Citation: Dhawankar, Piyush Shamroa (2021) Investigation of Vehicle-to-Everything (V2X) Communication for Autonomous Control of Connected Vehicles. Doctoral thesis, Northumbria University.

Investigation of Vehicle-to-Everything (V2X) Communication for Autonomous Control of Connected Vehicles

P S Dhawankar

PhD

2021

Investigation of Vehicle-to-Everything (V2X) Communication for Autonomous Control of Connected Vehicles

Piyush Shamrao
Dhawankar

A thesis submitted in partial fulfilment of the
requirements of the University of
Northumbria at Newcastle for the degree of
Doctor of Philosophy

Research undertaken in the faculty of
Engineering and Environmental Sciences

Northumbria
University
NEWCASTLE

February 2021

Abstract

Autonomous Driving Vehicles (ADVs) has received considerable attention in recent years by academia and industry, bringing about a paradigm shift in Intelligent Transportation Systems (ITS), where vehicles operate in close proximity through wireless communication. It is envisioned as a promising technology for realising efficient and intelligent transportation systems, with potential applications for civilian and military purposes. Vehicular network management for ADVs is challenging as it demands mobility, location awareness, high reliability, and low latency data traffic.

This research aims to develop and implement vehicular communication in conjunction with a driving algorithm for ADVs feedback control system with a specific focus on the safe displacement of vehicle platoon while sensing the surrounding environment, such as detecting road signs and communicate with other road users such as pedestrian, motorbikes, non-motorised vehicles and infrastructure. However, in order to do so, one must investigate crucial aspects related to the available technology, such as driving behaviour, low latency communication requirement, communication standards, and the reliability of such a mechanism to decrease the number of traffic accidents and casualties significantly. To understand the behaviour of wireless communication compared to the theoretical data rates, throughput, and roaming behaviour in a congested indoor line-of-sight heterogeneous environment, we first carried out an experimental study for IEEE 802.11a, 802.11n and 802.11ac standards in a 5 GHz frequency spectrum. We validated the results with an analytical path loss model as it is essential to understand how the client device roams or decides to roam from one Access Point to another and vice-versa. We observed seamless roaming between the tested protocols irrespective of their operational environment (indoor or outdoor); their throughput efficiency and data rate were also improved by 8-12% when configured with Short Guard Interval (SGI) of 400ns compared to the theoretical specification of the tested protocols.

Moreover, we also investigated the Software-Defined Networking (SDN) for vehicular communication and compared it with the traditional network, which is generally incorporated vertically where control and data planes are bundled collectively. The SDN helped gain more flexibility to support multiple core networks for vehicular communication and tackle the potential challenges of network scalability for vehicular applications raised by the ADVs. In particular, we demonstrate that the SDN improves throughput efficiency by 4% compared to the traditional network while ensuring efficient bandwidth and resource management. Finally, we proposed a novel data-driven coordination model which incorporates Vehicle-to-Everything (V2X) communication and Intelligent Driver Model (IDM), together called V2X Enabled Intelligent Driver Model (VX-IDM). Our model incorporates a Car-Following Model (CFM), i.e., IDM, to model a vehicle platoon in an urban and highway traffic scenario while ensuring the vehicle platoon's safety with the integration of IEEE 802.11p Vehicle-to-Infrastructure (V2I) communication scheme. The model integrates the 802.11p V2I communication channel with the IDM in MATLAB using ODE-45 and utilises the 802.11p simulation toolbox for configuring vehicular channels. To demonstrate model functionality in urban and highway traffic environments, we developed six case studies. We also addressed the heterogeneity issue of wireless networks to improve the overall network reliability and efficiency by estimating the Signal-to-Noise Ratio (SNR) parameters for the platoon vehicle's displacement and location on the road from Road-Side-Units (RSUs). The simulation results showed that inter-vehicle spacing could be steadily maintained at a minimum safe value at all the time. Moreover, the model has a fault-tolerant mechanism that works even when communication with infrastructure is interrupted or unavailable, making the VX-IDM model collision-free.

Acknowledgement

Firstly, I would like to express my sincere thanks to my principal supervisor Professor Krishna Busawon for his continuous support, motivation, guidance and encouragement throughout my study at Northumbria University. I am very fortunate to have such a great supervisor with excellent experience, who guided me through the technical phase and strongly advised me on being a good researcher and, overall, on how to be a person with a wonderful personality. I am also grateful to my second supervisor Professor Ahmed Bouridane for his help and continued support. My special thanks to Dr Prashant Agrawal and Dr Omprakash Kaiwartya for valuable discussions and useful feedback.

EU Erasmus Mundus (gLink) studentship had played a significant role in my PhD study at Northumbria University. I would also like to express my gratitude to the Faculty of Engineering and Environmental Sciences and the Department of Mathematics, Physics and Electrical Engineering at Northumbria University to support my PhD study. Moreover, I would like to thank Dr Nadhir Messai from Université de Reims, France, for inviting me to work in their labs for some part of my PhD research work.

Finally, I would like to convey my sincere acknowledgement to my parents, sister and brother-in-law for their continuous support and encouragement and my nephews for bringing happiness to our family.

Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work at Northumbria University. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

The ethical clearance for the research presented in this thesis has been approved. The approval has been sorted and granted by the Faculty Research Ethics Committee on 14th August 2017.

I declare that the Word Count of this Thesis is 35,803 words

Name: Piyush Shamrao Dhawankar

Signature:

Date: 28/2/2021

Table of Contents

List of Tables

List of Figures

Glossary of Abbreviations

AP	Access Points
ACC	Adaptive Cruise Control
AWGN	Additive white Gaussian noise
ACI	Adjacent Channel Interference
A-MPDU	Aggregate MAC Protocol Data Unit
A-MSDU	Aggregate MAC Protocol Service Unit
API	Application Programming Interface
ADVs	Autonomous Driving Vehicles
BS	Base Station
BSM	Basic Safety Message
BPSK	Binary Phase Shift Keying
BER	Bit-Error Rate
CF	Car-Following
CSMA/CA	Carrier Sense Multiple Access/ Collison Avoidance
eNB	Cellular Base Station
C-RAN	Cloud-Radio Access Network
CCK	Complementary Code Keying
CCH	Control Channel
CAN	Controller Area Network
DCC	Decentralised Congestion Control

dB	Decibel
DSRC	Dedicated Short Range Communication
DGPS	Differential Global Positioning System
DSAS	Digital Steering Angle System
DSSS	Direct Sequence Spread Spectrum
ECU	Electronic Control Unit
ETSI	European Telecommunications Standard Institute
EPC	Evolved Packet Core
ECFB	Explicit Compressed Feedback
FCC	Federal Communications Commission
FCC	Federal Communications Commissions
FEC	Forward Error Correction
FHSS	Frequency Hopped Spread Spectrum
GF	Generalised Force
GBPS	Giga Bits Per Seconds
GPS	Global Positioning System
HT-WLANs	High Throughput Wireless Local Area Networks
HSS	Home Subscriber Server
IEEE	Institute of Electrical and Electronics Engineers
IDM	Intelligent Driver Model
ITS	Intelligent Transportation System

IoT	Internet of Things
IP	Internet Protocol
LOS	Line of Sight
LTE	Long-Term Evolution
MAC	Medium Access Control
MBPS	Mega Bits Per Seconds
MANET	Mobile Ad-hoc Network
MME	Mobility Management Entity
MCS	Modulation Coding Scheme
MU-MIMO	Multi-User Multiple Input Multiple Output
MIMO	Multiple Input Multiple Output
NFV	Network Function Virtualisation
NOS	Network Operating System
NLOS	Non-Line of Sight
NBI	Northbound Interface
OBU	On-Board Unit
OVM	Optimal Velocity Model
OFDM	Orthogonal frequency division multiplexing
PDN-GW	Packet Data Network - Gateway
PER	Packet Error Rate
PHY	Physical Layer

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QPSK	Quadrature phase-shift keying
QoS	Quality of Service
RF	Radio Frequency
RSSI	Received Signal Strength Indication
RSU	Road Side Unit
SCH	Service Channel
SSID	Service Set Identifier
S-GN	Serving Gateway
SGI	Short Guard Interval
SNR	Signal to Noise Ratio
SDN	Software-Defined Networks
SBI	Southbound Interface
SDM	Space-Division Multiplexing
TDMA	Time Division Multiple Access
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
VDC	Vehicle Dynamics Control
V2P	Vehicle- to-Pedestrian

V2B	Vehicle-to-Base Station
V2X	Vehicle-to-Everything
V2I	Vehicle-to-Infrastructure
V2R	Vehicle-to-Road Side Unit
V2S	Vehicle-To-Sensors On-Board Communication
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc Network
VHT	Very High Throughout
VM	Virtual Machine
WSM	Wave Short Message
WAVE	Wireless Access in Vehicular Environment
WAP	Wireless Access Points
WLAN	Wireless Local Area Network
2G	2nd Generation
3G	3rd Generation
4G	4th Generation
5G	5th Generation

Glossary of Symbols

δ	Acceleration exponent
$a_n(t)$; $\dot{v}_n$	Acceleration of nth vehicle at time t
A	Amplitude
G_r	Antennas gain at the receiver
G_t	Antennas gain at the transmitter
$RSU_{Average}$	Average throughput at RSU
B	Bandwidth
B_r	Bit rate
K	Boltzmann constant
s_n	Bumper-to-Bumper gap between vehicles
f	Carrier frequency
$OFDM_{bw}$	Channel width of an OFDM symbol
a_{nj}	Coefficient of Laplacian Matrix
b	Comfortable deceleration*
t_c	Communication lag
$\leftthreetimes$	Constant coefficient
$m1, m2$	Constant exponents
s^*	Desired gap
s_0	Desired or Actual distance

$\dot{x_0}_n; v_0$	Desired velocity of the vehicles
D	Difference between average throughput
(d)	Distance between the transmitter and the receiver
E	Efficiency
λ	Free space wavelength
F_{range}	Frequency range
k_1, k_2 and k_3	Gains for achieving stability
T_g	Guard time
Δx_n	Headway distance between follower and leader vehicles
I_m	Implementation noise
L_{road}	Length of the road
l_n	Length of nth vehicle
a; $\ddot{x}_n$	Maximum Acceleration
D_R	Maximum data rate offered by the protocol
$EIRP_{max}$	Maximum EIRP
N_{Power}	Noise power
T	Noise temperature
n_{rec}	Number of receivers
P_s	Packet size
$PL(d)$	Path loss at a distance d
γ	Path loss exponent

$x_n(t)$	Position of the nth vehicle on the road at time t
$x_{n-1}(t)$	Position of the n-1th vehicle on the road at time t
$T_r; \tau$	Reaction time
Δv_n	Relative velocity between follower and leader
B_{th}	Resulting throughput of wireless channel
T	Safe time headway for a vehicle on a free road
k	Sensitivity parameter
T_{Signal}	Signal field duration
$\mathcal{F}_{sti}$	Stimulus function
Δ_f	Sub-Carrier spacing
T_{Symbol}	Symbol duration
P_t	Transmitted power
$\dot{x}_{n-1}; v_{n-1}$	Velocity of n-1th vehicle
$v_n; \dot{x}_n$	Velocity of nth vehicle
c	Velocity of the radio signal

Chapter 1

Introduction

1.1. Introduction and Motivation

The automotive industry has recently shifted from developing individually advanced vehicles to a well-connected and smart transportation system, including the new intelligent vehicles with autonomous driving control capability [1]. Autonomous Driving Vehicles (ADVs) are highly complex multidisciplinary products comprising a sensor system, automotive control, information processing, artificial intelligence and ultrafast communication capabilities. Governments and society can substantially benefit from autonomous driving vehicles, as it will help to minimise road accidents, improve traffic management and fuel usage along with road infrastructures [2]. Additionally, ADVs can be used for both civilian and military applications, such as extinguishing wild bush fires, transportation of dangerous goods, surveillance and combats [3].

To realise autonomous driving, vehicles need to be capable of sensing the surrounding environment and performing control and path planning without any human intervention [4]. These ADVs are equipped with multiple wireless radio access technologies, like Dedicated Short Range Communications (DSRC), IEEE 802.11 (Wi-Fi), cellular technologies such as Long-Term Evolution (LTE) and fifth-generation (5G) networks [5]. Global automakers and information technology companies, such as General Motors, Volkswagen, Toyota, Google, Waymo, and Amazon-owned Zoox are expected to have their ADVs on the market by the end of 2021 [6]. They also predict 25 per cent of the vehicles out on the road to be ADVs by 2035 [7].

However, several challenges still need to be fully addressed for autonomous driving, such as [8, 9]:

- To know the exact position of the vehicle and to decide how to reach the destination optimally.
- To comprehensively sense the surrounding dynamic environment, including other road users and the road infrastructure, to avoid any types of collision and accident.
- To detect the road signs as well as other static infrastructure such as lanes, crosswalks, speed bumps, etc.

Cruise control is a well-known system that allows a vehicle to independently reach and maintain a speed chosen by the driver. Adaptive Cruise Control (ACC) is a system that allows for automated driving that can adapt to traffic conditions and different driving situations [10]. It extends control of the vehicle over decisions traditionally left to the driver by additionally setting and maintaining a time gap (safe headway). The vehicle is equipped with radar or infrared sensors to detect and track the vehicle immediately ahead in order to control braking and thereby the deceleration necessary to avoid any collisions. It will also operate effectively in all speed ranges, including stop and go traffic. It is predicted that future ACC models will also contain the ability to avoid rear-end collisions [7]. However, ACC has no authority over lane-changing decisions and is limited in control in terms of velocity, acceleration and deceleration. Currently, some vehicles have a partly automated version of this system such as, Tesla’s “Autopilot” and Mercedes’ Distronic Plus system already in place that allows the user to choose when to activate ACC [11].

Moreover, these systems are only sophisticated enough to improve driver comfort without the ability to enhance a road network's capacity. Besides, such vehicles' driving behaviour is significantly affected by the surrounding/neighbouring vehicles rather than the road user itself [12]. These issues are not fully exploited due to the lack of communication ability among adjacent vehicles.

In existing ADVs, the sensor systems are equipped with a range of cameras, radar, or laser range finders and advanced autonomous driving algorithms to make driving decisions. The primary approach to detect the surrounding environments by utilising sensor systems could be highly limited in different environments in which vehicles are in (e.g., road/user obstacles, other vehicle behaviours, poor weather conditions) [13]. Hence, it is imperative to address the challenges regarding the lack of communication ability among the neighbouring ADVs for safety and smooth driving requirements. Moreover, the sensors used for ADVs have limitations in terms of range and face operational difficulties in particular weather conditions like rain, snow or fog. The range of sensors in ADVs is limited and only effective in Line of Sight (LOS) condition. Therefore, in Non-Line of Sight (NLOS), conditions with other vehicles and road infrastructure may result in accidents [14]. Hence, the primary approach adopted in developing a current system for detecting the surrounding environments by utilising sensor systems would not be the best choice, whereas vehicles face diverse conditions such as road/user obstacles, abnormal behaviour by other vehicles and poor weather conditions.

The rapid development of recent wireless communication technologies in the domain of vehicular networks is expected to support and boost autonomous driving development. They employ Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication techniques, together called as Vehicle-to-Everything (V2X) communication, which can be effectively used to detect surrounding conditions to minimise accidents and safe driving [15]. The V2X communications refer to information exchange between a vehicle and various elements of the intelligent transportation system (ITS), including other vehicles, pedestrians, Internet gateways, and transport infrastructure (such as traffic lights and road signs) [16]. This technology has a great potential of enabling a variety of novel applications for road safety, car manufacturer services, and vehicle traffic optimisation. Currently, V2X communications use one of two leading technologies: dedicated short-range communications (DSRC) and cellular networks.

Autonomous driving will be much safer when the driving decisions are made if more reliable information is available, provided by vehicular networks. For example, every vehicle can periodically broadcast safety-related messages about their current condition and position to neighbouring vehicles, which helps all vehicles know their surrounding environment accurately [17]. On the other hand, vehicular networks can also help to improve traffic efficiency significantly [18]. Therefore, a future mobile communication network architecture must be reconsidered for comprehensively exploring the potential of new technologies and being more flexible and scalable to adapt to various services and applications [19].

The management of vehicular networks in future is challenging, as it demands mobility, location awareness, high reliability and low latency of data traffic for many connected ADVs. Moreover, in the near future, it is unlikely that a single technology can support such a variety of V2X applications for a large number of autonomous vehicles.

In this research work, the challenges mentioned earlier for ADVs regarding V2I communication, data requirements, safe driving with platoon formations concerning several lanes, platoon size and cluster size for efficient use frequency and bandwidth is considered. Additionally, Network latency requirements are also analysed, which are mandatory constraints for all V2I applications where real-time end-to-end communication is necessary.

1.2. Problem Statement

The concept of vehicle automation and connected driving started more than a decade ago with a second-generation (2G) network along with recent improvement and deployment of technology with the help of 3G and 4G mobile communication networks [14].

However, the limited coverage on certain roads and rural areas delays the information transfer between the connected vehicles and affects the performance and efficiency of autonomous driving [20]. In addition, due to high mobility and the dynamic change of network topology in a vehicular network, it is difficult to provide satisfactory services through an existing wireless access network [21].

Recently IEEE 802.11p standard, also known as DSRC, has been proposed for vehicular ad hoc network. However, the standard does not address the hidden terminal problems, which affects the driving awareness/coordination (e.g., local, context and cooperative awareness). The term V2V is a dedicated short-range communication, and it uses multi-hop mode for communication to flood the information required for vehicular data application. However, due to the ad hoc nature of such networks and system mobility, such V2V only approach is not suitable for latency-sensitive and safety-critical ITS applications, consequently affecting the level of automation toward zero-accident driving in platooning and connected autonomous driving [22, 23]. The limitation originates from the inherent “short-range” characteristic of DSRC.

For instance, to provide in-vehicle Internet access via DSRC Internet gateways deployed along the roadsides, a vehicle needs to be within the “small” coverage region of a gateway (i.e., an RSU), which may happen only for a short time, particularly if the vehicle is moving with high speed. Such limitation does not exist for cellular network technologies, where the Base Station (BS) covers a much larger region as compared to that covered by a DSRC Internet gateway. Even when multi-hop communication is employed to extend the coverage of DSRC gateways (by allowing vehicles to relay packets to and from the Gateway), the existence of a network path between vehicles and Gateway at each time instant is not guaranteed particularly in low vehicle density scenarios. Moreover, even if a network path exists, the packet routing to/from the Gateway is a very challenging task, given the highly dynamic network topology caused by fast vehicle movement.

Therefore, the Long-Term Evolution (LTE) has raised interest in the research community to support reliable V2X communications for different applications. There are many enablers for cellular technology to back this interest, and they are as follows:

- High network capacity, which enables the support of high bandwidth demand and data-thirsty applications.
- Wide cellular coverage range reduces the frequency of horizontal handovers since the Vehicle-to-Base Stations (V2B) contact time is relatively long compared to that of the Vehicle-to-Road Side Unit (V2RSU).
- Mature technology, which eases the implementation and accelerates the deployment of V2X communications.

Despite these advantages, several challenges limit the ability of cellular technology to support reliable V2X communications. Moreover, due to the centralised control nature of cellular networks, vehicular data must pass by the BS first, limiting the applicability to V2V communications, particularly for safety applications with stringent delay requirements. Some of the V2V communication instances are as follows:

- A vehicle sends the safety message to a cellular BS in a unicast mode, which unicasts the message to every vehicle in the cell or to the relevant vehicles only.
- In broadcast mode, the BS broadcasts a safety message to all the vehicles in the cell, and it is up to each vehicle to determine the relevance of the received safety message.

As a result, vehicles receive many irrelevant messages and conduct unnecessary processing; due to the number of vehicles in a BS, coverage is much broader than that in the zone of a safety message's relevance. Although broadcast/multicast services can reduce the downlink load, the uplink channel becomes a bottleneck in a high vehicle density situation, given the fact that uplink transmissions are always achieved using unicast mode [24, 25]. In both cases, studies show that the downlink channel becomes a bottleneck even when there is a small number of vehicles in the cell [24-26]. The delay incurred in LTE networks may significantly deteriorate with a large number of connected vehicles registered to a base station. At the same time, a strict latency for delivering real-time information for autonomous driving is required. The volume of data (broadcast packet size of 1000 bytes per second) generated by sensors in ADVs is beyond the current vehicular networks' capacity to support distributed and local control in ITS [18].

Recently, the 5G and beyond generation has attracted ITS's attention for improving performance in terms of reduced latency, increased reliability and much higher throughput under higher mobility and connectivity density [27]. Moreover, integration of the Software-Defined Network (SDN) improves the network's efficiency by responding to the changes or events detected in real-time. Such dynamic reconfiguration of the forwarding devices is only possible via centralised applications which orchestrate the Internet of Things (IoT) collected information and network resources information jointly [28]. The open network programmability and logically centralised control feature of the SDN paradigm offer an attractive means to manage communication and networking resources in the vehicular environment and promise improved performance in connected vehicles/ADVs.

In the current literature review, there is currently no work reported on the connected vehicles/ADVs supported by the 5G (and beyond) network with SDN support. The SDN overcomes all the limitation of traditional networks (LTE) where the control plane (that decides how to handle network traffic) and the data plane (that forwards traffic according to the decisions made by the control plane) are bundled inside the networking devices. ITS's critical problems include modelling the novel architecture for ADVs, the wireless communication protocol, and the control mechanisms. The latter requires much flexibility due to the nature of instant road traffic; thus, SDN and network function virtualisation

(NFV) are promising candidates to address these. However, lack of research and foundation in these areas in existing literature make the proposed work itself more challenging. There is vast room for improvements by leveraging novel concepts such as SDN, which may revolutionise how a network can be designed and operated. This approach should show the applicability and some expected benefits of SDN in ITS.

1.3. Aim and Objectives

Considering the discussion in the preceding section, this thesis aims to develop and implement a control and communication scheme, as a proof of concept, for ADVs by considering wireless vehicular communication for a fleet of connected vehicles under a car following topology. This scheme is based on real-time V2I communication for autonomous vehicles and provides safety and traffic-related information for the diverse or heterogeneous driving environment. The specific objectives of this research include:

- To conduct comprehensive research on current and future ADVs and their mobility topologies to establish the future development of connected autonomous driving vehicles system.
- To investigate the development in wireless radio technologies that can operate in a heterogeneous environment, using Wireless Local Area Network (WLAN) and Wireless Access in Vehicular Environment (WAVE) based access technologies like IEEE 802.11a/n/ac and IEEE 802.11p.
- Propose a novel communication architecture using Software-Defined Networking (SDN) to investigate the flexibility and system efficiency over the legacy radio technologies.
- Propose a novel coordination/system model, which incorporates a Car Following Model with Vehicle to Infrastructure (V2I) communication capability to ensure vehicle platoon safety on urban and highway driving conditions.

- Experimental investigations of proposed coordination model under different events for a single platoon, a single-lane scenario with V2I communication affecting vehicles' motion.

