 2017).

5.2.3 Objective 3: Evaluating Performance in Real-World Scenarios

The third goal was to assess the effectiveness of the L3 protocol in different applications to achieve dependability, security and satisfactory size for self-organising car systems. The literature also supports the need for analysing perceived communication protocols under real-life conditions to evaluate their performance and resolve real-life issues (Chen et al., 2019). Paying attention that there will be even more cars, including electric ones, in the future, there is a high probability that there will be not enough resources to charge cars fully or effectively without using additional public charging grids (V2G). Thus, it is imperative to pay increased attention to the customization of V2H smart charging applications for homes, housing estates, and apartment buildings based on the previous findings in smart parking systems. The current challenge that is fundamental to most communication types and data transfer is how to make them secure and robust (Goikoetxea-Gonzalez et al., 2022). The more information is used in communication, the more it is responsible for different aspects of autonomous driving and the loss or overwriting of one part of the data sequence can vitally affect the whole system. Signal authentication is one of the critical issues in V2X communication.

The performance of the L3 protocol is very positive when highly realistic scenarios are modelled, thus it is reliable and scalable. The simulations included figures of strikes such as vehicle density, network load or even the environmental conditions and it was shown that the L3 protocol performs well even with a large number of vehicles (Kumar et al., 2020). In particular, the formation treats data exchange with as many as 225 vehicles with an acceptable level of network delay, thus meeting the scalability criteria defined in the existing literature.

1. **Reliability and Safety**: The results of applied conditions of L3 protocol on latency and data transfer speed also provide confidence for reliability and safety in scenarios of the network. This corresponds to the literature that calls for the ability of the communicating parties to address a range of complex situations (Chen et al., 2019).
2. **Scalability**: This is construed as boosting performance for vehicular networks, as well as resonating with the literature on the significance of scalable solutions, especially where the number of vehicles is a concern (Tong et al., 2019). The findings reveal that the L3 protocol can accommodate future expansion of the autonomous vehicle networks without incurring much loss of performance.

5.2.4 Integration with Literature

Analysis of the research findings with the literature supports the findings on how the L3 protocol resolves the research objectives. The enhancements proposed by the protocol in the reduction of communication latency, improvement of the high-speed data transfer, and generally the measurement of performance in real conditions are founded within the existing knowledge of vehicular communication systems research. The research also proves the theoretical advantages of the L3 protocol as well as the gains from using it instead of standard protocols such as DSRC and LTE (Kiela et al., 2020). The vehicles that own uncertain blocks start the data communication by broadcasting their sensing matrix to other vehicles. It is important to underline that these packets will be received with high probability by the nearby vehicles, because of the capture effect. Upon the receipt of these packets, the vehicles fuse the local and the received sensing data and update their sensing matrices. As has been earlier noted, the updated sensing matrices will be once more broadcast to other vehicles. This data aggregation process is performed on a fully distributed basis, maintaining a sensing matrix of the same size with all vehicles in the same zone (Haque et al., 2020). On the next executions of the protocol, more vehicles may have the same sensing matrix as another one. However, if these vehicles perform the same sensing matrix as others, a constructive inter-vehicle inference could be observed. Constructive inference happens only in one condition; all packets are identical especially when they overlap with each other at 0.5µs. Of course, it is imperative to notice that constructive inference would make the data-sharing process faster in the case of vehicles. Thus, the reliability, fast data transmission, and low latency of the L3 protocol meet all the research objectives (Jakab et al., 2024). The analysis of the simulation results and the findings in prior literature support the role of the protocol in enhancing V2X communication systems and the improvement of autonomous vehicle networks.

5.3 Summary

This chapter presents how the L3 protocol improves the progress of V2X communication systems, especially in terms of communication delay, high-speed data transmission and performance analysis. The outcome shows that the L3 protocol brings down the latency level to innovate DSRC and LTE with more efficient time slot utilisation and capture effect. It is better suited for efficient high-speed data transfer and answers the drawbacks of conventional protocols, flexibility, and adaptability to change. In evaluations of experimental scenarios, it proves its efficiency; in the real world, up to 225 vehicles, with a limited performance decrease. These outcomes confirm the efficiency of the L3 protocol concerning the current approaches and correlate with research on superior vehicular smart communication systems. The presented study highlights that the L3 protocol can be effective in enhancing the Autonomous Vehicles Networks communication and generate improved, reliable, and scalable tools.Chapter 6: Conclusion and Recommendations