1.4. Original Contribution

The outcomes of this research introduce several original contributions to the knowledge for innovative research and are summarised as follows:

1) A detailed investigation and measurement results for an experimental study on throughput, range, efficiency and backward compatibility performance of IEEE 802.11 wireless standard over 2.4 and 5 GHz frequency spectrum in an indoor LOS environment is carried out. The detailed analysis considering a number of key systems features of physical layers (PHY) of IEEE 802.11 standards predominately, Multiple Input Multiple Output (MIMO), Multi-User Multiple Input Multiple Output (MU-MIMO), Channel Bonding, and Short-Guard Interval (SGI) over the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) platform in a heterogeneous wireless network environment. Three tests were proposed to investigate the throughput, range and backward compatibility of the wireless protocols and their results are as follows.

i) *Throughput Test*: The results show that Channel Bonding, SGI, MIMO, MU-MIMO help achieve a higher data rate and throughput. The results are published in [B2], [C1] and [J2].

ii) *Range Test:* The results show that IEEE 802.11n/ac operates with greater efficiency in the range of 30-35 meters. Also, the protocols' range and data rate using over 5 GHz frequency spectrum is comparatively more efficient than the protocols operating in the 2.4 GHz frequency spectrum. The results are published in [C1] and [J2].

iii) *Backward Compatibility Test:* The results show that the client always connects to access points with higher Signal to Noise Ratio (SNR) and Received Signal Strength Indication (RSSI) Values. The seamless roaming is observed between legacy and recent amendments of IEEE 802.11 protocols. The results are published in [J2].

2) Next, a detailed investigation of the Autonomous Driving Technology and Vehicular Communication system is carried out to develop a reliable communication infrastructure for handling safety-critical information originating from the vehicular network. The novel communication infrastructure is proposed for ADVs operating on the four-lane road scenario. The Time Division Multiple Access (TDMA) based slotted channel access is used for calculating the data rate requirement for safety-related application. The data rate requirement for three clusters of ADVs on a four-lane road scenario is evaluated with respect to multi-hop communication. Furthermore, the throughput performance comparison is made between traditional and Software-Defined Networks (SDN). For this, a testbed is created using Cisco and HP SDN network devices, and throughput tests are performed using multiple hosts to evaluate the overall system's performance. The use of SDN offers a substantial improvement over the traditional network and reduces bandwidth fluctuation. The results are published in [C2] and [J4].

3) Finally, we proposed and investigated the simultaneous integration of the V2I communication model with the Car-Following model to demonstrate the impact of real-time communication and overcome the complexity and coordination issue in a vehicular network. Where the model provides feedback to the platoon vehicle leader about the state of communication and safety/traffic-related information. This Hybrid Data-Driven Model also estimates the Packet Error Rate (PER) with a fading channel at Signal to Noise Ratio (SNR). The throughput of the V2I

communication channel is also calculated with respect to the position and velocity, and coverage of the roadside unit. The four V2I communication scenarios are proposed to demonstrate Urban LOS/NLOS and Highway LOS/NLOS environment. This approach reflects the effect of cooperative platoon driving and platoon based vehicular communication. The results show the model is collision-free for an infinite length of platoon string and can also work with a lack of V2I communication. The results are published in [J1].

The summary of the research issues, existing solutions and original contributions of the thesis in automated and autonomous driving is graphically presented in Figure 1.1.

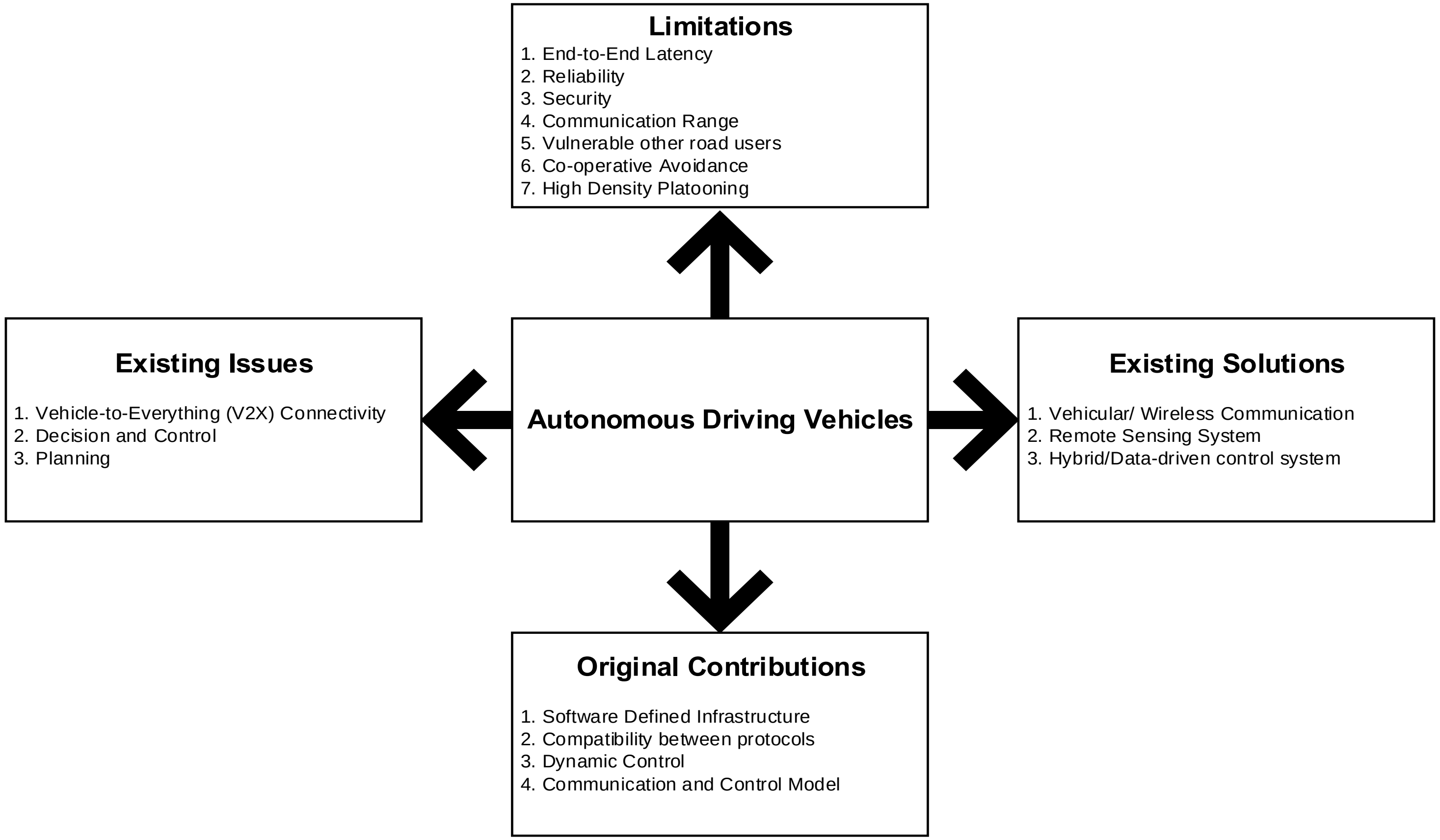

Figure 1. 1. The summary of the issues, existing solutions and original contributions for Autonomous Driving Vehicles.

1.5. Thesis Structure

This thesis is mainly focused on the research work dedicated to the Autonomous Driving Vehicles' system performance improvement and simultaneous integration of car-following model and vehicle to everything communication. The thesis is organised into six chapters. Following the introductory sessions in Chapter 1, the brief overview of Chapter 2 to Chapter 6 is listed as follows.

Chapter 2 covers the literature review and developments in autonomous driving vehicles and vehicular communications. It discusses the level of automation in driverless vehicles/cars and their communication standards and protocols. A brief discussion on various driverless vehicles platform, software tools and field trials are provided. The chapter discusses the communications technologies developments in detail, offers a classification of various protocols and presents a taxonomy of vehicular communication developments.

Chapter 3 provides an overview of IEEE 802.11 wireless standards, introducing their operation principles and backward compatibility in a heterogeneous environment. The theoretical and practical throughputs of the protocols are investigated, along with their interoperability with each other for seamless communication. Moreover, the hand-off process is examined for these protocols to understand suitable migration strategy and successful deployment for the enterprise wireless network.

Chapter 4 presents a novel communication architecture for a vehicular network with the support of Software Defined Network technology. The data rate requirements are evaluated for the vehicular network for the efficient bandwidth and frequency use of the communication channel. The network latency requirements for the real-time and priority-based services for the application are analysed. Moreover, to attest, SDN's benefit over the traditional network is evaluated by developing a test environment.

Chapter 5 presents a novel data-driven control system model using MATLAB for the vehicle platoon's safety in urban and highway traffic environment. The model integrates the car-following model with the IEEE 802.11p communication model to compute, control, and communicate between Autonomous driving vehicles in a real-time environment to attest their safety and cooperation within a platoon.

Finally, **Chapter 6** provides the conclusion and discusses possible future aspects for the extension of the work.

1.6. Publications and Awards

1.6.1. Journal Articles

[J1]. Piyush Dhawankar, Prashant Agrawal, Bilal Abderezzak, Omprakash Kaiwartya, Krishna Busawon and Simona Raboacă Maria, "Design and Numerical Implementation of V2X Control Architecture for Autonomous Driving Vehicles," *MDPI Mathematics*, 9(14), 1696 (2021).

[J2]. Piyush Dhawankar, Arvind Kumar, Noel Crispi, Krishna Busawon, Kashif Qureshi, Tariq Ibrahim Javed, Shiv Prakash and Omprakash Kaiwartya, "Next-Generation Indoor Wireless Systems: Compatibility and Migration Case Study," IEEE Access, vol. 9, pp. 156915-156929, 2021, doi: 10.1109/ACCESS.2021.3126827.

[J3]. Khalid Muhamad, Yue Cao, Naveed Ahmed, Waqar Khalid, and Piyush Dhawankar, "Radius-bases multipath courier node routing protocol for acoustic communications," *IET Wireless Sensor Systems*, vol. 8, no. 4 (2018): 183-189.

[J4]. Piyush Dhawankar, Mohsin Raza, Hoa Le Minh, and Nauman Aslam, "Software Defined Approach for Communication in Autonomous Transportation Systems," *EAI Endorsed Transactions on Energy Web*, vol. 4, no. 4 (2017): 152924.

1.6.2. Conference Papers

[C1]. Piyush Dhawankar, Hoa Le-Minh, and Nauman Aslam, "Throughput and Range Performance Investigation for IEEE 802.11 a, 802.11 n and 802.11 ac Technologies in an On-Campus Heterogeneous Network Environment," in *11th International Symposium on Communication Systems, Network & Digital Signal Processing (CSNDSP)*, Budapest, Hungary, 2018, pp. 1-6.

[C2]. Piyush Dhawankar, Hoa Le-Minh, Nauman Aslam, and Mohsin Raza, "Communication Infrastructure and Data Requirement for Autonomous Transportations," in *2nd International Workshop on Sustainability and Green Technologies*, Danang, Vietnam, 2017.

1.6.3. Book Chapters

[B1]. Khalid Muhammad, Yue Cao, Kezhi Wang, Piyush Dhawankar, and Mohsin Raza, "Towards Autonomous Valet Parking: A Broader Prospective," in *Towards Sustainable and Economic Smart Mobility: Shaping Future of Smart Cities, World Scientific Publishing*, 2019.

[B2]. Piyush Dhawankar, and Rupak Kharel, "IEEE 802.11 Based Heterogeneous Networking: An Experimental Study," in *International Conference on Application of Computing and Communication Technologies*, pp. 237-246 *Springer, Singapore*, 2018.

1.6.4. Awards

[A1]. Received PhD Scholarship from the EU Erasmus Mundus (gLink) funding Programme. [2016 - 2019].

[A2]. Received Scholarship from the Université de Reims, France, to work with the subject experts, which resulted in knowledge exchange and collaborations. [2018].

Chapter 2

State-of-the-art Wireless and Vehicular Communication Technologies for Automated and Autonomous Driving

In this chapter, we are going to present a comprehensive literature review on wireless communication technologies, Vehicular ad hoc network (VANET), Software Defined Networks (SDN) and Car Following (CF) models. We focus mainly on the Institute of Electrical and Electronics Engineers (IEEE) standards/protocols used for wireless communication in a VANET domain and explore software-defined networking for autonomous driving vehicles for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. Moreover, car-following models will be discussed to understand the car-following behaviour to integrate V2V and V2I communication for autonomous driving vehicles.

2.1. Communication Technologies for Autonomous Driving

The hardware architecture for autonomous driving vehicles requires a significant number of devices, including the Electronic Control Unit (ECU), to collect drive input to control the vehicle's behaviour. The ECU and other associated devices are connected with dedicated buses, used for communication between these components. This section detailed the architecture pertaining to the connectivity of vehicles. Here we list several communication technologies required by an autonomous driving vehicle to guarantee communication between them. Figure 2.1 below schematised the information exchanged by connected vehicles by several different communication technologies.

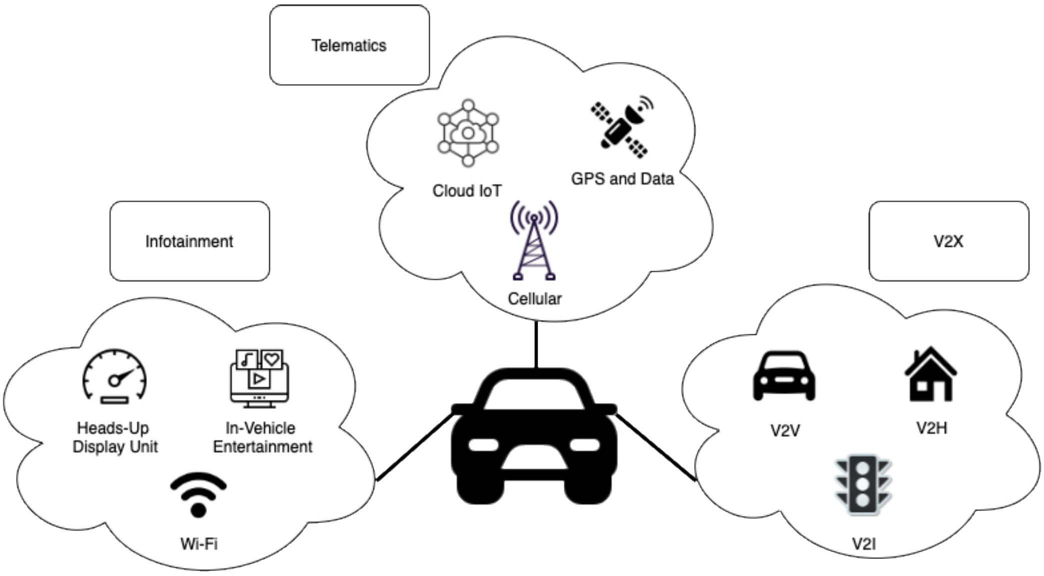

Figure 2. 1. Overview of Connected Vehicle System [29]

1. Vehicle-To-Sensors On-Board Communication (V2S) or Intra-Vehicle connectivity indicates the transmission of information from ECUs to sensors (inside and around the vehicle) and vice-versa. This information exchange communication can be facilitated by either wired (e.g., over the Controller Area Network (CAN) bus) or wireless network. For wireless communication between sensors and ECUs, several communication technologies such as Bluetooth, Zigbee, Ultra-Wideband, RFID or 60 GHz Millimetre waves can be employed. The communication through wireless medium minimises the need for cabling and provides more flexibility for Intra-Vehicle network infrastructure; however, it is still prone to security and reliability issues [30].
2. Vehicle-to-Vehicle Communication (V2V), or Intra-Vehicle Connectivity, defines the transmission of information between multiple vehicles without any centralised remote controller intervention. This type of communication helps avoid accidents, improve route optimisation, and share multimedia information such as pictures of accidents on the road or parking space available nearby and social interaction. These connected vehicles form a vehicular ad hoc Network (VANET) to disseminate information between them and other road objects. Moreover, the concept of Vehicle-

to-Pedestrian (V2P) communication is introduced by some companies to inform the road user (pedestrian) about the dangerous vehicle in the vicinity [31]. Network management for connected vehicle poses a significant challenge in managing VANET due to the dynamic nature of the vehicular network topology.

Moreover, the data transmission between vehicles is interrupted by the dynamic movement of vehicular nodes and other road users and obstacle in the surrounding environment. Network management is quite difficult in such a dynamic environment as the approaching vehicles are likely to stay in a communication range for a limited amount of time. Therefore the exchange of information is between vehicles and infrastructure is quite limited [32]. Some of the VANETs applications are as follows: Cooperative traffic monitoring, collision warning and message transfer, digital map downloading, value-added advertisement, electronic toll collection, and parking availability notifications are some existing examples of the application of VANETs [33].

3. The Vehicle to Infrastructure (V2I) communication refers to the information exchange between connected vehicles and intelligent road infrastructures such as street signs, roadside units, sensors and traffic light. Communication between vehicles and infrastructure is crucial for road safety and traffic management, and V2I communication can be facilitated by the Dedicated Short-Range Communication (DSRC) system [34].
4. Infotainment services are a fundamental requirement for connected vehicles. The audio or video entertainment, a navigation system, and in-car internet are must for a modern vehicle to enhance user experience and comfort. The current solution for this is using the cellular network infrastructure to allow vehicles to connect 3G/4G networks; however, in future, Wi-Fi and WiMAX can facilitate it [35].

2.2. Vehicular Ad-Hoc Network (VANET)

A VANET is an extension of a Mobile Ad-hoc Network (MANET) that incorporates wireless communication between nearby vehicles to improve road safety and safeguard vehicles [36]. An Intelligent Transportation System (ITS) is a sophisticated application in the domain of vehicular communication and safety with several research areas involved. Moreover, it provides a robust platform for V2V and V2I communication. Figure 2.2 below shows an example of V2V and V2I communication.

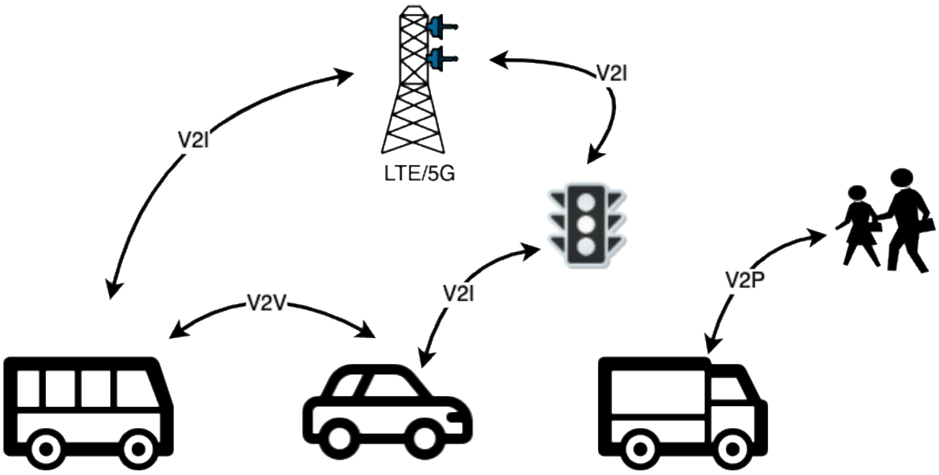

Figure 2. 2. Overview of V2V and V2I communication for Cooperative Driving [37]

To understand the vehicular communication and wireless communication in a heterogenous environment, we would look at the some of the important wireless and radio communication characteristics that are crucial for planning and designing infrastructure for vehicular communication and they are as follow [38-40]:

1. Multipath is the propagation phenomenon caused by the reflection and refraction of the radio signals during transmission of signal from transmitter to receiver. The signal reaches the receiver by two or more paths and reflected or refracted due to water bodies and terrestrial objects such as, mountains and buildings. When the signal is received from two or more paths at the receiver, it can create an interference and phase

shifting of signal. In some instances, this interference can cause fading of radio signal causing deterioration of the signal strength beyond usable limit.

2. Fading is caused by attenuation of radio signal due to various variables such as, time, geographical location, multipath propagation, and change in radio frequency. Fading occurs when the signal is received from multiple paths and therefore receiver experiences differences in attenuation, delay and phase shift of each signal received on that wireless channel. This results in constructive or destructive interference, amplifying or attenuating the signal power at the receiver. In some instances, this destructive interference causes temporary failure of communication due to severe loss in Signal-to-Noise ratio (SNR) of the radio signal.
3. Doppler effect is caused by change in wavelength and frequency of radio signal from two objects moving in same or different directions. If the frequency shift is high, it might be difficult to demodulate the signal and due to change in frequency the signal might interfere with the other nearby signals. That is the reason IEEE 802.11p (vehicular communication protocol) only have a 5 MHz frequency bandwodith instead of 20 MHz.

The vehicles communicating with each other and infrastructure over the wireless network may sound reasonably simple; however, deployment of VANET has some significant challenges, as mentioned below:

1. Due to outdoor heterogeneous environment and weather conditions, VANET has to manage unpredictable wireless communication characteristics, such as multi-path propagation, fading and doppler effect.
2. Due to network topology's dynamic nature for connected vehicles in the VANET environment, it is challenging to operate and control the transmission events, which results in low channel efficiency and packet collision.

3. Several wireless protocols used in the VANET environment, operating on the broadcast mechanism and without a more robust authentication scheme, result in privacy and security issues such as a broadcast storm for time-critical sensitive vehicular applications.

2.3. Wireless Communication Standards

Indoor smart indoor devices are significantly growing day-by-day around us. According to a recent report by Statista [41], the UK's smart home revenue is expected to grow at the annual rate of 14.3% between 2020-24, and the project value of the market is $7423m by 2024. Smart indoor devices' market penetration rate was 16.4% in 2020, and it is expected to hit 44.8% by 2024. Towards realising the indoor Internet of Things (IoT), some critical scientific-technological developments lead the way forward in embedded hardware and software research theme [42]. It includes advanced embedded systems, edge and green computing, low power transmission, physical layer security, and ultra-channel access [43]. Wireless channel access is one of the key technologies in developing a smart indoor IoT environment considering the expected growth in the number of smart indoor devices. The indoor wireless access is exceptionally challenging for sensor-enabled small smart devices considering the constraints, including dynamic channel fading, ultra-bandwidth sharing, and power and security-centric physical layer signal transmissions [44].

The original IEEE 802.11 standards are wireless specific and were ratified and embodied in a document in the year 1997 [45]. The data rates in IEEE 802.11 standards have increased significantly from 1 Mbps in the year 1997 to 600 Mbps in IEEE 802.11n-2009 standard and are still ascending to 1.3 Gbps and 7 Gbps in IEEE 802.11ac-2012 standard [46, 47]. Existing wireless access schemes are incredibly vulnerable to the realistic implementation of indoor IoT networking. For example, IEEE 802.11ac is a more scalable, faster, and improved version of IEEE 802.11n with a wider bandwidth and Gigabit Ethernet capacity [48]. The IEEE 802.11n and 802.11ac amendments are also known as High Throughput Wireless Local Area Networks (HT-WLANs). In IEEE 802.11 standards, 802.11a specifications deliver up to 54 Mbps of theoretical data rates [49]. However, the recorded practical throughput of IEEE 802.11a is 25 Mbps [50]. Diversity in the IEEE 802.11n standard enabled at least a four-fold throughput improvement over legacy protocols [50]. The IEEE 802.11ac standard incorporates a whole lot of sophisticated features that have been developed to enhance physical layer throughput, Quality of Service (QoS), signal coverage, as well as reliability [51]. These enhancements include wider frequency channel (up to 160 MHz), MIMO (up to 8), Multi-User MIMO, higher spectral efficiency and high-density modulation (up to 256-QAM) with channel bonding mechanism, which enhances the user experience and overall performance [52]. The MIMO system is one whose transmitter and a receiver having multiple antennas to transmit and receive a wireless signal [53]. The IEEE 802.11p and IEEE 1609-family standards are developed for vehicular communications in telematics. The Federal Communications Commission (FCC) and European Telecommunications Standard Institute (ETSI) has mandated the use of a frequency spectrum of 5.9 GHz for Dedicated Short-Range Communications (DSRC) in the vehicular environment and safety-related application of ITS [54]. This growing connectivity via computing and communication-enabled smart devices is increasing due to the co-existence of several wireless heterogeneous technologies, resulting in interoperability issues among devices.

2.3.1. The IEEE 802.11 PHYs

The physical layer (PHY) of IEEE 802.11 standards mostly works on infrared (IR), 2.4 GHz Frequency Hopped Spread Spectrum (FHSS), and 2.4 GHz Direct Sequence Spread Spectrum (DSSS). The advancements in DSSS and their Complementary Code Keying (CCK), which is used in IEEE 802.11b standards, gained a higher data rate than others;

therefore, the market of IR and FHSS did not establish well. The Orthogonal Frequency Division Multiplexing (OFDM) was first introduced in the IEEE 802.11a standards and operate in the 5 GHz frequency spectrum generating 54 Mbps of data rates [53]. The PHY layer system of 802.11p is adopted from IEEE 802.11a, and it uses 52 sub-carriers which are modulated using Binary or Quadrature Phase Shift Keying (BPSK/QPSK), 16 quadrature amplitude modulation (16-QAM) or (64-QAM) and forward error correction (FEC) coding is used with a coding rate of 1/2, 2/3 or ¾ [55]. Table 2.1 below shows an overview of 802.11 PHYs.

Table 2. 1. Overview of 802.11 PHYs [46, 52, 53, 55]

	802.11	**802.11b**	**802.11a**	**802.11g**	**802.11n**	**802.11ac**	**802.11p**
PHY Technology	DSSS	DSSS/CCK	OFDM	OFDM DSSS/CCK	SDM/OFDM MIMO	SDM/OFDM MU-MIMO	BPSK/QPSK/16/64-QAM
Data Rates (Mbps)	1,2	5.5,11	6 - 54	1 – 54	6.5 – 600	6.5 - 6933.3	3 - 27
Frequency Band (GHz)	2.4	2.4	5	2.4	2.4 and 5	5	5.850 - 5.925
Channel Bandwidth (MHz)	25	25	20	25	20 and 40	20, 40, 80 and 160	10
MIMO Streams	1	1	1	1	4	8	-
Release	Jun-1997	Sep-1999	Sep-1999	Jun-2003	Oct-2009	Dec-2013	2010

2.3.2. The 802.11a

The 802.11a employs OFDM as a PHY modulation scheme and operates in a 5 GHz frequency spectrum [56-58]. The OFDM converts the high-speed binary data streams to low-speed data streams, which transmit the signal simultaneously multiple sub-carriers [59, 60]. The 802.11a has 52 sub-carriers, out of which 48 are data sub-carrier while the remaining 4 are the pilot sub-carriers [61]. Table 2.2 below shows the main parameters of the OFDM standard for 802.11a.

Table 2. 2. Main Parameters of OFDM for 802.11a

Parameters	**Values**
Data rate	6,9,12,18,24,36,48,54 Mbps
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding rate	½, 2/3, ¾
Number of subcarriers	52
Number of Pilots	4
OFDM symbol duration	4 microseconds
Guard interval	800 microseconds
Subcarrier spacing	312.5 KHz
-3 dB bandwidth	16.56 MHz
Channel Spacing	20 MHz

2.3.3. The IEEE 802.11n

The interoperability, compatibility and data rate efficiency issue between legacy protocols such as IEEE 802.11a/b/g leads to the development of IEEE 802.11n standard by the IEEE task force in the year 2009 [62]. The improvements in the data rate of 802.11n are three folds over the 802.11 legacy protocols, and it claims to achieve the data rate of 600 Mbps while operating in both the frequency spectrum, i.e., 2.4 and 5 GHz [46]. The 2.4 GHz spectrum is overly crowded and congested due to several legacy protocols, wireless devices, and microwaves traditionally operate in that frequency.

Table 2. 3. Data Rates of 802.11n [63]

Nominal configuration	**Bandwidth (MHz)**	**Number of Spatial Streams**	**Constellation size and rate**	**Guard Interval**	**PHY Data Rate (Mbps)**	**Throughput (Mbps)**
Min	20	1	64QAMr5/6	Long	65	46
Low-end product (2.4 GHz only+)	20	1	64QAMr5/6	Short	72	51
Midtier product	40	2	64QAMr5/6	Short	300	210
Max product	40	3	64QAMr5/6	Short	450	320
Amendment max	40	4	64QAMr5/6	Short	600	420

However, 802.11n operates in both 2.4 and 5 GHz spectrum; therefore, it can achieve full performance if implemented in a less congested 5 GHz spectrum. Table 2.3 shows the data rates of IEEE 802.11n. The 802.11n have introduced many new improvements over the legacy protocols, resulting in higher data throughput and efficiency. Some of these features are tested in this research and are described below.

2.3.4.1. Frame aggregation

The frame aggregation is introduced in 802.11n, which combines multiple data frames into a single aggregate data frame, improving the MAC efficiency [62]. When multiple data frames are transmitted over the wireless network, the overhead of each frame is aggregated. Therefore, it does reduce the size of the entire frame and improves the inter-frame time lag. Two types of frame aggregation techniques are defined in IEEE 802.11 standards, and they are as follows:

i. Aggregate MAC protocol service unit (A-MSDU)
ii. Aggregate MAC protocol data unit (A-MPDU)

The combination of multiple MSDUs' and MPDUs' received on the MAC layer creates A-MSDU and A-MPDU, respectively. The A-MPDUs' is created on MAC layer before it can transmit out to the PHY layer. This aggregate function works for both MSDUs' and MPDUs' in a similar manner to create a single level aggregation scheme individually; however, two-level aggregation can be achieved by combining multiple MSDUs' and MPDUs' at the MAC layer [64]. Therefore, frame aggregations improve the overall latency of the wireless network [65].

2.3.4.2. Short guard interval (SGI)

The guard interval (GI) is introduced in IEEE 802.11 standards to shield a particular wireless transmission from interfering with each other and other interferences present in the environment. It is a fixed time slot between symbols transmitted over a wireless network to eliminate intersymbol interference [66]. The GI also protects the wireless communication from propagation delays, echoes and reflection in a heterogeneous environment [67]. Moreover, the GI time of 800ns present in 802.11a/g can be reduced in 802.11n to 400ns to improve the throughput performance by 10% [68]. This reduction in guard time from 800ns to 400ns is called Short Guard Interval (SGI). However, it is only supported when both the transmitter and client can support SGI in their radios. Table 2.4 shows the effect of SGI on 802.11n data rate (Mbps). It shows the data rates in Mbps that can be achieved for 20 and 40 MHz channel bandwidth with 400ns and 800ns of GI.

Table 2. 4. Data Rates and Short Guard Interval of 802.11n [69]

802.11n (2.4GHz and 5GHz)					
MCS Index	**Spatial Streams**	**20MHz Channel Rate (Mbps)**		**40MHz Channel Rate (Mbps)**	
		SGI= 800ns	**SGI= 400ns**	**SGI= 800ns**	**SGI= 400ns**
0	1	6.50	7.20	13.50	15.00
1	1	13.00	14.40	27.00	30.00
2	1	19.50	21.70	40.50	45.00
3	1	26.00	28.90	54.00	60.00
4	1	39.00	43.30	81.00	90.00
5	1	52.00	57.80	108.00	120.00
6	1	58.50	65.00	121.50	135.00
7	1	65.00	72.20	135.00	150.00
8	2	13.00	14.40	27.00	30.00
9	2	26.00	28.90	54.00	60.00
10	2	39.00	43.30	81.00	90.00
11	2	52.00	57.80	108.00	120.00
12	2	78.00	86.70	162.00	180.00
13	2	104.00	115.60	216.00	240.00
14	2	117.00	130.00	243.00	270.00
15	2	130.00	144.40	270.00	300.00

2.3.4.3. Channel Bonding

The Channel Bonding feature is introduced in 802.11n by the Internet Engineering Task Force (IETF) [70]. One of the prominent features of channel bonding is to fuse (merge) two 20 MHz channels into one 40 MHz channel, which shows improvement in the overall data throughput of the wireless system [71]. It can also be seen from Table 4 above, the throughput of 802.11n at 40 MHz channel is almost double with every Modulation Coding Scheme (MCS) index value compared to the 20 MHz channel. However, proper implementation of 40 MHz is necessary as the unplanned channel bonding deployment can result in overall performance degradation. There are only 3 non-overlapping channels present in the 2.4 GHz frequency spectrum using 20 MHz channel width; however, if 40 MHz channel is configured in 2.4 GHz spectrum, all the channels are overlapping partially with the adjacent one resulting in Adjacent Channel Interference (ACI) which cause a severe performance degradation [72]. To overcome ACI, 40 MHz channels can be configured in the 5 GHz frequency spectrum where 24 non-overlapping channels are available for seamless data transmission to achieve better overall throughput using the channel bonding feature.

2.3.4.4. Multiple Input Multiple Output (MIMO) systems

The MIMO is an antenna technology introduced into wireless communication to improve the signal performance and to achieve maximum available throughput. It employs multiple antennas at source (transmitter) and destination (receiver) to transmit and receive the multiple streams of wireless signals [73]. This concurrent transmission of a signal through multiple antennas at the sender's end and received with multiple antennas at the receiver's end enhanced reliability, range and throughput of the 802.11n MIMO system [74].

These wireless signals transmitted from the transmitter travels through multiple paths in the wireless environment (air) and received by the receiver with some delay (in a nanosecond). In some cases, this leads to nullify or corruption of the signal at the receiver's end. This signal path and propagation delays between network nodes are due to the reflection, scattering, diffraction and refraction of the signal [75]. The multi-path delays can be very destructive within legacy protocols such as 802.11a/b/g as they only transmit single streams of data transmission. However, this can be avoided in 802.11n by using two very unique processing functions employed by the MIMO technology, as explained below:

1. **Precoding** [76]: Precoding refers to the course of action performed on the signal processed at the transmitter end and is also referred to as multi-stream Beamforming. With the beamforming feature, the access points can focus all of the wireless signals to a specific receiving devices or client's location, rather than spreading a signal in all direction. The more direct signal is aimed at the receiver with Beamforming, thus improving the signal strength, range, and reliable throughput.
2. **Spatial Multiplexing** [77]: Spatial Multiplexing (SM) or Space-Division Multiplexing (SDM) is used in MIMO wireless communication to transmit independent and separated channels/spatial streams of RF chains to boost throughput performance. These independent spatial streams are used to transmit data streams by their multiple MIMO antennas. Using the approach of sending spatial streams and MIMO helps increase the system's data rate at the cost of more power consumption due to added complexities of MIMO related processing and circuits.

2.3.4.5. Band Steering

Band steering is initiated and governed by Wireless Access Points (WAPs) to manage several client devices on the network. The WAPs enabled with the band steering can work or switch between 2.4 and 5 GHz frequency bands. Unlike legacy protocols such as 802.11a/b/g, 802.11n can facilitate band steering to operate on both the frequency band [74]. Table 2.5 below lists different frequency bands of some of the IEEE 802.11 standards. The typical operating range for a WAPs is either 2.4 GHz or 5 GHz band, depending on IEEE's 802.11 standards. WAPs and client's devices' efficiency is diminished due to the overuse of 2.4 GHz frequency band as 802.11b/g/n, and other devices such as Microwaves, Bluetooth and many Wireless devices strictly operate in it.

Table 2. 5. Frequency Spectrum for IEEE 802.11 Amendments [78]

Frequency Band/Wi-Fi	2.4 GHz	5 GHz
IEEE 802.11b/g	Y	N
IEEE 802.11a	N	Y
IEEE 802.11n	Y	Y
IEEE 802.11ac	N	Y
IEEE 802.11p	N	Y

However, 802.11n, which operates in both the frequency band, can benefit from a less crowded 5 GHz frequency band where the client and WAPs can support higher transmission rates with increased client's capacity. Band steering is a prominent solution for constantly evolving Wi-Fi technology and client demand for higher data rates with backward compatibility with the legacy protocols over 2.4 GHz and 5 GHz band [79].

2.3.4. The 802.11ac protocol

Table 2.6 below summarise the data rates on different devices with 80 and 160 MHz of channel bandwidth. The 802.11ac is an improved, faster and more scalable version of IEEE 802.11n [63]. 802.11ac provides higher data throughput than the 802.11n in multi-user Wireless Local Area Networks (WLANs) [53]. The 802.11ac strictly operates in the 5 GHz frequency band and works on 20, 40, 80 and 160 MHz of channel bandwidth to achieve a throughput from 433 Mbps to 6.77 Gbps [52, 80]. The 802.11ac support extended feature of 802.11n such as wider channel bandwidth, improved modulation and coding scheme for gaining higher spectral efficiency, multi-user MIMO (MU-MIMO) and improved Beamforming to gain Very High Throughout (VHT) [81]. Table 2.6 below summarise the data rates on different devices with 80 and 160 MHz of channel bandwidth.

Table 2. 6. Data Rates on 80 and 160 MHz Channel Bandwidth of 802.11ac [63]

Nominal Configuration	**Bandwidth (MHz)**	**Number of Spatial Stream**	**Constellation Size and Rate**	**Guard Interval**	**PHY Data Rate (Mbps)**	**Throughput (Mbps)**
Min	80	1	64QAMr5/6	Long	293	210
Low-end Product	80	1	256QAMr5/6	Short	433	300
Midtier Product	80	2	256QAMr5/6	Short	867	610
High-end Product	80	3	256QAMr5/6	Short	1300	910
80 MHz amendment Max	80	8	256QAMr5/6	Short	3470	2400
Low-end Product	160	1	256QAMr5/6	Short	867	610
Midtier Product	160	2	256QAMr5/6	Short	1730	1200
High-end Product	160	3	256QAMr5/6	Short	2600	1800
Ultra- High-end Product	160	4	256QAMr5/6	Short	3470	2400
160 MHz amendment Max	160	8	256QAMr5/6	Short	6970	4900

2.3.4.1. Frame aggregation

The frame aggregation features in IEEE 802.11 standards improve the data throughput by reducing inter-frame timing between the symbols and allowing multiple MSDUs to be sent to the same receiver concatenated in a single MPDU. In 802.11ac, the significant improvement in frame aggregation compared to the 802.11n can give up to 400 % higher throughput for higher MCS indexes of 802.11ac [82]. The frame aggregation in 802.11ac also works on similar principles as 802.11n; however, 802.11ac supports enhanced A-MSDU and A-MPDU with a larger size to accommodate more transmission frames. The maximum size of A-MSDU and A-MPDU is increased from 7935 to 11406 bytes (without security encapsulation overhead) and 65535 to 104875 in 802.11ac, respectively [80]. Due to the aggregated and larger size of MSDU and MPDU, more packets can be sent over the wireless signal to the receiving stations (STAs). Consequently, this approach reduces and balances the load evenly on STAs as no packets are waiting in the queue to be transmitted, resulting in higher data throughput over the network.

2.3.4.2. Channelisation

The channelisation refers to sharing point-to-point communication over the air by adjusting the WAPs to communicate on their specific channels to avoid any inter-channel interference. These channels are assigned by the Federal Communications Commissions (FCC) to allow specific channels to communicate or transmit a signal over Radio Frequency (RF). In a WLAN environment, 802.11 standards specify communication protocols to achieve higher data throughput within the available channels. In 802.11 standards, new additional feature such as wider channel widths and multiple spatial streams allows communication protocols to achieve maximum data rates.

In recent amendments of 802.11ac, more channels are added to the RF band, which supports 20, 40, 80 and 160 MHz channels width [83]. The principal of channelisation is extended from 802.11n with more non-overlapping channels available for data transmission in 802.11ac. This is very useful to mitigate the problem of in-band channel interference in 802.11n. There is a high probability of channels overlapping due to a limited number of channels available for data transmission in a multi-user wireless environment. In 802.11ac, only non-overlapping channels are defined by the IEEE standards. The 40 MHz channels are formed by merging two adjacent 20 MHz channels without partially overlapped 40 MHz channels, and 80 MHz channels are formed by two 40 MHz contiguous channels, without partially overlapped 80 MHz channels. The 802.11ac only have two 160 MHz channels, and similar operations are applied to it to avoid in-band interference. More non-contiguous channels of 80 MHz are included to increase the throughput gains and data rate from two 160 MHz channels. With this channelisation approach, 802.11ac can achieve data rates of 866.6 Mbps over 160 MHz channel width using a single stream, 256-QAM, 5/6 coding and 400ns of short guard interval [84].

2.3.4.3. MU-MIMO systems

According to [85], "MU-MIMO is a technique where multiple stations, each with potentially multiple antennas, transmit and receive independent data streams simultaneously". The WAPs configured with 802.11n can transmit multiple data streams to only a single client device, transmitting multiple data streams to multiple clients when configured with 802.11ac [83]. The 802.11n employs MIMO technology to transmit data to their clients, whereas 802.11ac employs MU-MIMO technology to communicate with their client. Therefore, clients gain a higher data rate by using WAPs configured with 802.11ac than those configured with 802.11n [84]. 802.11ac supports 8 multiple streams with MU-MIMO technology which helps distribute the data streams to multiple clients/stations simultaneously compared to 802.11n, where 4 spatial streams distribute the data streams to one client/station [86].

The Single User (SU) and Multi-User (MU) MIMO transmission can be understood from the example in Figure 2.3. In Figure 2.3(a), it can be noticed that a multi-antenna station (AP) is communicating with a single client user at a given time. Here, the station uses space-time codes to provide diversity gains and consequently increasing reliability. Moreover, the link capacity is also increased due to transmitting different information on different streams [87]. In Figure 2.3(b), the basic idea of MU-MIMO is illustrated; here, the station can serve multiple single or multi-antenna client users simultaneously. In a perfect world, the station's communication using simultaneous data streams enabled by MU-MIMO is only constrained by the number of antennas present on AP (transmitter) or client users (receiver). For example, in Figure 2.3(b), three client users together possess five receiving antennas distributed among them; however, the AP has only four antennas to communicate with them.

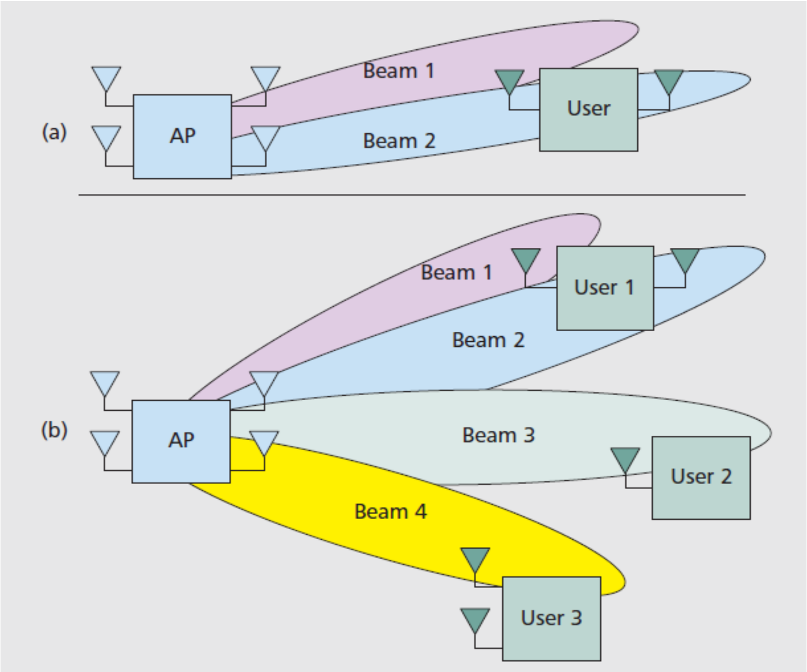

Figure 2. 3. Different MIMO Concepts: a) SU-MIMO beamforming; b) Downlink MU-MIMO beamforming [51]

2.3.4.4. Transmit beamforming

Several transmit beamforming options available in 802.11n makes it difficult for multiple manufactures device to interoperate seamlessly. By introducing a complex signal processing in the WLAN chipset of 802.11ac, transmit beamforming can be achieved. Moreover, to mitigate the issue of interoperability between different manufacturers, 802.11ac employs Explicit Compressed Feedback (ECFB) [88]. Multiple antennas with high gain are used to transmit to the 802.11 clients to improve overall system performance. This results in a higher downlink Signal-to-Noise Ratio (SNR) and provides a higher data rate over a more extended range [89]. This transmit beamforming system is unique to 802.11ac and can be used to enable both SU-MIMO and MU-MIMO. The wireless signals are reflected or refracted on their path to the receiver once transmitted from the transmitter causing wireless signals to propagate multiple paths. To mitigate the issue of multi-path effect, engineers use channel sounding to evaluate the radio environment for wireless communication, especially MIMO systems. In channel sounding, this multidimensional spatial-temporal signal is processed to estimate the channel characteristic to design a wireless system [90]. Therefore, the Beamforming directs the wireless signals precisely towards the receiver to allow data streams to be sent to single or multiple users.

2.3.5. 802.11p: Dedicated Short-Range Communication (DSRC)

IEEE 802.11p/WAVE (Wireless Access in Vehicular Environments)/DSRC (Dedicated Short-Range Communications) is an emerging standard intended to support wireless access in VANETs. These communication types can be defined as one-way or two-way access for short to medium range wireless communications channels. These channels are specifically designed for an automotive purpose and involve a set of wireless protocols and standards from PHY to the application layer in VANETs [91].

The 802.11p standards are designed to enable the deployment of VANETs in a high-speed vehicular environment. The 802.11p standard is an amendment of the 802.11-2007 standard, which combines the physical layer of IEEE 802.11a along with Quality of Services (QoS) from IEEE 802.11e. The IEEE 802.11p standard/protocol is based on Orthogonal Frequency Division Multiplexing (OFDM) communication and is designed to enable the deployment of Vehicular Ad-hoc Network (VANET) at high speed and sparse density of driving environment[92]. Moreover, small modifications are proposed to achieve a robust connection under high velocities by [93, 94].

The clock speed of 20 MHz of 802.11a is halved to 10 MHz bandwidth with doubling the time-domain parameters and reducing the data rates to achieve a stable and robust connection deployment for the vehicular network. Consequently, the effect of Doppler spread is reduced by decreasing the channel bandwidth and inter-symbol interference is also reduced is reduced by using a larger guard interval which is caused by multi-path propagation. From the ADVs application perspective, it is imperative to have a robust Physical-layer protocol that is capable enough to provide reliable Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication in a wide variety of driving environments [95].