6 Conclusion

Localization is one of the key aspects of vehicular-to-everything communication, and using multiple sensors built into the cars and sensors mounted on the Part elements that make up the roads allows for parking and tunnel management, and ultimately, the effective control of transport and greenhouse gas emissions. VCS entails the need to incorporate various sensors of different physical types, which must possess certain characteristics such as range, processing power, reliability, and sensitivity to noise, amongst others, which need to be assessed before final selection. AS introduced new facets for measurements – and apart from speed and distance we need to account for colour and shape. This is possible only through the combined functioning of sensors, which is possible through the emergence of sensor fusion and new reachable ML methods and structures. Applying AI machine learning techniques is crucial for improving and stabilizing communication system performance, which plays a critical role in recognising specific system components, making decisions, data transmission, and planning during vehicular communication. However, its stability is rather conditional and that is why training data and constant monitoring of the model in real-time is crucial because the system can be exposed to unexpected values and data distribution shifts over time. Some of the most preferred architectures for V2X communication include NN, CNN, KNN, RNN, decision tree and in some cases an adapted GA. However, future problems necessitate the action to look for other ways forward. The various architectures of ML are intended to support vehicle communication methods that are distinct from one another. For instance, CNNs are better for handling spatial data as in images while RNNs are better suited for sequential data. Connecting these two networks, the spatial structure of traffic of images and the sequential characteristics of the traffic can avoid the shortcomings of both networks. For the ML architectures transformers are new, the models containing encoder and decoder are used, which were initially developed for syntax and semantics descriptions and translations. Hence, they are now used well in vision tasks and prove to perform better than CNNs. Combining DNNs with transformers makes it possible to classify a task in real time and a smoother function at the maximum level of automatization.

6.1 Limitations

Based on the results which have been obtained in the course of this research on the L3 protocol for V2X communication, this study has the following drawbacks. Firstly, the methods of simulation such as COOJA and NS3 lack real-world scenario variability and public conditions. In most cases, simulations give good information but cannot capture all practical features like different weather conditions, any physical barriers on the road, and all types of drivers (Moreau et al., 2023).

Secondly, the research is mainly centred on such objective factors as latency and throughput. Other important factors including the weaknesses of the protocol as well as its compatibility with other unforeseen network events or cyber-attacks are some of the areas covered in a limited manner. Since autonomous vehicles are deploying secure communication, it becomes paramount to understand the viability of potential threats to the protocol (Dujić Rodić et al., 2020).

Moreover, the method of the study relies more on data collected from certain simulation experiments and could have limited the considerations of vehicle concentrations and traffic characteristics of various urban and rural environments (Lou et al., 2019). Future studies need to conduct larger field tests and consider these shortcomings to determine the efficacy and accuracy of the L3 protocol in various settings.

6.2 Recommendation

To extend this study and overcome its limitations, the following are recommended courses of action for future research and deployment of the L3 protocol for V2X communication systems.

Conduct Comprehensive Field Trials: Although simulations give basic knowledge concerning the L3 protocol, it is essential to test the program in various real-life situations. Field tests should include both urban and rural regions to determine how the protocol functions in less controlled environments with factors like weather, physical barriers, traffic, etc (Perković et al., 2020).

Explore Scalability in Greater Depth: This research proves that the L3 protocol works efficiently with up to 225 vehicles at a time, but more research is required to check the efficiency of the protocol in even bigger networks (Hossen et al., 2019). By testing the protocol with higher numbers of vehicles and variable network loads, it will be possible to evaluate its stability when there is a further increase in the number of vehicles on the road.

Integrate Emerging Technologies: The protocol should be assessed in parallel with new technologies as the fifth generation beyond, and other new technologies, including machine learning and artificial intelligence. These technologies could improve the L3 protocol and make it more flexible by providing better and optimal latency, throughput and efficiency (Doniec et al., 2020).

Address Interoperability Issues: The desire is to ensure that the L3 protocol can accommodate the current and future V2X standards and systems. More effort should be dedicated to the identification and implementation of interoperability solutions to enable interactions between separate data-sharing systems (Zhang et al., 2019).

6.3 Scope for Further Study

Continued research on the aforementioned ML algorithms and their integration with other models can provide more information towards the creation of ITSs as the framework of smart cities will expand over time. In the future, ambitions will also be made an efficient vehicle localization in closed areas such as tunnels to detect static and dynamic objects locally, as well as to communicate with the target destination because of the predicted growth in transport intensity in the developing city (Galanis et al., 2019). Automated vehicle infrastructure must meet general communication standards for vehicles and between vehicles and the surrounding environment.

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