In the United States, for the 802.11p, the FCC allocated 75 MHz in the 5.850-5.925 GHz band in contrast to the ETSI, which allocated 70 MHz in the 5.855-5.935 GHz band. The allocated frequency band is divided into six service channel (SCH) and one control channel (CCH) with equal bandwidth of 10 MHz. According to ETSI, every channel is assigned for a specific application: from the range 5.855 GHz to 5.875 GHz is dedicated to ITS non-safety applications, 5.875 GHz to 5.905 GHz, is dedicated to safety and traffic efficiency applications, and 5.905 GHz to 5.925 GHz to future applications in ITS [96]. The DSRC system supports a vehicle speed up to 200 km/h, the nominal transmission range of 300 m to 1000 m, and the default data rate of 3 Mbps to 27 Mbps [97].

The system integrates 52 subcarriers using modulation techniques, such as binary and quadrature phase-shift keying (BPSK/QPSK), 16 quadrature amplitude modulation (16-QAM or 64-QAM). Moreover, Forward Error Correction (FEC) coding is incorporated with a coding rate of ½, 2/3, or ¾. For network security issue in the WAVE standards, the IEEE 1609 high layer standards are implemented. The IEEE 802.11p operates on about 9 channels, each of which has a frequency, as shown in Figure 2.4 below. Channel 178 at 5.890 GHz is predominantly used for safety communication and link establishment [98, 99]. However, the two channels on both the end of channel frequency bands are used for exceptional cases such as security solutions and manage congestion control on the other channels. The other service channels are responsible for bidirectional communication between different types of units.

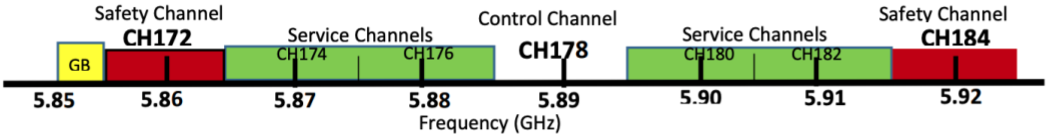

Figure 2. 4. IEEE 802.11p Channel Frequency Bands [96]

Tables 2.7 and 2.8 below depicts the communication parameters, modulation schemes and data rates for IEEE 802.11p PHY.

Table 2. 7. Communication Parameters of 802.11p PHY Layer [100]

Parameters	**Notation**	**IEEE 802.11p**
Channel width	$Ofdm_{bw}$	10 MHz
Symbol Duration	*Tsymbol*	8 μs
Guard Time	*Tg*	1.6 μs
PLCP Preamble Duration	*Tprem*	32 μs
Signal Field Duration	*Tsignal*	8 μs
Sub-carrier Spacing	Δf	0.15625 MHz
Frequency Range	*Frange*	USA: 5.860-5.925 GHz EU: 5.875-5.925 GHz
Maximum EIRP	$EIRP_{max}$	USA : 30 W (44.8 dBm) EU : 2 W (33 dBm)
SIFS Duration	*Tsifs*	32 μ s
Slot Time	*Tslot*	13 μ s
CW Min (VO, VI, BE, BK)	*CWmin*	3,3,7,15 CCH Channel
CW Max (VO, VI, BE, BK)	*CWmax*	7,7,15,1023 CCH Channel
AIFSN (VO, VI, BE, BK)	*Aifsn*	2,3,6,9 CCH Channel
Multi-channel Operation	–	USA: Channel Switching Single Radio EU: One Radio CCH + One Radio SCH

Table 2. 8. IEEE 802.11p Modulation Scheme and Data Rates [101]

Modulation Type	**BPSK**	**QPSK**	**16-QAM**	**64-QAM**
Coding Rate	1/2 3/4	1/2 3/4	1/2 3/4	2/3 3/4
Coded bit rate in Mbps	6	12	24	36
Data Rate in Mbps	3, 4.5	6, 9	12, 18	24, 27
Data bits per OFDM symbol	24, 36	48, 72	96, 144	192, 216

2.4 Software Defined Network (SDN)

As mentioned in Section 2.2 above, several challenges need to be addressed for VANETs, such as Internetworking Issue (Heterogenous V2X Networks such as DSRC, LTE-V 60 GHz and Wi-Fi), adaptive network configurations for rapidly changing vehicular topologies, and dynamic resource allocation. The network management for VANET is very challenging as it demands very sturdy and flexible network management. However, the rigid nature of underlying network infrastructure provides very few possibilities for further innovations and improvements since most of these network devices are generally closed, proprietary and vertically integrated [102].

A new paradigm in networking, SDN tends to resolve these issues between multiple vendor devices and their interoperability with each other. For example, SDN separates or decouples the data (i.e., User Equipment) and control (i.e., Network/SDN Controller) plane. The network switches in the data plane are simply used for forwarding packets, while a logically centralised software program (SDN controller) controls the behaviour and decision making for the entire network. Therefore, SDN greatly simplifies network devices as they no longer need to understand and process thousands of protocol standard but merely accepts instructions from the SDN controller. This approach opens up many new possibilities for network management and configuration methods on different vendor devices in a heterogenous vehicular environment. Figure 2.5 below shows the logical multi-domain architecture of SDN.

The access points are network devices that usually contains both a control and a data plane. The control plane decides if the data traffic is permissible or not on the link and where to route the traffic on the network. In contrast, the data plane forwards the traffic to the particular node/user in a network once the control plane's decision is made via OpenFlow.

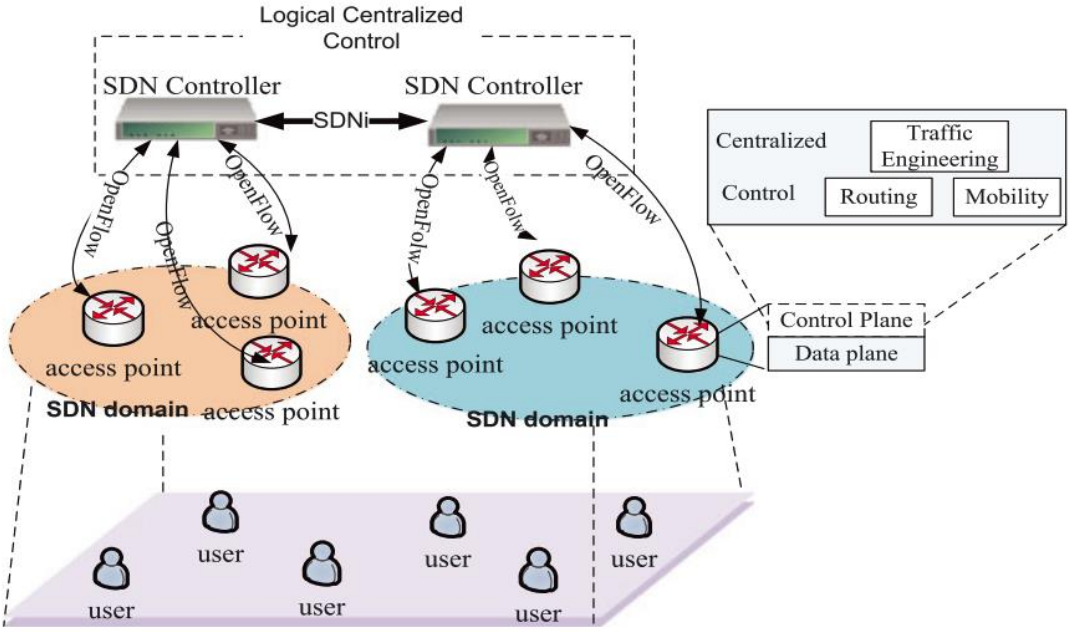

Figure 2. 5. Network Architecture of Software-Defined Networking [103]

In SDN infrastructure, the access points' data and control plane are logically separated by an SDN controller to imparts a centralised control of these access points. Therefore, the SDN controller has a global view of the network environment, and it communicates using the OpenFlow protocol with access points or other network peripherals [104].

Usually, thousands of devices can be managed by a single SDN controller. However, for multi-tier/domain and heterogeneous network environment, several SDN controllers can be deployed. In such a scenario, SDN controllers manage their domain individually and operate on their policies defined for that particular domain. The communication and control mechanism between these SDN controllers can also be controlled logically via SDNi protocol [105], which helps SDN controllers to exchange information about different domains and gain a holistic picture of the network topology.

2.4.1. SDN for Vehicular Networks

SDN provides flexibility, programmability and centralised control of network topologies, extending its benefits to vehicular communication for managing network and communication resources. This can benefit in optimising channel allocation, network selection and reducing interference in multi-channel and multi-radio environment, consequently improving packet routing in multi-hop communication for high-speed vehicular scenarios. Figure 2.6 below depicts a high- and low-level reference architecture of Software Defined Vehicular Network and summarised some of the main components and perspective of software-defined VANETs.

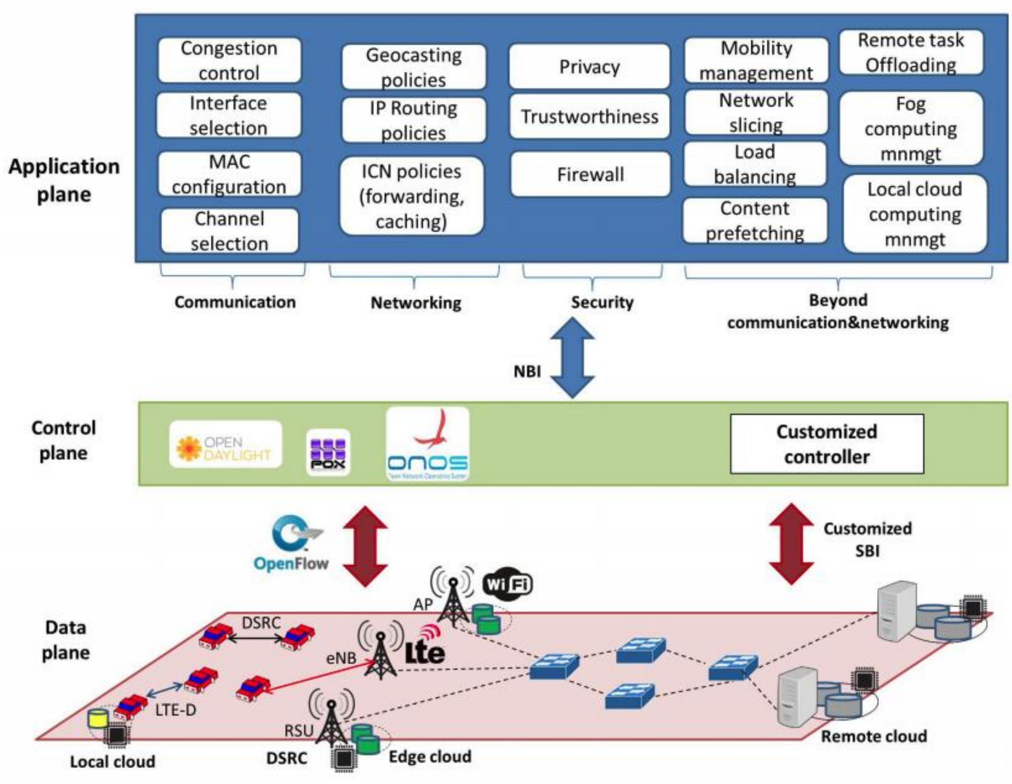

Figure 2. 6. High and Low-Level Architecture of Software-Defined Vehicular Network [106]

It can be seen that the data plane consists of several network switches, RSUs, BSs cellular network nodes and vehicular devices. The control plane consists of several different SDN controllers, including the legacy (OpenFlow) controller and other controllers specifically designed for a high-level vehicular application in the application plane. These controllers manage and track the devices in the data plane and administer the forwarding rules into them via an Application Programming Interface (API), which are also called as Southbound Interface (SBI) (for example, OpenFlow). Towards the controllers' top, a network application is present and connected by the Northbound Interface (NBI). These multiple controllers operate independently of each other; however, they share important information about a specific operation with one another. They perform operations such as deciding and configuring Communication/Radio access technologies/protocols, routing and forwarding decisions (IP or non-IP based), enforcing security policies, and orchestration of resources like network utilisation and low latency communication.

2.4.1.1. SDN Control for Real-time Constraints

A fully centralised SDN controller for a vehicular network would not be sufficiently capable enough to manage the flow of multiple status information exchanges between vehicular applications. These applications are very time-sensitive and demand very-strict or low latency of data communication between a controller and the controlled network elements. Moreover, configuring a controller with such a complicated design would adversely affect the vehicular network's real-time communication requirement. Therefore, a hybrid controller design is required with a hierarchical organisation of controllers, where primary and secondary controllers should be defined to maintain a global view of the network topology and managing low-latency vehicular applications, respectively [107].

In the hybrid SDN controller design for vehicular networks, the controller allocates some designated tasks to the local base stations (BSs) and Road-side Unit (RSUs) and works mutually to balance the load and operation mechanism of the entire vehicular networks [108, 109]. Moreover, the BSs and RSUs are enforced with the controller's abstract policy rules according to their local knowledge of the vehicular network. The vehicles position are continuously varying, and their road and position status estimations can be calculated by the trajectory scheme proposed by [110], which also helps reduce the overhead incurred while tracking the varying vehicle positions.

2.4.1.2. Extending SDN Control to RSUs and OBU

The RSUs are used to control and monitor the vehicle's communication and safety on the road, and for that, they use OBUs in the vehicle to collect/transfer information from the vehicle about their trajectories and driving status information. The RSUs can be enabled with SDN for VANETs by programming or configuring like an OpenFlow switches. Moreover, it can be extended to the OBUs, which will act as an abstracted end-user in the data plane and operated by the SDN controller for information sharing between neighbouring vehicles (V2V one-hop and multi-hop communication) and RSUs [108-110].

2.4.1.3. Broadening the SDN Scope Beyond Packet Forwarding

SDN dynamically adapt forwarding decisions according to the information collected by the SDN controller from multiple nodes on the network. Consequently, improving the network utilisation and communication reliability. For example, the SDN controller keeps a record of multiple paths between source and destination, and in case of any path failure, the packets can be dynamically routed through the next available path without delay. Moreover, in a vehicular environment, the SDN controller also controls other functions (non-routing related) than just packet forwarding [111]. For example, the controller also manages the transmissions power levels of nodes to avoid any interferences in a dynamic high-density vehicle scenario on the road.

2.4.1.4. Congestion Control

Traditionally, in VANET, the parameter settings are hard-coded on the chip or decided on the knowledge available from one-hop or two-hop communication based on local information collected by the vehicles. The parameters such as transmission rates, data rates, transmission power and inter-packet generation interval can be modified dynamically to improve vehicular networks' performance by incorporating non-local (global) information provided by the SDN. For example, the channel load estimation can be more precisely calculated and managed by an SDN controller than multiple vehicles by using a critical decentralised congestion control (DCC) scheme to improve the overall VANET performance [112].

2.4.1.5. Multi-Radio Multi-Channel Resource Assignment and Virtualising MAC

For vehicular communication, radio interface and data type (depending on the type of traffic) can be dynamically assigned to the vehicles' multi-radio OBUs by an SDN controller. This decision-making depends on the channel interference level and data priority, which consequently improves the performance of medium access control (MAC) protocols on each channel.

The extension of virtualisation techniques used in the development of new MAC protocols design will allow SDN controller to inform a specific RSU/OBU to operate on proper MAC instance, for example, Time Division Multiple Access (TDMA) or Carrier Sense Multiple Access/ Collison Avoidance (CSMA/CA), on a specific channel to fulfil the requirement of a particular instance of a vehicular application [113]. Moreover, the vehicular applications can benefit from a TDMA scheme, as it provides ultra-low latency with high-reliability for autonomous driving applications [114].

2.4.1.6. Heterogeneous Access Technologies

The vehicular technology can be benefitted from having to operate using multiple wireless access technologies such as LTE, LTE Direct, DSRC, WiMAX and Wi-Fi in a heterogeneous deployment of VANETs. Moreover, SDN can help widen the scope of the communication technologies available for the vehicle's interface (OBUs) to interact with neighbouring vehicles over V2V or non-local vehicles using V2I technologies. These communication technologies can be assigned to the control or data plane in SDN technology, where the SDN controller can select the most suitable wireless technologies to use for a particular transmission in a heterogenous data plane [107, 110]. For example, a Cloud-Radio Access Network (C-RAN) can customise the service provision from BSs depending on the vehicular network's traffic load and service requirements [107].

2.5 Car Following Behaviour

Car Following (CF) behaviour characterises the vehicles' longitudinal interaction with other vehicles on the road. The CF model was initially introduced in 1950 and 1953 by Reuschel and Pipes, respectively [115, 116]. A CF model can be defined as a mathematical model of a follower vehicle's movement in a single lane scenario, where the follower vehicle changes its driving states (acceleration and deceleration) according to the vehicle in front without overtaking. Moreover, it provides a bridge between the macroscopic traffic flow theory and microscopic traffic flow models [117]. Over the past decades, a number of mathematical models on car-following behaviour have been proposed by traffic engineers and traffic psychologists based on empirical examination and conceptual principles. The foundation of these models is based on simulations and traffic control theories. One of the early linear CF models has been proposed by Chandler et al. [118] and Herman et al. [119] while non-linear models proposed by Reuschel [116], Pipes [115], Gazis et al. [120], Newell [121], Bando et al. [122], Helbing and Tilch [123] and Jiang et al. [124].

The first prototype of the car-following model was proposed by Chandler et al. [118] in 1958 at the General Motors Laboratory. According to the vehicle's relative velocity in the front, the entire model was based on the change in the follower driver's acceleration/deceleration profile. Furthermore, this model was further extended by discussing the impact of leading neighbouring vehicles' car-following behaviour by studying local and asymptotic stabilities of traffic flow in the vehicle fleet by Herman et al.[119]. The first analytical studies of the car following models were proposed by Reuschel and Pipes, which others followed, and many such models were developed based on the model of Pipes [115, 116].

A non-linear follow the leader model of traffic flow was proposed by Gazi et al. [120] in 1961. This model provided a steady-flow equation for traffic flow from the collected observational and experimental data. Furthermore, Newell proposed another non-linear car-following model considering headway distance as a stimulus, as he believed the driver's stimulus originates from headway distance instead of the relative speed between the follower's and leader vehicle in a fleet [121]. Another more concurring optimal velocity (OV) car-following models was proposed by Bando et al. [122] in 1995. This model is more prevalent among the research community as it further discusses several properties of actual traffic flow, such as unstable traffic flow, rise in traffic congestion and formulation of stop-and-go traffic scenarios. However, empirical data suggests that the OV model produce unrealistic acceleration and deceleration profile, which Helbing and Tilch further investigated by proposing a generalised force (GF) model considering negative velocity difference to mitigate this issue in 1998 [123].

2.5.1. Car Following Models

As discussed above, numerous car-following models have been developed to explain CF behaviour under varying conditions. These CF models are mostly based on a stimulus-response scheme, which General Motors research laboratories initially proposed. The CF scheme presumes that every driver responds to a particular stimulus, as stated in the following equation [125]:

$$Response \ = Sensitivity \times Stimulus$$

or

$$[Response]_n \propto [Stimulus]_n$$

From the above relationship, it can be seen that for the n^{th} vehicle, all the neighbouring drivers can only respond by accelerating and decelerating their vehicles velocities when responding to the traffic conditions. The difference in their views about the stimulus has given rise to the multiple theories of CF models. Therefore, a stimulus can be thought of as consisting of more than one entity/variable such as vehicle's speed/velocity, relative speed/velocity or headway distance and can be expressed by a function as,

$$a_n^t = \mathcal{F}_{sti}\,(v_n\,,\Delta x_n\,,\Delta v_n),$$

where, $\mathcal{F}_{\text{sti}}$ is the stimulus function that depends on the speed of the current vehicle, v_n, relative position, Δx_n and relative speed, Δv_n with the front vehicle.

Based on these theories, a single-lane highway car following model was proposed by Bando et al. in 1995 [122]. This model was based on OV (optimal velocity) functions, and it optimised OV principles with the help of distance headway, the motion function is expressed as follows

$$a_n(t) = k\left(V\big(\Delta x_n(t)\big) - v_n(t)\right).$$

Here, $v_n(t)$ denotes the velocity of the *n*th vehicle at time *t;* $\Delta x_n(t) = x_{n-1}(t) - x_n(t)$ is the headway distance between the n^{th} vehicle (follower) and the leader vehicle (*n-1*) at time *t*; $x_{n-1}(t)\ and\ x_n(t)$ are the positions of the (*n-1*) and *n* vehicles, respectively; *k* is the sensitivity parameter of the driver, and $V(\cdot)$ is the OV function which can be formulated as,

$$V\big(\Delta x_n(t)\big) = v_1 + v_2\tanh(c_1(\Delta x_n(t) - l) - c_2).$$

Here, *l* is the length of the vehicle n, and $v_1, v_2, c_1, and\ c_2$ are the parameters of the OV functions, which lacks the physical meaning and must be calibrated.

2.5.2. The Intelligent Driver Model (IDM)

A cellular automaton can realise the main principle of microscopic models, and these models consider CF behaviour with respect to time continuity. A well-known CF model such as Gazis-Herman-Rothery (GHR), Optimal Velocity (OV), and Collision Avoidance is used to simulate the interaction between neighbouring vehicles in an on-road traffic situation [117, 120, 126].

2.5.2.1. Derivation

The acceleration function for a specific vehicle *n* is described as follows [120, 126]:

$$\dot{v}_n(t+\ T_r) = \frac{-\leftthreetimes\ v_n^{m1}\Delta v_n}{s_n^{m2}}$$

In the above equation, $\dot{v}_n$ is the acceleration of the nth vehicle, reaction time is denoted as T_r , $\leftthreetimes$ is a constant coefficient, $m1$ and $m2$ are constant exponents that determine the Ordinary Differential Equation (ODE) order, while bumper-to-bumper gap (s_n) to the vehicle ahead is defined by the equation below where l_n defines the length of the nth vehicle:

$$s_n = x_{n-1} - x_n - l_n$$

The relative velocity and the deceleration strategy are directly proportional to the approach rate of vehicle *n* to the leader vehicle or vehicle in front v_{n-1} which is given by

$$\Delta v_n(t) = v_{n-1}(t) - v_n(t) \tag{2.1}$$

It can be seen from the (2.1), that the acceleration of the nth vehicle is directly depended upon the velocity of $(n-1)$th vehicle in the referenced model, which is not appropriate for free-traffic and low-density driving conditions. Moreover, these types of models are also not suitable for predicting accurate gap, s_n between the vehicles in dense traffic situations as the gap between the vehicles does not relax to an equilibrium value. For example, if the relative velocity Δv_n between two vehicles is zero, then the smallest value of s_n will not necessarily initiate deceleration, which will result in an accident. Also, these models do not consider any speed limit restriction for vehicles speeding on the free road. To address the abovementioned challenges, Newell proposed OV model with an acceleration function as follows [121]:

$$\dot{v}_n(t + T_r) = V\big(s_n(t)\big) = v_0\left[1 - e^{\frac{-(s_n - s_0)}{v_0 T}}\right] \tag{2.2}$$

In Equation 2.2, the term v_0 [miles/hr] is the desired velocity, which allows vehicles to accelerate until a certain threshold speed along with the safe time headway T [seconds] on a free road scenario. Moreover, desired or actual distance s_0 is introduced to keep a safe gap between two vehicles to avoid any collision or accident. However, these add on dependency on density makes it generate unrealistically high acceleration on the order of $\frac{v_0}{T_r}$. Similar OV model to Newell is proposed by Bando et al. [122] and it is as follows:

$$\dot{v}_n = \frac{V(s_n) - v_n}{\tau} \tag{2.3}$$

Here, the velocity relaxation time, τ can be compared with the reaction time, T_r in Newell's models. Bando's model required $\tau < 0.9$ for keeping the model collision-free, but it suffered from generating problematically high acceleration. Both the OV models (Newell's and Bando's) suffered unpredictable high acceleration since the model did not consider vehicle interactions, which are the most sustainable real-life traffic condition characteristics.

The IDM is a highly complicated and deterministic CF model (time-continuous and autonomous) from the OV family, with more improvements to provide accident-free driving. This model combines the vehicles' desired velocity on a single road and free driving condition with implementing a new breaking strategy to avoid any collisions or accidents. The acceleration function for IDM is given below with their standard parameters lists in Table 2.9:

$$\ddot{x}_n(s_n, \dot{x}_n, \Delta\dot{x}_n) = a\left[1 - \left(\frac{\dot{x}_n}{\dot{x}_{0,n}}\right)^{\delta} - \left(\frac{s^*\ (\dot{x}_{n,}\ \Delta\dot{x}_n)}{s_n}\right)^2\right], \tag{2.4}$$

where the desired gap s^*, which is essential for new braking strategy is determined by,

$$s^*(\dot{x}_{n,}\Delta\dot{x}_n) = s_{0,n} + T\dot{x}_n + \frac{(\dot{x}_n\Delta\dot{x}_n)}{2\sqrt{ab}} \tag{2.5}$$

Table 2. 9. IDM Standard Parameters

Notation	**Description**	**Realistic Bound**	**Realistic Values**
$\dot{x}_{0,n}$	Desired velocity	[0,50]	33.33 $\mathrm{m/s}$
T	Safe Time Headway	[1,3]	1.6 $\mathrm{m/s}$
a	Maximum Acceleration	[0.5,2]	2 $\mathrm{m/s^2}$
b	Comfortable Deceleration*	[0.5,2]	2 $\mathrm{m/s^2}$
δ	Acceleration Exponent	-	4 $\mathrm{m/s}$
l	Length of Vehicle	[5,10]	5 m
s_0	Linear Jam Distance	[0,5]	2 m

The essential characteristics of the IDM Model, which makes it collision-free, are as follows:

1. The model is collision-free with a unique dependency on Δv_n.
2. All the model parameters are known to be relevant and can be easily interpreted.
3. They are also empirically measurable and within the expected order of magnitude.
4. The model is stable, and it can be calibrated using empirical data.
5. The model functions can be numerically/analytically simulated.
6. An identical macroscopic model is known for IDM, which simplifies the model's calibration [127].

2.5.3. Consensus-based model car following models

Another important class of car-following models are the so-called consensus-based (or microscopic) car-following model. These are mainly models derived using cooperative control whereby all the car is following the leader (node 1) by maintaining a reasonable gap, as shown in Figure 2.7 below.

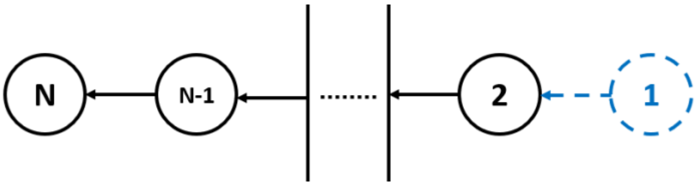

Figure 2. 7. Car following topology

The model can be mathematically expressed as [128],

$$\ddot{x}_n = a + \mathrm{k}_1(\dot{x}_n - \dot{x}_1) + \sum_{j\in N_j} a_{nj}\left(k_2\left(x_n - x_j - l_n\right) + k_3\left(\dot{x}_n - \dot{x}_j\right)\right) \qquad (2.6)$$

where $\ddot{x}_n$ and $\dot{x}_n$ are the acceleration and velocity of the n^{th} vehicle respectively, the position and length of the vehicles are denoted by x_n and l_n respectively, k_1, k_2 and k_3 are gains to be designed to achieve stability and a_{nj} are coefficient of the Laplacian matrix associated with the above graph, N_j is the set $\frac{\{1,2,\ldots,N\}}{\{j\}}$.

It should be noted that the above model is solely based on stability consideration in order to avoid a collision. It does not take into account the behavioural attributes of the driver. For this reason, throughout this work, we will use the IDM model (2.4) - (2.5). However, it should be noted that the control and communication scheme developed and implemented in this work can be applied by using any appropriate car-following and communication model.

2.6 Chapter Summary

In this chapter, the state-of-the-art communication technologies suitable for autonomous driving vehicles were presented. We have identified some of the suitable technologies from the literature which will help shape our hypothesis and they are as follows:

1. We explored different communication technologies for ADVs such as channel access mechanism, V2V, V2I, V2P, and VANETs.
2. We explored IEEE communication standards for indoor and vehicular communication such as 802.11a/n/ac/p.
3. We explored SDN to accommodate the demands of vehicular communications such as internetworking issue between different vendors, adaptive network configurations and dynamic resource allocation.
4. Finally, we explore Consensus and CF models to understand their behaviour and characteristics.

To address the requirement for safe driving ADVs, we are going to investigate and develop a hybrid data-driven model using the technologies listed above. The theoretical analyses and challenges of the abovementioned technologies in this chapter will be investigated practically in the following chapters to attest its suitability for vehicular communication in autonomous driving vehicles. The next chapter will discuss and investigate how wireless protocol standards in the 5 GHz frequency spectrum operates in a heterogeneous indoor environment and we will test their backward compatibility with the legacy protocol standards.

Chapter 3

Investigation of Backward Compatibility of IEEE 802.11a/n/ac Protocols

3.1 Introduction

As mentioned in the Chapter 1 (Section 1.3), we aim to develop and implement a V2X control and communication scheme for a connected vehicle fleet. However, while implementing V2X, one needs to have a set of rules/standards for the data to travel from Vehicle-to-Vehicles (V2V) and Vehicles-to-Infrastructure (V2I) in a wireless setting. In this regard, the Wireless Local Area Network (WLAN) technology provides an easy-to-use auto-configuration and self-healing capability for wireless broadband connections and, as a result, has become the core of internet communication. This development has introduced many prototyping and augmentation to IEEE 802.11 standards' legacy protocols, causing interoperability issues among different devices. In Chapter 2 Section 2.3, the advancement in IEEE 802.11 Wireless Protocols is discussed. We shall recall these protocols' main features and investigate how they can be employed for vehicular networks. The IEEE 802.11 wireless standard works on multiple PHY layer and a single Medium Access Control (MAC) Layer in WLAN, and they operate in a frequency spectrum of 2.4 GHz to 5 GHz. The deployment of a wireless network in a 2.4 GHz frequency spectrum over the years has affected the performance of the wireless network due to congestion of a spectrum, and it leads to an increase in interference between neighbouring devices [129]. The emerging wireless technologies, which operate in the 5 GHz frequency spectrum, have a number of advantages over 2.4 GHz in terms of more non-overlapping channels with wider channel bandwidth to gain higher throughput and less distortion from neighbouring devices. However, 5 GHz wireless network technology suffers from signal attenuation at higher frequencies, resulting in a lower communication range than 2.4 GHz network technology. Therefore, 802.11 WLAN's efficiency is severely compromised due to interference by other Wireless LAN technologies operating in the same environment, affecting the data throughput and efficiency of Wireless Network. The IEEE 802.11ac works in the 5 GHz frequency spectrum, and their devices performance evaluation has been widely explored over simulation platform. However, there is not much experimental evaluation done in practical scenarios to attest their performance and backward compatibility with legacy devices [130, 131].

In this context, this chapter conducts an experimental study on the evaluation of throughput, range, efficiency and backward compatibility (interoperability and roaming) performances of IEEE 802.11a, 802.11n and 802.11ac standards operating at 5 GHz frequency spectrum in an indoor Line-of-Sight (LOS) heterogeneous wireless environment. Moreover, deciding a suitable migration strategy could be capable enough to migrate from legacy protocols to IEEE 802.11ac or co-exist with them in an enterprise network deployment and check if they are suitable for vehicular communication. To this end, we first proposed an experimental testbed for examining the maximum throughput of IEEE 802.11 standards and compared their theoretical and experimental throughput over Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) protocols for different sets of parameters and features. Secondly, we proposed multiple tests for determining each protocol's range capability, efficiency and backward compatibility with each other in a realistic heterogeneous environment. Finally, the experimental results are compared with a simplified analytical path loss model to validate the roaming process between protocols and find the roaming threshold value at which the client roams from one network to another. The evaluation aims to attest a migration strategy that would be best suitable for a stable wireless deployment in a heterogeneous enterprise and vehicular network.

3.2 Migration strategy

The development of wireless standards has given rise to many new protocols that enhanced data throughput and efficiency in a Wi-Fi environment. This tremendous growth in Wi-Fi deployment has improved range and provided better service to users on wireless networks in the last decade. The latest amendment of IEEE 802.11ac has broken all the barriers in speed, reaching a speed of 1.3 Gbps and claiming to be backward compatible with legacy protocols. Therefore, the deployment of IEEE 802.11ac has many benefits over the legacy protocols, and an enterprise or other vehicular applications can decide the strategies mentioned below for migration from legacy protocols to IEEE 802.11ac.

3.2.1 Clean slate design

The clean slate strategy can be used to migrate from legacy protocols to a newer IEEE 802.11ac. In a clean-slate design, the existing design's valuable information is considered along with the network's future aspects while building utterly new network architecture if required [132]. This strategy is the best solution but expensive. The data rate of IEEE 802.11ac is much higher than legacy protocols, and if an enterprise network is planning to migrate from IEEE 802.11a/b/g/n, then the clean slate strategy is the best suited. The IEEE 802.11ac access points come with two radios that can support the legacy protocol IEEE 802.11n and work on the 5 GHz band, which is less crowded and can gain higher data throughput [133].

3.2.2 Rip-and-replace

The rip-and-replace migration can be considered as replacing the existing access point one-by-one with the newer ones [134]. The main idea behind the rip-and-replace is to keep the old hardware and install them in a location in an enterprise where it can still be in use. This strategy is useful and economical but comes with some drawbacks since all the network infrastructure is being designed to work with the legacy protocols and the newer IEEE 802.11ac protocols demand a completely new approach for its network infrastructure. This would affect the network coverage, range and throughput of the latest IEEE 802.11ac protocol. The IEEE 802.11ac access point supports only a 5 GHz frequency spectrum, and their signals will not travel as far as the protocols operating on the 2.4 GHz frequency spectrum. The rip-and-replace migration strategy is an easy to implement and faster way to upgrade the network infrastructure.

3.2.3 Phased migration

The phased migration is a migration technique in which all the upgradation is done in phases, and careful planning is required for the phased migration [135, 136]. While migrating from IEEE 802.11n to IEEE 802.11ac to meet end-user performance demands, careful planning and implementation are required without compromising an existing network's operations. The phased migration saves the cost of upgrading the whole network infrastructure at once since it can be done in phases and would overcome the drawbacks of the clean slate and rip-and-replace migration method. The first step would be to analyse the performance of the existing system and find the coverage holes. Once it is being analysed, a new design for partial parallel deployment can be considered. Therefore, it can be a cheaper alternative before upgrading the entire network infrastructure from legacy protocols to a newer IEEE 802.11ac while keeping the network functioning and supporting the end-user requirements.

3.3 Hand-off process

The hand-off process is mainly a process where a mobile node control of an access point is changed during an active data transmission [137]. The clients go through many different stages in a hand-off process which affects the whole protocol stack, including the data link layer, network layer, transport layer and application layer. These stages are discussed below.

3.3.1 Scanning

There are mainly two types of scanning process available in an access point and client's radio, i.e., Active and Passive scanning [137, 138]. While in active scanning, the clients send a probe to the other access points and remain connected to the one access point. In passive scanning, the clients do not send probe requests to other access points, whereas it just listens to the beacons from other access points. This process is energy-efficient as access points do not have to scan other access points continually. When the clients in the scanning process have identified the more robust and better signals, it drops the connection to the connected access point and connects the other access point with a stronger signal. This instance is called a roaming trigger.

3.3.2 Authentication

The authentication process is when a client sends a probe to all the nearby access points and waits for their reply. The client chooses the access point according to their signal strength and data transmission rates and will send a request for connection (authentication) to the access point and wait for its approval/rejection [139].

3.3.3 Re-association

In the authentication process, the client connects to the access point, or if it is roaming, it sends the re-association request to a new access point. As the new access point accepts the client's request, it sends the disassociation request to the older access points and connects to the new access point. This process is called Re-association. Once all the above process is completed successfully, and the client migrates from one access point to another, it is called a Hand-off process [46, 140].

The clients who roam between different access points have to consider the following parameters.

- The client and access point power levels.
- Data rates offered by the access points.
- Signal strength offered by the access points.

These parameters are inter-related, and to gain higher data rates and connects with the stronger signal strength, the client has to spend a considerable amount of power and energy. The clients roaming algorithms (embedded in the device hardware) decides the amount of energy to spend while choosing to connect access points with more robust signal strength with lower range or lower signal strength with a higher range.

3.4 Test Methodology and Experimental Setup

This section shall propose three different tests, and all the tests are independent of each other. For this, we have chosen a suitable indoor environment and created a testbed for benchmarking with the necessary hardware and software for the experiments. Even though not conducted in a real vehicular environment setting (for obvious cost constraints), the primary motivation for conducting the tests was to evaluate the possible impact that the protocols can have on a heterogeneous vehicular network. This will help us get a clear understanding of each protocol's capability and interoperability for enterprise and vehicular networks.

3.4.1 Devices and Software for Developing Experimental Setup

For the network diagram shown in Figure 3.1, two Cisco 3560 switches with 12-fibre gigabit Ethernet and 2-copper gigabit ports are used at the distribution and access layer, respectively. The speeds of 1000 Mbps of gigabit Ethernet on these switches provide the bandwidth to meet new and evolving network demands by alleviating bottlenecks and boost system performance. The Cisco Catalyst 3560 switches deliver extremely high-performance for hardware-based IP routing. Additionally, Cisco's Fast Ether Channel technology on these switches enhances fault tolerance and offers high-speed aggregated bandwidth between switches and routers, including individual servers. The Layer 2 trace-route functionality of these switches' eases troubleshooting by identifying the physical path that a packet takes from source to destination. The IP traffic generator used on a server, which acts as a host, connected to the 1-gigabit port on the distribution switch. Also, the Fibre optic port provides the downlink from the distribution switch to the access layer switch as both IEEE 802.11n and 802.11ac support the data rates range up to 600 and 1300 Mbps, respectively. All connections terminate at the access layer. Thus, facilitating the requirements of our experiments.

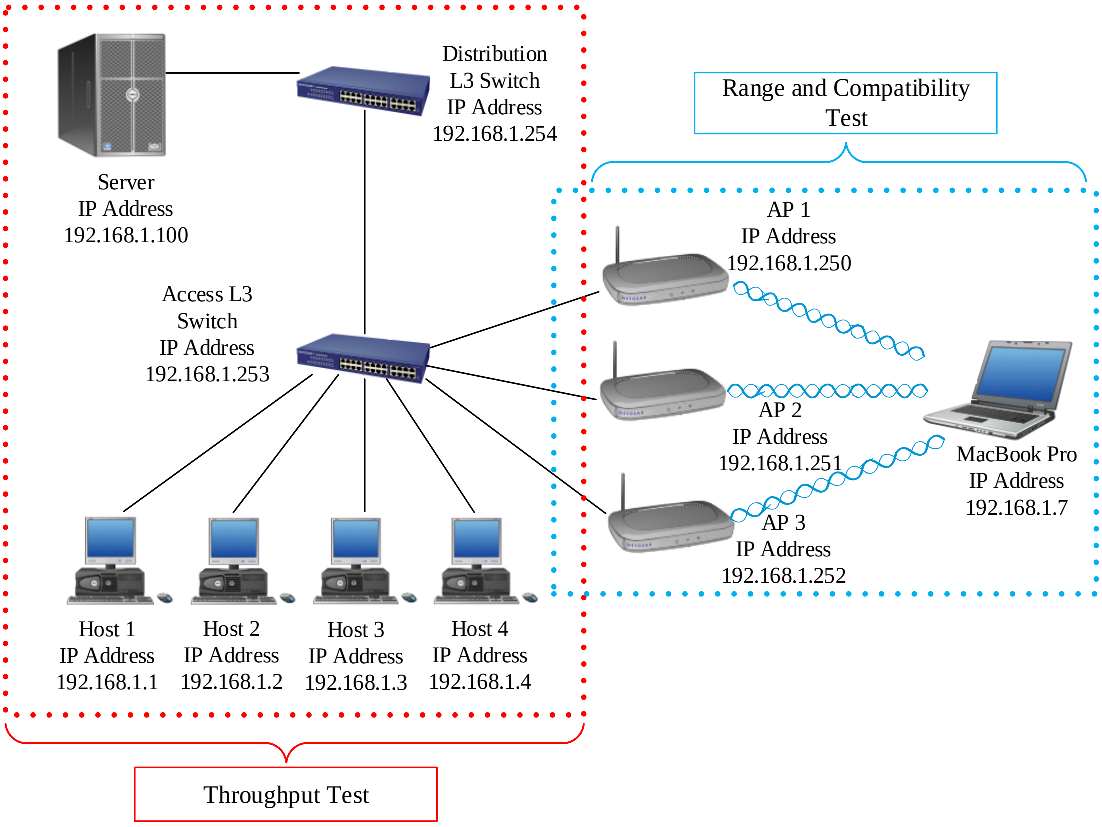

Figure 3. 1. The Network Diagram for Throughput, Range and Compatibility Tests

Three wireless access points (WAP) are configured, the Cisco AIR-AP-1242AG-E-K9 used for testing IEEE 802.11a and Cisco AIR-AP-1262N-E-K9 for IEEE 802.11n. These access points are equipped with a 2 × 3 MIMO system with two spatial streams operating on 20 and 40 MHz channels, providing data rates up to 300 Mbps with beamforming features. In addition, these access points support the 1000BASE-T interfaces, which supports gigabit Ethernet technology. The Asus RT-AC66U access point is used to test IEEE 802.11ac, as it works on dual-band 2.4 and 5 GHz to achieve super-fast data rates by using 3 × 3 MIMO and multiple streams, providing data rates of 450 to 1300 Mbps for IEEE 802.11n and 802.11ac, respectively. A Jperf (Software tool) is used to measure a wired or wireless network's throughput and performance by varying parameters.

The host machine used as client and server is configured with Windows 7 Service Pack 1 64-bit with AMD Athlon dual-core processors running at 2.20 GHz with 8 GB RAM to provide sufficient computational resources. Each host consists of two network adapters to connect the wireless infrastructure and an on-board network card to connect the wired network. For the throughput, range and compatibility test of wireless protocols, a MacBook Pro with a 2.5 GHz Intel i5 processor with 4 GB of RAM is used with external wireless adapters such as Cisco-Linksys WUSB600N and ASUS dual-band USB-AC56, which facilitates the wireless network connectivity as these network adapters offer simultaneous multiple streams operation based on IEEE 802.11 amendments [141]. The Cisco-Linksys WUSB600N supports dual-band and has two omnidirectional internal antennas that facilitate beamforming and MIMO functionality, while ASUS USB-AC56 also operates dual-band with two internal and one external antenna to facilitates the MU-MIMO. A software tool, a Wi-Fi scanner, is used on the MacBook Pro for gathering transmission information, including signal strength, noise, Signal to Noise Ratio (SNR) and effective data rates. For the proposed test, the transmission power and data rates on AP and network adapter are configured with the values listed in Table 3.4.

3.4.2 Test Environments

Due to the heterogeneous wireless environment, an observation of the spectrum is mandatory. Figure 3.2 shows a 2.4 GHz spectrum for IEEE 802.11n. It shows multiple peaks at different channels, indicating multiple wireless network present in that frequency spectrum. The peaks around channel 12 and 13 in the spectrum are automatically selected using the Least Congested Frequency (LCF) settings on IEEE 802.11n access points operating at 2.4 GHz frequency. Figure 3.3 shows the spectrum during testing. Figure 3.4 shows the 5 GHz frequency spectrum before the test. Comparing Figures 3.2 and 3.4, it is clear that the spectrum in 5 GHz is much free compared to the spectrum in 2.4 GHz, and comparatively, the free spectrum signifies fewer hosts and ultimately less interference. Less interference in a 5 GHz frequency spectrum will lead to improved performance and throughput. The Channel bonding can be seen in Figure 3.5, and Channel 112 is selected by the Dynamic Frequency Selection (DFS) algorithm in this test. Due to the Channel Bonding feature of IEEE 802.11n, we observe a broader concentration of traffic around channel 108 and 112.

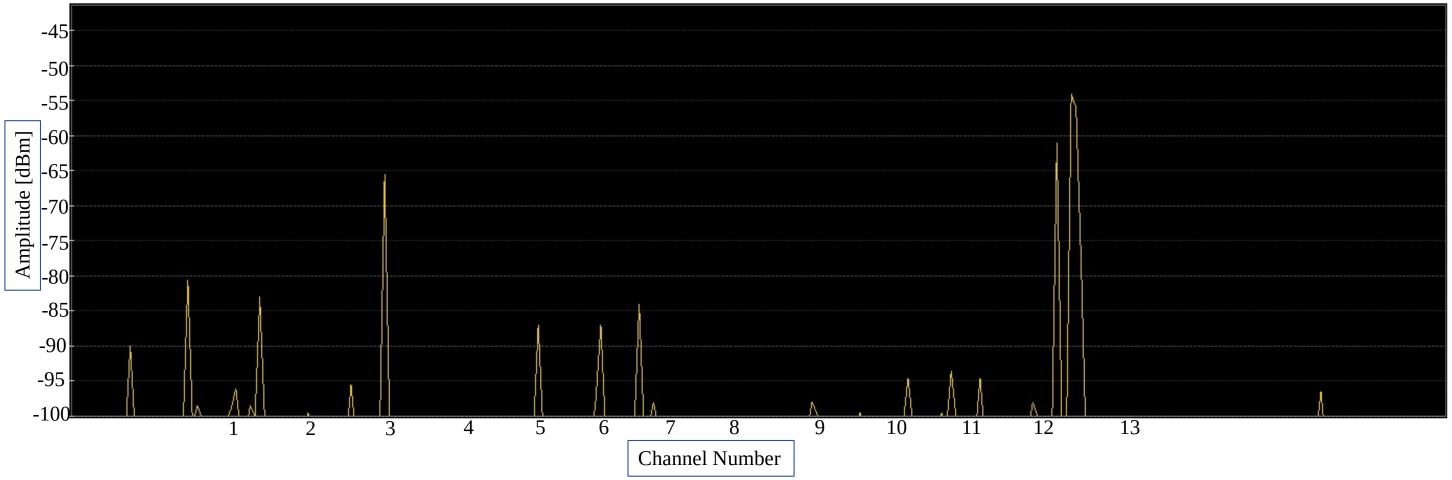

Figure 3. 2. The spectrum analysis of an indoor environment before testing at 2.4 GHz

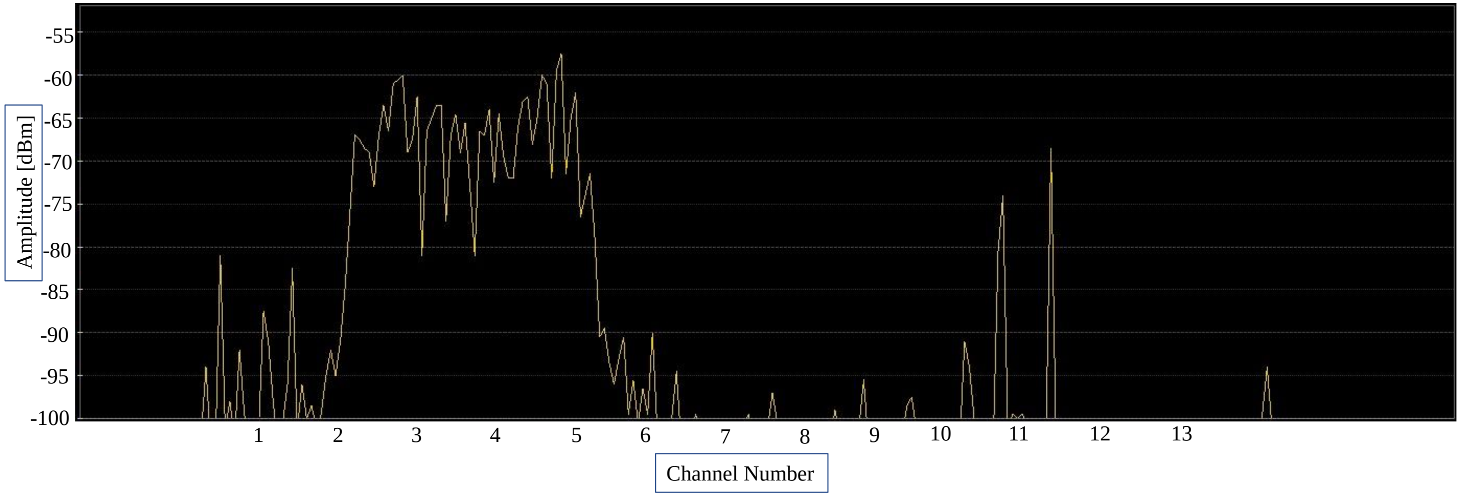

Figure 3. 3. The spectrum analysis of an indoor environment during testing at 2.4 GHz

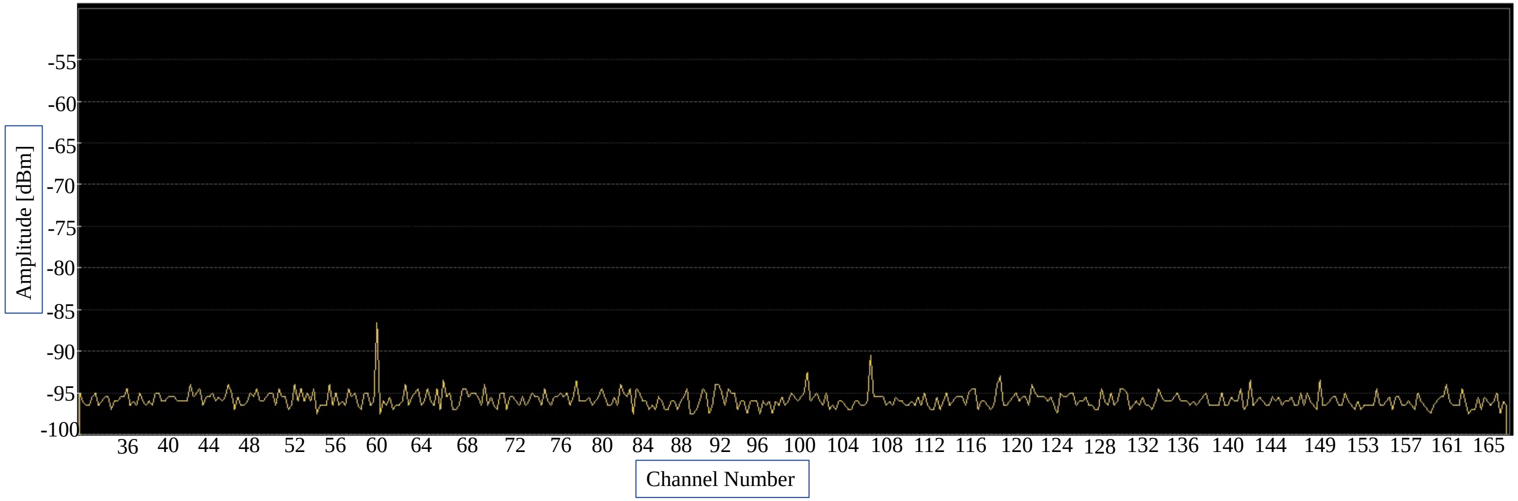

Figure 3. 4. The spectrum analysis of an indoor environment before testing at 5 GHz

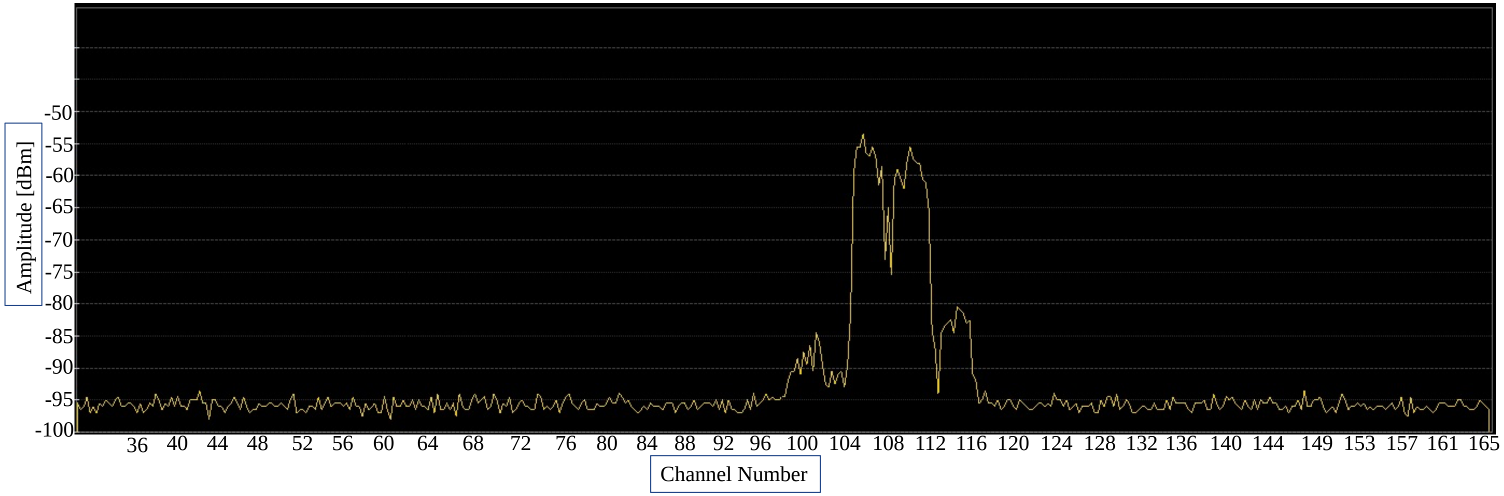

Figure 3. 5. The spectrum analysis of an indoor environment showing channel-bonding during testing at 5 GHz

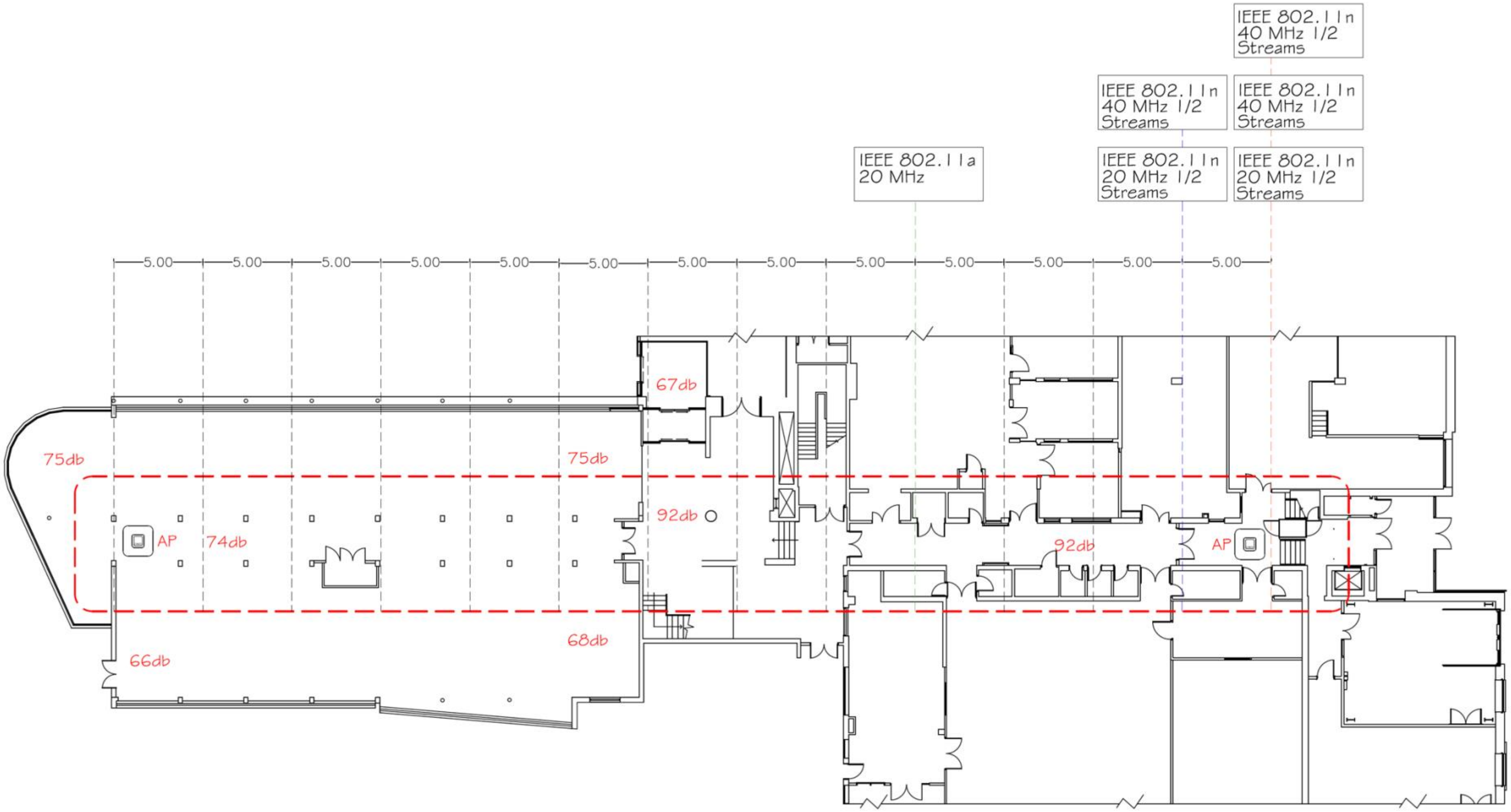

Figure 3. 6. The Ellison Building D and E Block's ground floor at Northumbria University used for Range and Compatibility Tests. Access Points (AP) position is marked on either end of the hallways along with achieved a signal range of the protocols.

3.4.3 Throughput Test

This test aims to understand the capabilities of IEEE 802.11ac against IEEE 802.11a/n and a wired network. Benchmarking is the first step in determining the potential of IEEE 802.11ac. The goals for benchmarking tests are to study the relative throughput of gigabit Ethernet, 802.11ac and 802.11a/n in a heterogeneous environment. This test will help us determine performance improvements offered by channel bonding, short guard interval and multiple streams. All the 5 GHz variations of 802.11n/ac along with IEEE 802.11a and gigabit Ethernet have been tested using transport layer protocols such as TCP and UDP.

3.4.3.1. Test Methodology

Table 3.1 summarises the test cases for a throughput test. The cases are designed with numerous settings, including frequency spectrum, channel bonding, short guard interval and multiple streams. The practical throughput is obtained and compared with advertised data rates by transmitting continuous data streams by a number of hosts to the server and vice-versa. The host sends a continuous stream of data to the server for a fixed period of 10 seconds, and the throughput is recorded at the receiving host. However, only one host transmitting a single stream of data does not reach the link saturation; hence multiple streams of data by several hosts are sent simultaneously to the server. The obtained results show the maximum practical throughput generated by each protocol tested on TCP and UDP. Ten runs are recorded to get more accurate results, and their averages are used as a final result.

Table 3. 1. Test Cases used for Throughput Test

Test Number	Test Cases
1	Wired
2	802.11a 5GHz 20MHz
3	802.11n 5GHz 20MHz, 1 Stream and SGI=ON
4	802.11n 5GHz 20MHz, 2 Streams and SGI=ON
5	802.11n 5GHz 40MHz, 1 Stream and SGI=ON
6	802.11n 5GHz 40MHz, 2 Streams and SGI=ON
7	802.11ac 5GHz 20MHz, 3 Streams and SGI=ON
8	802.11ac 5GHz 40MHz, 3 Streams and SGI=ON
9	802.11ac 5GHz 80MHz, 3 Streams and SGI=ON

3.4.4 Range Test

This test is designed to test how data rates faired over distance in an indoor environment. This test's outcome will become a practical point of reference for the design proposal of IEEE 802.11ac to co-exist with IEEE 802.11a/n. For this test, a long corridor of 65 meters has been chosen and shown in Figure 3.6. A MacBook Pro is used to connect the access points with an external USB network adapter mentioned in section 3.4.1. The access points are configured and placed at one end of the corridor and the test cases used are as shown in Table 3.2. The distance resolution is 5 meters, i.e., the corridor is divided into 5-meter segments, where the measurements are taken. For range test, transmission power and data rates on AP and network adapter are configured with the highest values as depicted in Table 3.4.

Table 3. 2. Test Cases used for Range Test

Test Number	Test Cases
1	802.11a 5GHz 20MHz Channel width
2	802.11n 5GHz 20MHz Channel width, 1 stream
3	802.11n 5GHz 20MHz Channel width, 2 streams
4	802.11n 5GHz 40MHz Channel width, 1 stream
5	802.11n 5GHz 40MHz Channel width, 2 streams
6	802.11ac 5GHz 20MHz Channel width, 3 streams
7	802.11ac 5GHz 40MHz Channel width, 3 streams
8	802.11ac 5GHz 80MHz Channel width, 3 streams

The measurements were taken walking towards and away from the access points to get the comprehensive readings. The tests were performed for ten runs in each direction, and their averages are used to get the precise set of results.

3.4.5 Backward Compatibility Test

This test's main intention is to have a better understanding of the clients' roaming behaviour while access points operating with multiple protocols in an indoor heterogeneous enterprise network. It is essential to learn the client's roaming behaviour from IEEE 802.11a to IEEE 802.11n/ac and vice-versa. It is also crucial to determine if a client always connects to IEEE 802.11ac irrespective of signal strength and data rates offered by other legacy protocols operating on access points to prove the proposed hypothesis right. All the experiments are performed in a corridor depicted in Figure 3.6, with all the hosts and access points are configured with 802.11a/n/ac. The length of the corridor is 65 meters, and it can be seen from Figures 3.2 and 3.4 that some interference is present due to other wireless networks present in an environment; thus, it cannot be considered an interference-free indoor environment. All test hosts at any given location have a direct LOS with an access point. In addition, this framework is created only with the access point with no centralised wireless controller; thus, hosts make the roaming decisions independently.

These tests are designed to recognise the parameters that affect a client's roaming from one access point to another and record the parameter values when roaming is observed. Since different test cases have different roaming points, it was decided to take readings at every 5 meters where results could be recorded and later analysed. At each of these points, Received Signal Strength Indication (RSSI) values from both the access points are noted along with the distance and checked if the client roamed from one access point to another. In Figure 3.6, AP1 and AP2 denote the access points configured with 802.11a and 802.11n/ac, respectively, and the range is measured in meters, and the hand-off (roaming) process is observed.

Table 3. 3. Test Cases used for Compatibility Test

Test Number	Test Cases
1	802.11a 5GHz 20MHz vs 802.11n 5GHz 20MHz SGI=ON
2	802.11a 5GHz 20MHz vs 802.11n 5GHz 40MHz SGI=ON
3	802.11a 5GHz 20MHz vs 802.11ac 5GHz 20MHz SGI=ON
4	802.11a 5GHz 20MHz vs 802.11ac 5GHz 40MHz SGI=ON

3.4.5.1. Test Methodology

The first set of access points are configured with IEEE 802.11a and IEEE 802.11n, and they are kept at a distance of 65 meters from each other. The client is initially connected to one of the access points. The test is conducted with clients connecting to one access point and walking towards the other until roaming is observed. The tests include all possible variations of the IEEE 802.11a versus IEEE 802.11n/ac in the 5 GHz frequency spectrum. The pilot tests are designed to understand the client's roaming process from one protocol to another and vice-versa. The combination of different data rates and transmission power for each access point is used. The proposed test cases for the first pilot test are as follows:

1. Dissimilar Service Set Identifier (SSID) with different authentication scheme.
2. Similar SSID with similar authentication scheme.

The output of the above pilot test has determined the construction of the next extended pilot tests. The extended pilot tests are designed to determine if the roaming of the client is observed or not, and they are as follows:

1. Maximum data rate and transmission power are enabled with the same SSID and same authentication scheme for IEEE 802.11a versus all the variant of IEEE 802.11n/ac.
2. Maximum data rate and lower transmission power are enabled with the same SSID and same authentication scheme for IEEE 802.11a versus all the variant of IEEE 802.11n/ac.

The extended pilot tests provided many vital and decisive conclusion, and the output of these tests are kept in consideration, and the final tests are designed according to it. Table 3.3 depicts the test cases for handover tests between IEEE 802.11 protocols, and final tests are designed considering the following factors:

1. Minimum power and maximum data rates enabled on both access points.
2. The transmitting power for IEEE 802.11a is kept at 2 mW, while IEEE 802.11n and 802.11ac are kept at 1 mW.
3. Maximum data rates enabled on all the access points for IEEE 802.11a/n/ac.

3.4.6 Path Loss Model

The analytical channel estimation model compares the experimental results with the path loss model. The comparison is made for the range and backward compatibility tests. The path loss model considers the effect of path loss of the wireless signal during transmission from the transmitter (AP) to the receiver (MacBook Pro). The model calculates the SNR and RSSI at the receiver with respect to the distance while comparing with the experimental model, which affects the fading signal strength over the distance. The attenuation of radio signal during propagation is termed path loss, and it includes the propagation losses due to the free space, absorption and diffraction [142]. The path loss is one of the widely adopted statistical channel metrics and is considered the most significant quantity for any wireless channel. The path loss is a function of the surrounding environment and the distance between the transmitter and the receiver (d), given by d^{γ}, where γ is the path loss exponent, which depends on the surrounding environment. An increase in the path loss leads to SNR attenuation, limiting the transmission range and data rates of the wireless channel between the receiver and the transmitter [143]. Therefore, in our model, the path loss will determine the transmission range of the APs. We estimate the path loss using the free-space path loss model [144], described as

$$PL(d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\gamma\log_{10}(d) \tag{3.1}$$

Where, $PL(d)$ is the Path Loss at distance d [meters], λ is the free space wavelength defined as the ratio of the velocity of radio signal c to the carrier frequency f of the radio signal. The SNR, without considering fading, can be calculated using [145].

$$SNR = P_t + G_t + G_r - PL(d) - N_{Power} - I_m \tag{3.2}$$

where, P_t is the transmitted power [dBm], G_t is the antenna gain at the transmitter [dBi], G_r is the antenna gain at receiver [dBi], N_{Power} is the noise power [dB], and I_m is the implementation noise [dB]. N_{Power} is the additional power attenuation per meter [watts] and is given by

$$N_{Power} = 10\log_{10}(KTB) + N_{Figure} \tag{3.3}$$

where K is the Boltzmann constant [joules per kelvin], T is the noise temperature [kelvin], B is the bandwidth [hertz], and N_{Figure} is the noise figure [dB]. In our model, we considered an SNR of $15\ dB$ obtained at the maximum distance between the transmitter and receiver at which transmission occurs. Therefore, the transmission range of the APs is evaluated from (3.1) and (3.2) for a threshold SNR of $15\ dB$. In addition, (3.1) and (3.2) are used to obtain the SNR at each distance d from the transmitter. Table 3.4 details the values of all the parameters used to calculate the path loss and SNR at a certain distance for a wireless channel.

Table 3. 4. Parameters to calculate Path Loss of Wireless channel for Range and Compatibility Test

Parameters	**IEEE 802.11a**	**IEEE 802.11n**	**IEEE 802.11ac**
Channel Bandwidth	20 MHz	20/40 MHz	20/40/80 MHz
Centre Frequency	5 GHz	5 GHz	5 GHz
Transmit Power	17/2 dBm	20/1 dBm	20/1 dBm
Antenna Gain	3.5 dBi	3.5 dBi	5 dBi
Receive Antenna Gain	4 dBi	4 dBi	4 dBi
Path Loss Exponents	3.6	3.6	3.6
Noise Power	10 dB	10 dB	10 dB
Implementation Margin	5 dB	5 dB	5 dB

3.5 Empirical Results and Discussion

The test cases result in the model proposed in the previous section are discussed in this section. The test cases were initially compiled, and tests were conducted using the designs specified in Section 3.3. This section presents the result of each subsection from the previous chapters in the same order, mapping to the corresponding subsection in Section 3.3.

3.5.1 Throughput Test

All the outcomes obtained from the experiment are summarised in Table 3.5, while test cases adopted from Table 3.1. The wired test, also called Ethernet, shows the maximum throughput achieved with an increase in the number of hosts to provide higher data throughput for all the hosts operating on TCP and UDP and comparing them to all the wireless protocols used in this experiment. The IEEE 802.11a performance degraded as the number of hosts transmitting data over the same link simultaneously. The maximum throughput recorded by IEEE 802.11a on TCP and UDP is 23.25 and 26.61 Mbps, respectively. The performance of IEEE 802.11n with 20 and 40 MHz channel bandwidth with data transmitting simultaneously over TCP using one and two streams shows maximum throughput of 52.6 and 91.7 Mbps.

Table 3. 5. Comparisons of Average Throughput against a number of hosts for TCP and UDP

Test Cases	**TCP [Mbps]**				**UDP [Mbps]**			
	Host 1	**Host 2**	**Host 3**	**Host 4**	**Host 1**	**Host 2**	**Host 3**	**Host 4**
1	687.8	850.8	855	837.5	131.5	244.5	421.9	532.1
2	23.2	20.7	19.5	18.17	25.83	26.33	26.61	22.81
3	44.2	50	52.6	44	59.22	61.33	61.39	60.73
4	67.7	75.1	90.9	91.7	113.9	114.5	112.8	113.6
5	74.7	91.4	94.09	94.41	116.5	117.5	117.5	117.1
6	114.7	122.8	134.9	144.2	180.6	196.7	192.8	188.5
7	76.1	93.4	104.2	96.27	108.2	111.9	114.6	108
8	106.8	145.5	160.8	170.1	125.5	201.5	209.1	215.5
9	110.4	175.2	189.3	217.3	117.6	199.2	215.9	223.5

However, the performance of IEEE 802.11ac for 20, 40 and 80 MHz channel bandwidth with multiple streams show decrements in throughput when all the four hosts are transmitting data simultaneously. The maximum average throughput achieved over TCP and UDP for some of the test cases from Table 3.5 are shown in Figures 3.7 and 3.8, respectively.

The throughput achieved on IEEE 802.11n with 40 MHz channel bandwidth on single-stream (Test Case Number 5 in Table 3.5) is almost double the throughput achieved on 802.11n with 20 MHz channel bandwidth (Test Case Number 3 in Table 3.5). The maximum-recorded TCP throughput on IEEE 802.11n with 40 MHz single stream is 91.41 Mbps, while IEEE 802.11n with 20 MHz on single-stream provides 52.6 Mbps. Similar results obtained with IEEE 802.11ac with 20, 40 and 80 MHz channel bandwidth using TCP and UDP. Therefore, it can be concluded that the channel bonding (i.e., 40 MHz and 80 MHz) feature of IEEE 802.11n and 802.11ac improves the data throughput even with new hosts adjoin the network, and this nature is observed over both TCP and UDP.

The maximum throughput recorded on IEEE 802.11ac with four hosts transmitting simultaneously over TCP and UDP using 80 MHz channel bandwidth generates 217.38 Mbps and 223.54 Mbps, respectively.

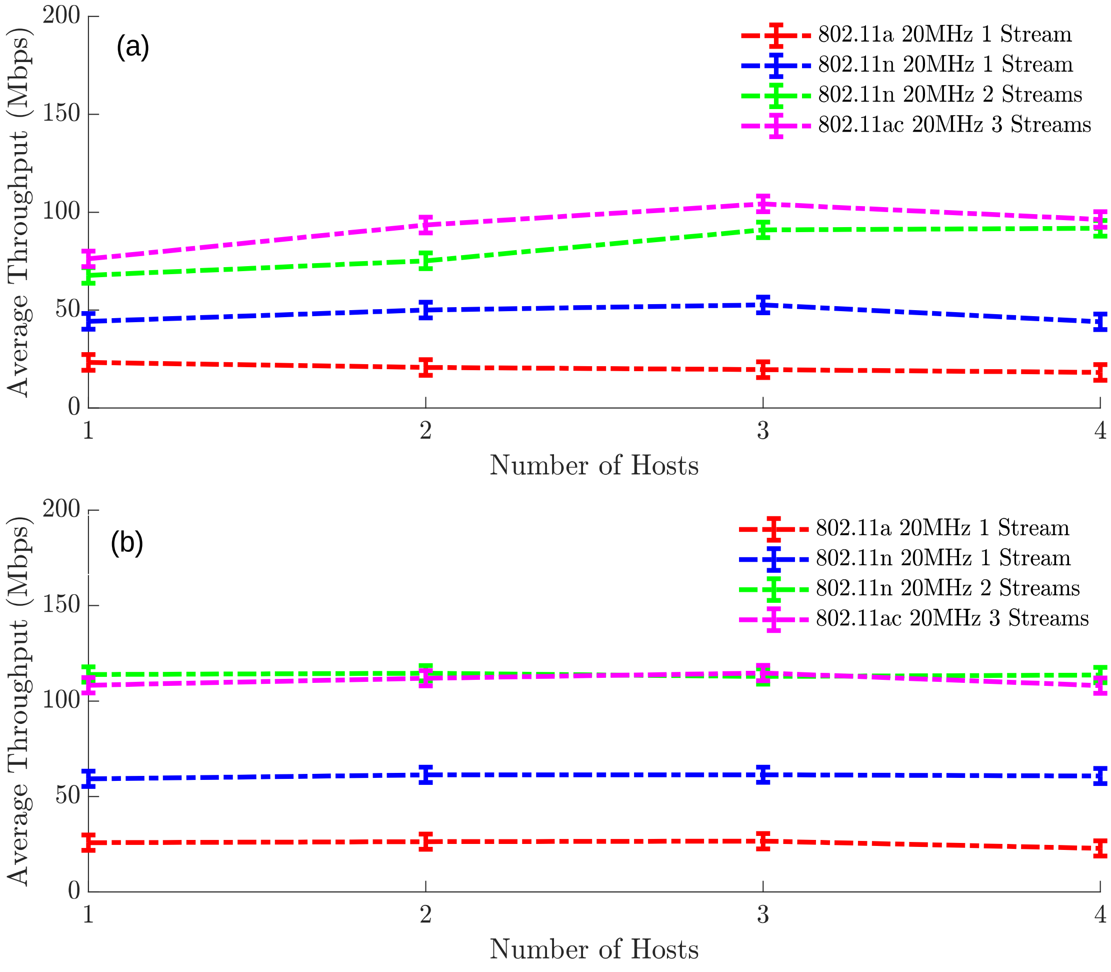

Figure 3. 7. The Average Throughput of protocols on TCP (a) and UDP (b) without Channel Bonding

In addition, the IEEE 802.11ac with four hosts transmitting simultaneously on 40 MHz channel bandwidth generates the throughput of 170.1 Mbps on TCP, while with 80 MHz bandwidth generate the throughput of 217.38. Figure 3.8 shows the results of the test cases for channel bonding.

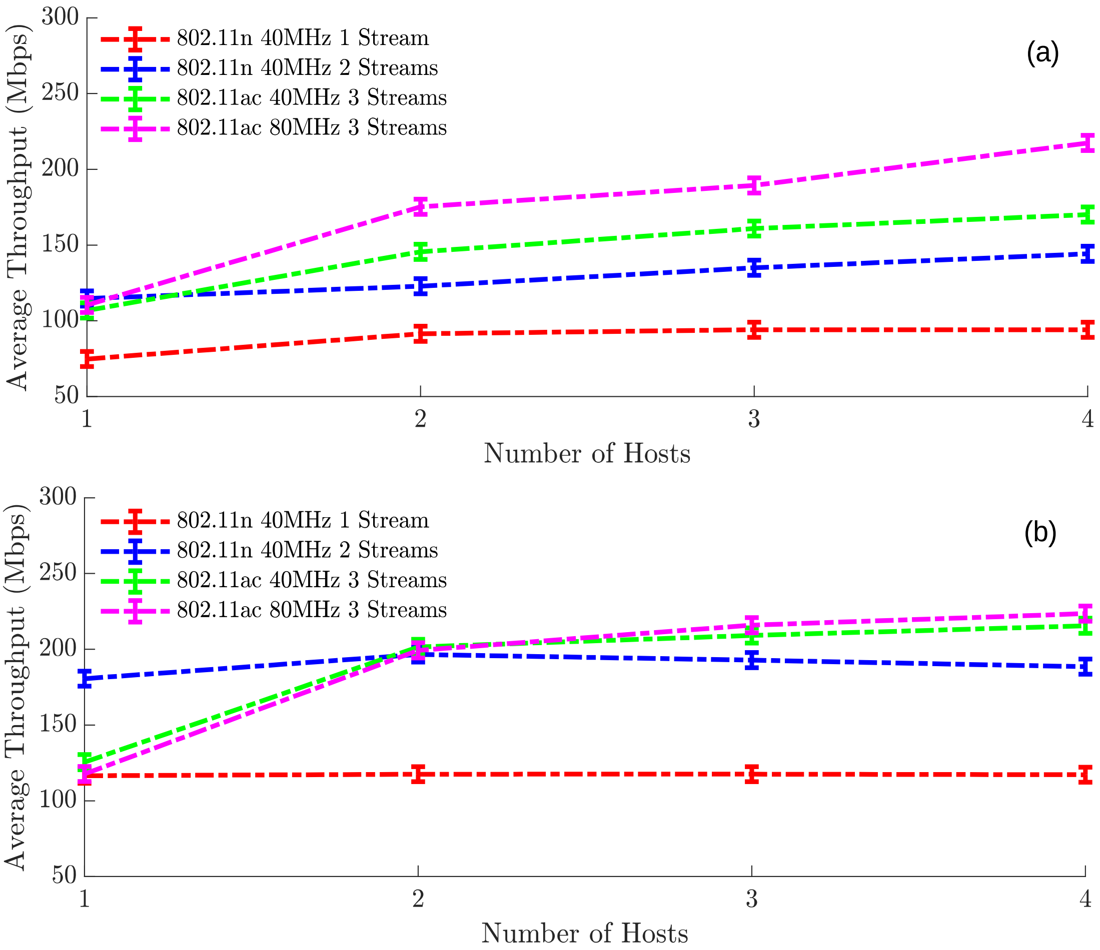

Figure 3. 8. The Average Throughput of protocols on TCP (a) and UDP (b) with Channel Bonding

The test results show the increase in the number of hosts results in throughput degradation, which affects the overall network's performance. In addition, it has been seen that the multiple streams generate higher throughput than a single stream, and the channel-bonding feature almost doubles the throughput, compared to the similar number of streams used for all other variations of IEEE 802.11n and IEEE 802.11ac.

3.5.2 Efficiency of Protocols

This section analyses the results from sections 3.5.1 for the IEEE 802.11 protocols throughput efficiency. Every single protocol offers different data rates; therefore, to compare all data rate, throughput and efficiency of protocols on the same scale, we calculate their efficiency, E, as follows:

$$E = \left(\frac{T_{10}}{D_R}\right) \times 100 \tag{3.4}$$

where, T_{10} is the average throughput obtained from 10 runs, and D_R is the maximum data rate offered by that protocol. Figures 3.9 and 3.10 shows that the efficiency of TCP and UDP on wired and wireless networks, respectively. The wired network is full-duplex, while the wireless network is half-duplex. Therefore, the wireless network is susceptible to collisions, and hence the efficiency of the wireless network deteriorates as the load on the network is increases.

It can be seen from Figure 3.9 that IEEE 802.11a achieves the throughput efficiency of 43.055% for a single host, compared to 33.648% with multiple hosts transmitting simultaneously over TCP. However, for IEEE 802.11n and ac over TCP, an increase in throughput efficiency is observed as the new host joins the network. Although IEEE 802.11n with 20 MHz channel bandwidth, transmitting one stream achieves the maximum TCP throughput efficiency of 35.09%, compared to 30.59% with two streams. We expected to see better throughput efficiency with multiple streams than single streams; however, the test results show that multiple streams are less efficient than single streams. Similarly, in IEEE 802.11n with 40 MHz channel bandwidth, the TCP throughput efficiency of 62.94% and 48.06% is achieved with one and two streams. In addition, the IEEE 802.11ac with 20 MHz channel bandwidth over three streams achieves throughput efficiency of 12.03%, while other variants with channel bonding feature of 40 and 80 MHz shows 19.64% and 25.10% of throughput efficiency respectively. The data rates achieved by the IEEE 802.11ac and all their variants are better than IEEE 802.11n; however, in terms of TCP throughput efficiency, IEEE 802.11ac fails to keep up with IEEE 802.11n. The IEEE 802.11n and IEEE 802.11ac act like a wired network in terms of throughput due to MIMO and MU-MIMO's feature incorporated in them, respectively.

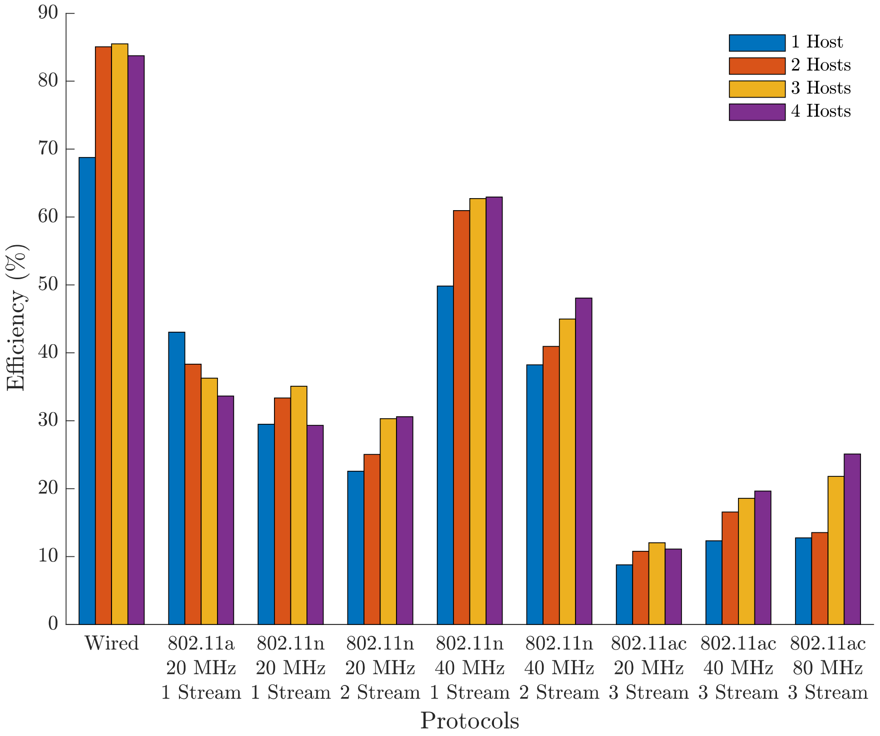

Figure 3. 9. Protocols Efficiency over TCP

These features introduced in wireless protocols have significantly improved their throughput and range performance. The channel bonding feature with multiple streams makes IEEE 802.11n work on full potential and higher data rates. However, the TCP throughput efficiency is deteriorated due to the fact of not using the complete spectrum, resulting in a single stream performing better than multiple streams. Similar tests performed with UDP for all wireless protocols and their variants shows better throughput efficiency than TCP. This is because UDP is considered the best-effort delivery protocol, which makes it faster than TCP, and it operates without any overhead for setting up the connection and does not require an acknowledgement. In addition, similar test results are observed for both TCP and UDP.

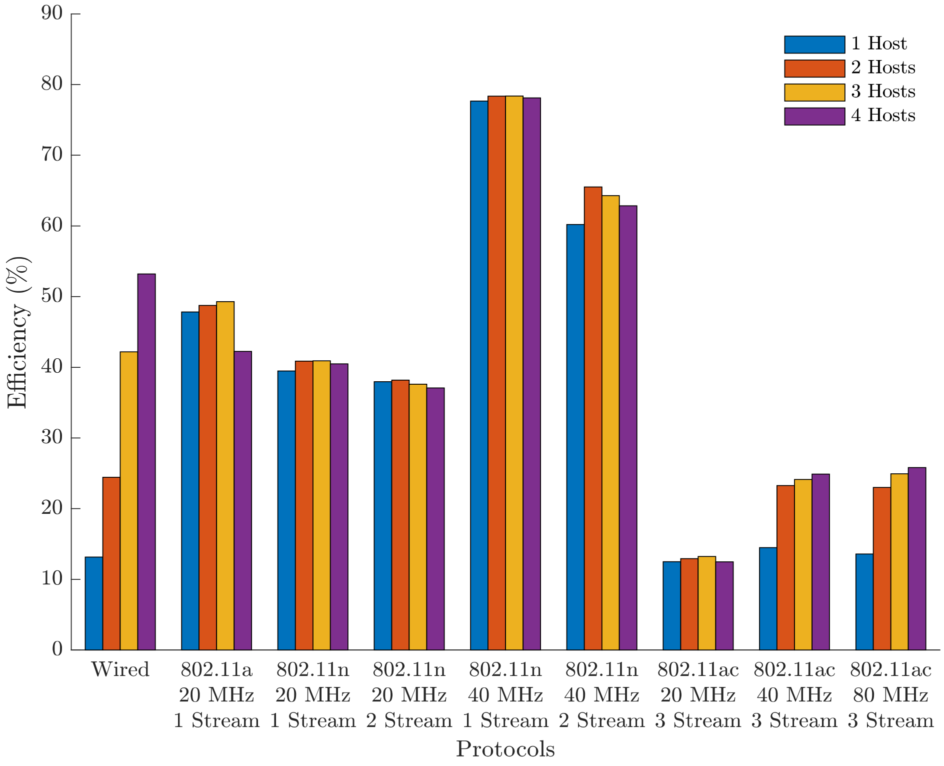

Figure 3. 10. Protocol Efficiency over UDP

3.5.3 Range Test

The range test is designed to compare the advertised data rate faired over a distance and to derive the SNR at a given distance. In this test, the theoretical throughput is considered over effective throughput. It can be seen from Figure 3.11, the advertised data rates by a client operating at a shorter distance from the APs provide higher data rates, while lower data rates are recorded due to deterioration of the signal strength as the client moves further away from the access points. It is evident from the results that the IEEE 802.11a starts at the bottom of the graph than any other variations of IEEE 802.11n and IEEE 802.11ac. The IEEE 802.11a provides the maximum data rate in the range of five meters from the AP. However, as the client moves away to the 40 meters mark, it cannot connect to the AP.

The IEEE 802.11n and IEEE 802.11ac with channel bonding, MIMO and MU-MIMO have higher data throughput and begin with higher data rate during this test. In addition, IEEE 802.11n with channel bonding using two streams shows the maximum data rate of

279 Mbps, compared to one stream, which is almost half of that. While considering their data rates in the range of 25-35 meters, the one stream has better data rates than the two streams. However, in the close range of 0-25 meters, the two streams provide optimum data rates. If IEEE 802.11n is compared with IEEE 802.11a, it is evident that the maximum data rate offered by IEEE 802.11a of 54 Mbps is achieved only in the first five meters of range while IEEE 802.11n and their variants show higher data rate at a distance of 30 meters. The IEEE 802.11ac, also tested within this test, shows the signal strength to a far distance compared to any other protocols tested in this experiment. The comparison is made between IEEE 802.11n with channel bonding using one stream to IEEE 802.11ac without channel bonding, where the data rates offered by both are suitable for a longer distance than IEEE 802.11a. However, IEEE 802.11n cannot connect to the client after 60 meters, while IEEE 802.11ac remains connected even after 60 meters of distance. The IEEE 802.11ac with channel bonding outperforms every other protocol tested as the range and signal strength of IEEE 802.11ac in close and long-range is higher than any variant of IEEE 802.11a and 802.11n.

Figure 3.12 compares the SNR ratio with distance. It shows that whenever a client moves away from the access point, their data rates and SNR values drop, which results in poor connectivity. Here, we compared the experimental test results with the path loss model to observe the protocols' behaviour. The results depict that the IEEE 802.11a cannot connect to a client after 40 meters while IEEE 802.11n and IEEE 802.11ac are well connected to the clients even after 60 meters of distance. According to the industries best practice, 20 dB rule for SNR; the IEEE 802.11a would not be usable after 20 meters while IEEE 802.11n and IEEE 802.11ac can be usable even after 30-35 meters.

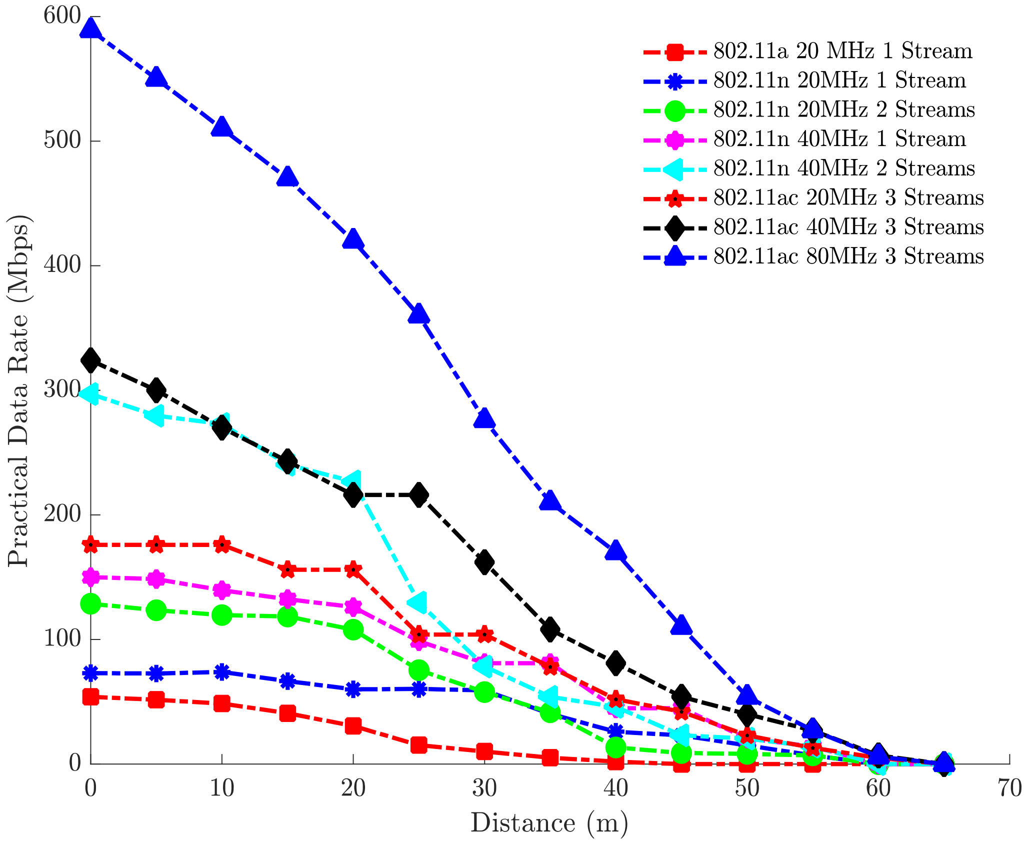

Figure 3. 11. Practical Data Rate of Protocols With respect to the Distance

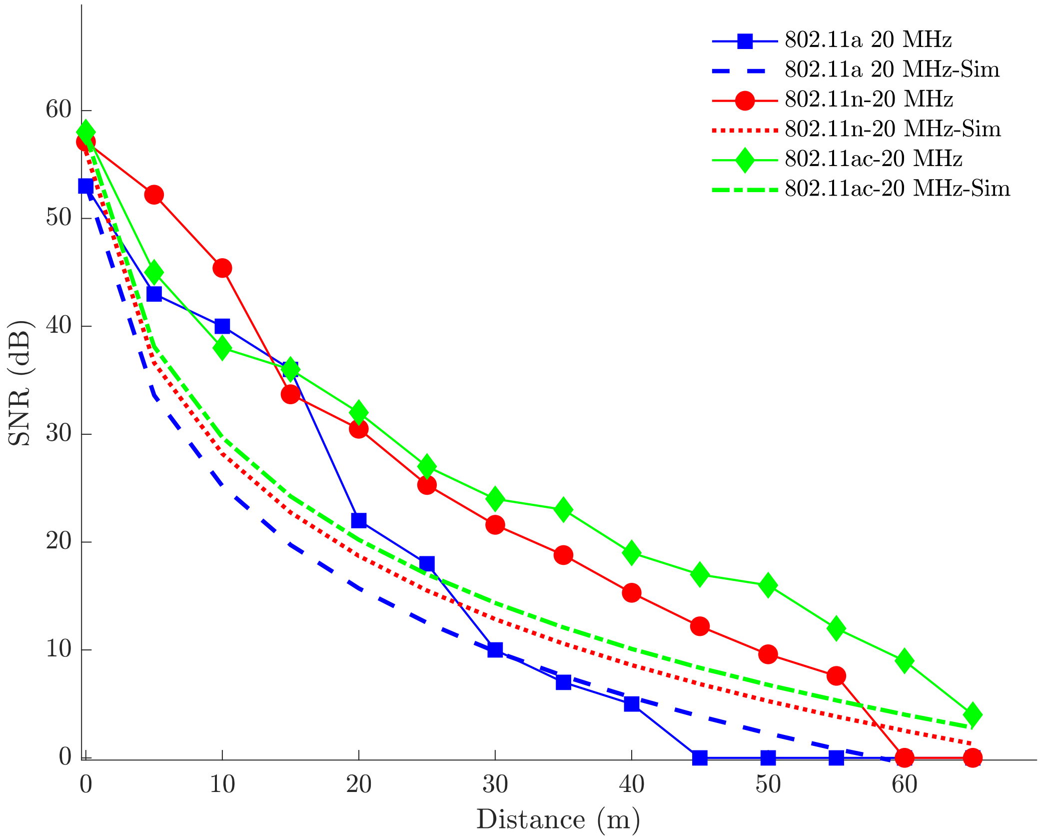

Figure 3. 12. Practical and Analytical/Simulation SNR fading of Protocols With respect to the Distance

3.5.4 Backward Compatibility Test

In this section, the test methodology from section 3.4.5 and 3.4.6, followed by test cases from Table 3.3, are investigated. For case-1, Figure 3.13 shows that AP-1 is configured with IEEE 802.11a with transmitting power of 2 mW while AP-2 configured with IEEE 802.11n and IEEE 802.11ac with both transmitting powers of 1 mW. The client (MacBook) is initially connected to AP-1, and the readings are taken walking towards AP-2 with a distance resolution of 5 meters for ten runs. The RSSI values are noted down, and the point of roaming is recorded wherever roaming is observed. A similar approach is adopted for roaming from AP-2 to AP-1. All test results in this section compare an analytical and experimental model on measurement and handover point at which client roam form one protocol to others.

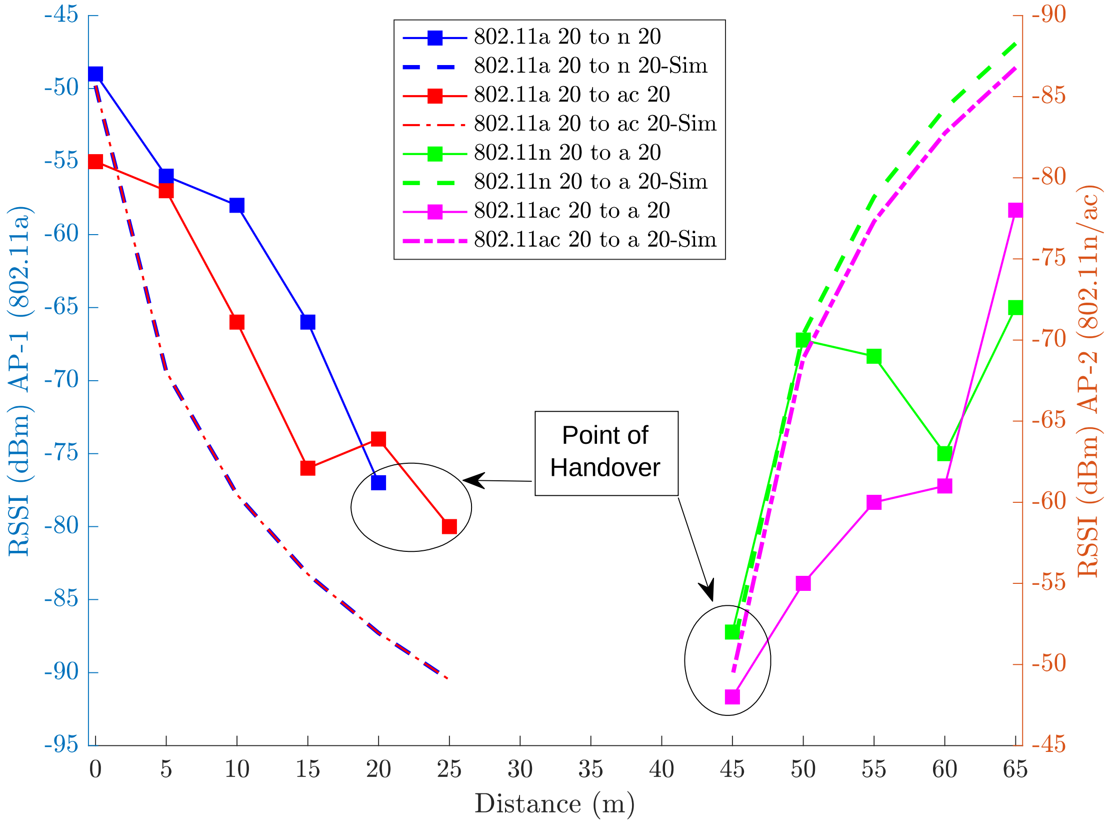

Figure 3. 13. Handover from 802.11a to 802.11n/ac with respect to the Distance and Analytical/Simulation calculation

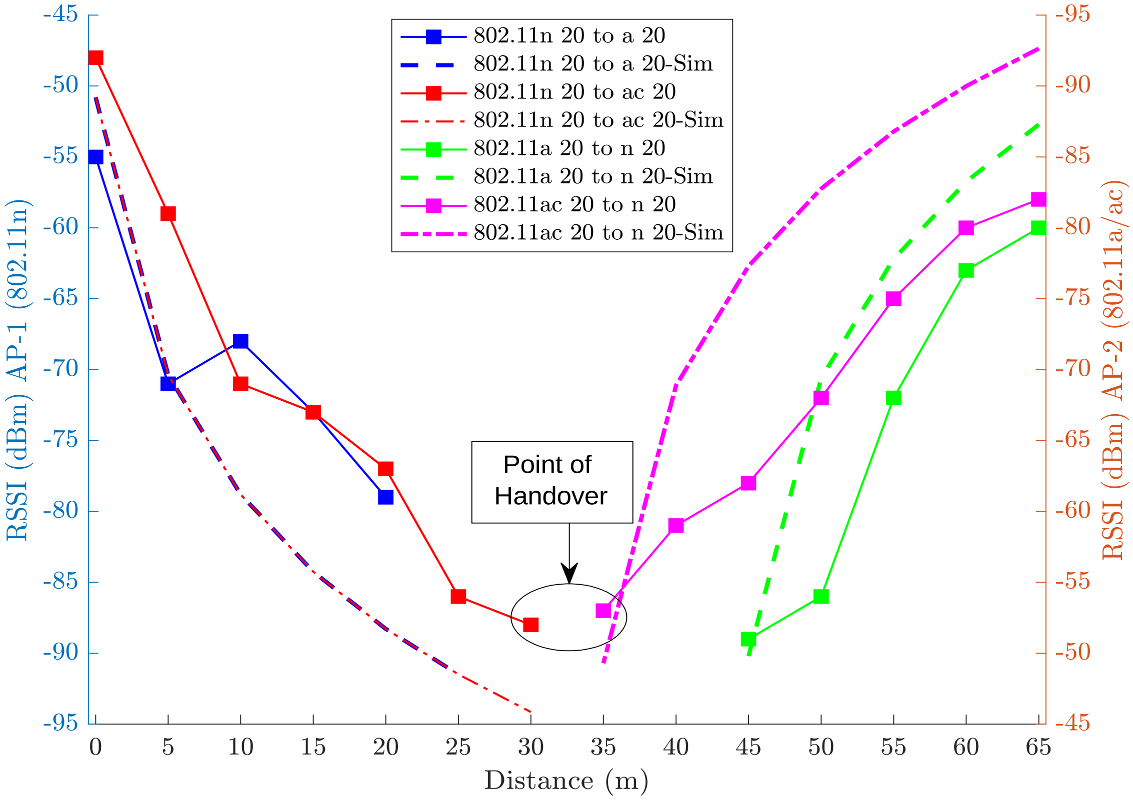

Figure 3. 14. Handover from 802.11n to 802.11a/ac with respect to the Distance and Analytical/Simulation calculation

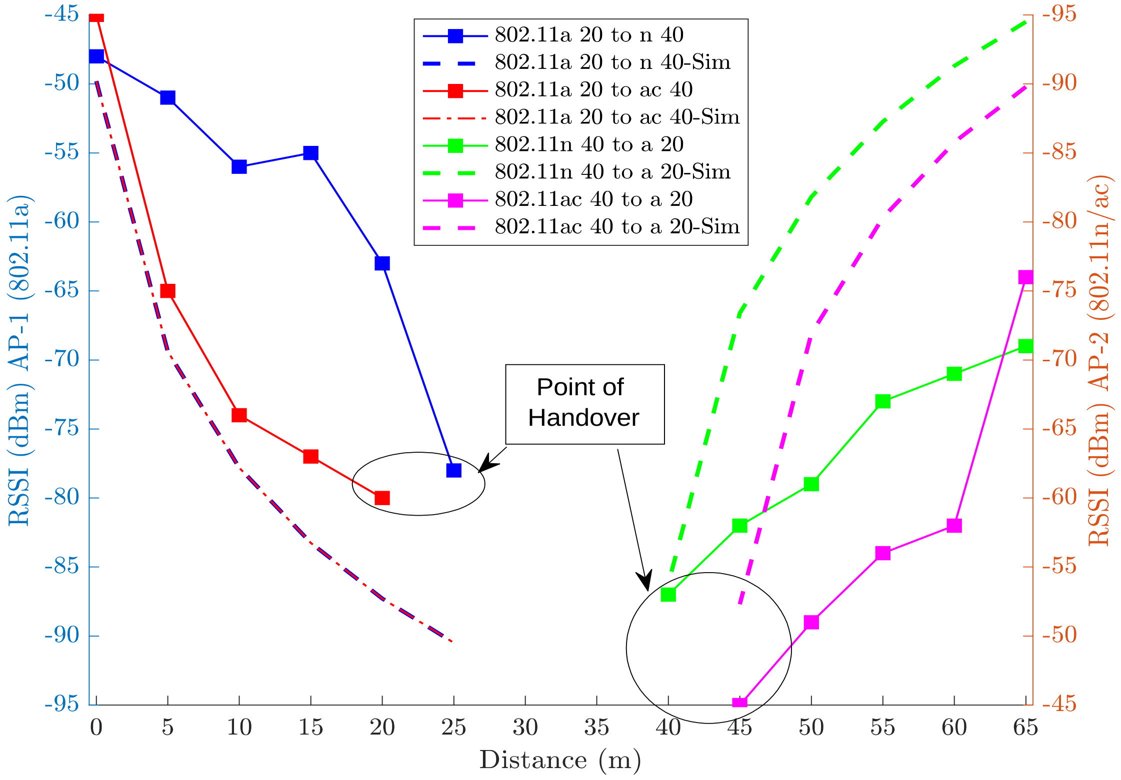

Figure 3. 15. Handover from 802.11a to 802.11n/ac with respect to Channel Bonding, Distance and Analytical/Simulation calculation

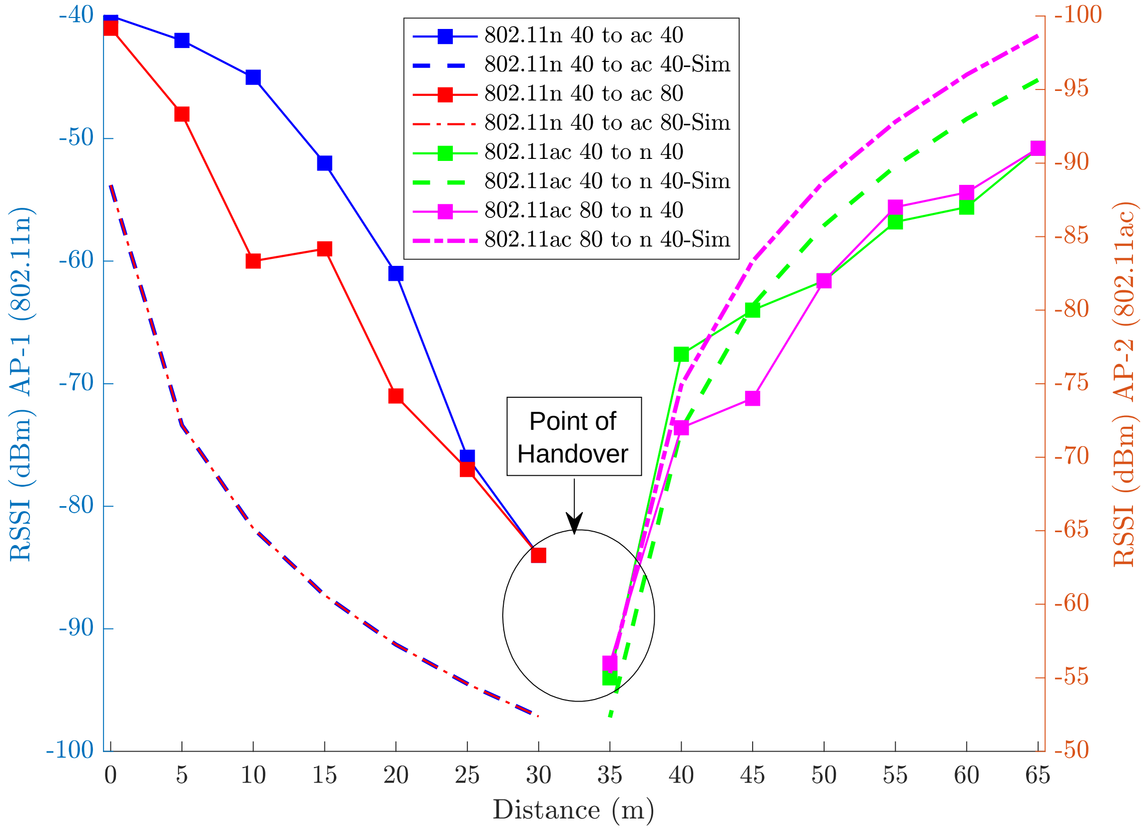

Figure 3. 16. Handover from 802.11n to 802.11a/ac with respect to Channel Bonding, Distance and Analytical/Simulation calculation

Figure 3.13 shows the results of test case 1 from Table 3.3 for observing bi-directional roaming from IEEE 802.11a to IEEE 802.11n/ac. The results represent the client's roaming that is initially connected to 802.11a and moving towards 802.11n/ac. It can be seen that the client roams from IEEE 802.11a to IEEE 802.11n with 20 MHz bandwidth at an average difference in RSSI of -25 dBm and a distance of 22 meters. Similar results were obtained when the client roamed from IEEE 802.11a to IEEE 802.11ac with a 20 MHz bandwidth at an average difference in the RSSI value of -30 dBm at a distance difference of 20 meters. It also shows the cases where the client initially connected to 802.11n/ac and moved towards 802.11a. It is noted that the client roams from IEEE 802.11n to IEEE 802.11a with an average difference in RSSI of -25 dBm and at the 25 meters distance between them. Similar results obtained when the client roamed from IEEE 802.11ac to IEEE 802.11a at an average difference in RSSI value of -33 dBm and a distance difference of 20 meters.

Figure 3.14 shows the results for test case 2 from Table 3.3 for observing bi-directional roaming from IEEE 802.11n to IEEE 802.11a/ac. The results represent the client's roaming that is initially connected to IEEE 802.11n and moving towards IEEE 802.11a/ac. It can be seen that the client roams from IEEE 802.11n with 20 MHz bandwidth to IEEE 802.11a with 20 MHz bandwidth with an average difference in RSSI of -26 dBm and at an average distance of 25 meters. Similar results obtained when the client roamed from IEEE 802.11n with 20 MHz bandwidth to IEEE 802.11ac with 20 MHz bandwidth at an average difference in RSSI value of -33 dBm and an average distance of 32 meters.

Figure 3.15 represents the cases where the client initially connected to IEEE 802.11a and moving towards IEEE 802.11n/ac with 40 MHz bandwidth. This test is designed to observe the roaming between protocols with 20 MHz bandwidth operating with protocols with channel bonding features operating at 40 MHz bandwidth. It can be seen that the client roams from IEEE 802.11a with 20 MHz to IEEE 802.11n with 40 MHz with an average difference of -26 dBm RSSI value and at the difference in their distance of 20 meters. Similar results obtained when the client roamed from IEEE 802.11ac with 40 MHz to IEEE 802.11a with 20 MHz at an average difference in RSSI values of -35 dBm and an average distance of 25 meters.

Figure 3.16 represents the cases where the client initially connected to IEEE 802.11n with 40 MHz channel bandwidth and moving towards IEEE 802.11ac with 40 and 80 MHz channel bandwidth. This test is designed to observe the roaming between protocols with channel bonding feature. It can be seen that the client roams from IEEE 802.11n with 40 MHz to IEEE 802.11ac with 40 MHz bandwidth at an average difference in RSSI of -29 dBm and the distance of 30 meters. Similar results were obtained when the client roamed from IEEE 802.11ac with 80 MHz channel bandwidth to IEEE 802.11n with 40 MHz bandwidth at an average difference RSSI values of -30 dBm and an average distance of 35 meters.

Here, we compared the experimental test results with the path loss model to observe the protocols' behaviour. The test results confirm that the roaming threshold exists, and it is above 20 dBm. The client moves away from the access points until the roaming threshold is triggered, and it searches for the network with a higher RSSI value to associate with that network. When the client reaches their roaming threshold, it starts to scan for the other network with higher signal strength (RSSI) and connects to it. The tests performed above shows that roaming is possible between any variations of IEEE 802.11a, 802.11n and 802.11ac. For the above tests to be completed successfully, all the access points are configured to deliver a maximum data rate and minimum transmission power. With this setup, the bidirectional roaming is observed, and it can now be safely concluded that roaming from 802.11ac to the legacy protocols is possible with the network adapter and operating system used during this test. Some of the observations derived from the compatibility test are as follows:

1. Roaming is not observed with different SSIDs and authentication scheme.
2. Roaming is observed with similar SSIDs and authentication schemes configured on the access points.
3. Transmission power affects the range of protocols.
4. The factor called roaming threshold to exist, and once the client reaches this roaming threshold, it initiates the roaming process
5. Bidirectional roaming is observed between all the variants of IEEE 802.11ac with legacy protocols, and in order to save power, the client sacrifices the throughput.

3.6 Chapter Summary

This chapter has conducted a laboratory-based experimental study to evaluate throughput, range, efficiency, and backward compatibility (interoperability and roaming) performances of IEEE 802.11a, 802.11n and 802.11ac standards in an indoor heterogeneous wireless environment. Even though not conducted in a real vehicular environment setting, the primary motivation was to evaluate and extrapolate the possible impact that these protocols mentioned above can have on a heterogeneous vehicular network. In the laboratory setting, the laptop employed emulates a moving vehicle.

For this, we have systematically elaborated the effect of test scenarios in an indoor line of sight environment. The throughput test results show that the theoretical throughputs are never achieved during this experiment and TCP, and UDPs advertised data throughputs are never reached, where TCP and UDP achieved 50% and 65% of the actual advertised data rate, respectively, for the tested protocol. The short guard interval, i.e., 400 ns, boosts the date rate by 8-12%. The range test results show that the IEEE 802.11n and 802.11ac operate efficiently at the range of 30-35 meters, and a client can connect to a network even at 60-65 meters. However, in IEEE 802.11a, the client could not connect to the access point after 40 meters, and the maximum data rate of 54 Mbps is only achieved at the first 5 meters.

The proposed hypothesis for backward compatibility test is proven correct, where the client connects to the access point with higher signal strength and RSSI values, and it is now safely concluded that the seamless roaming is observed from legacy protocols to the 802.11ac and vice-versa. In phased migration, the upgradation from legacy protocols to the latest wireless standards includes analysing the existing network infrastructure's performance and finding coverage holes. In addition, careful planning is required and upgrading the infrastructure in phases, which is very cost-effective compared to upgrade the entire network infrastructure at once. The test results imply that the phased migration strategy would be the best for implementing stable wireless network deployment. The 802.11ac has all the functionality and capability that can meet the growing need of wireless culture; thus, it is useful for general IoT applications and, in particular, for vehicular networks for autonomous driving vehicles.

Chapter 4

Communication Infrastructure for Autonomous Driving Vehicles (ADVs)

4.1 Introduction

In the previous chapter, we assessed the validity and usage of various protocols in an emulated wireless network in an indoor laboratory setting. However, the development of a control and communication scheme for autonomous vehicles also requires establishing a suitable communication architecture by considering the dynamic nature of ad-hoc wireless and vehicular networks.

In this chapter, we proposed a novel communication architecture for a vehicular network with Software Defined Network (SDN) technologies to support multiple core networks and tackle potential challenges raised by ADVs, as mentioned in Section 2.2. Initially, the data requirements are evaluated for the vehicular network with respect to several road lanes and vehicle cluster size to use frequency and bandwidth efficiently. Secondly, the network latency requirements are analysed, which are mandatory constraints for all applications where real-time end to end communication is necessary. Finally, a test environment is formulated to evaluate the vehicular network's improvement using an SDN-based approach over the traditional core (Cisco) network.

4.2 SDN and NFV based Vehicular Communications for ADVs

The concept of leveraging wireless communications in vehicles has fascinated researchers since the 1980s [146]. Several factors have led to this development, including the broad adoption of IEEE 802.11 technologies; by the embrace of vehicle manufacturer of information technology to address the safety, environmental, and comfort issues of their vehicles; and the commitment of the large national and regional government to allocate wireless spectrum for vehicular wireless communications. Vehicular communication is an important and emerging area of research in the field of vehicular technology. The development of software and hardware in communication systems leads to a new generation of communication networks.

Communication networks are dynamic and complex. Unsurprisingly, configuring and managing them continues to be challenging. Establishing a reliable communication infrastructure capable of handling critical information originating from the vehicular network needs significant changes in the existing network architecture. Since conventional networks are mostly hierarchical, built with tiers of Ethernet switches arranged in a tree structure, they are only suitable for static networks and cannot facilitate the dynamic traffic flow in vehicular networks. Although suitable for client-server computing, the existing network architecture poses severe limitations to today's enterprise data centres' dynamic computing and storage needs. These limitations are also posed to carrier environments, which will act as a backbone and service provider for the future ADVs to communicate driving and safety information with the neighbouring vehicles [147].

Furthermore, due to the lack of communication ability among neighbouring vehicles, autonomous driving vehicles cannot fully predict neighbouring vehicles' behaviour. The primary approach to detect surrounding environments utilises sensor systems, which could be profoundly affected in different driving conditions such as other road/user obstacles, vehicle behaviours and poor weather conditions. For this, V2V and V2I communication together called Vehicle-to-Everything (V2X) communications [148], can serve as a second layer of protection in autonomous driving, where every vehicle can periodically broadcast safety-related messages with their current parameters such as speed, position, and acceleration to their neighbouring vehicles, which can help other vehicles accurately map their surroundings [17].

To facilitate the vehicular communications among ADVs and overcome limitations of the traditional network architecture, certain technologies such as Network Function Virtualization (NFV) and SDN could provide possible solutions to handle the ever-increasing communication requirements of the next generation of ADVs.

The NFV is a complementary technology to SDN, which has the potential to impact future computer networking dramatically. It refactors the architecture of a legacy network by virtualising as many network functions as possible. NFV aims to virtualise a set of network functions, also known as network softwarisation, by deploying them into software packages assembled and chained to create similar services provided by the legacy network. Therefore, NFV has dramatically increased the number of hosts requirement for network connectivity and fundamentally altered assumptions about the physical location of hosts [149]. SDN's benefits can be realised throughout the network from access level to mobile backhaul to the Evolved Packet Core (EPC), leveraging SDN's flow-based paradigm, granular policy management, and network virtualisation and traffic steering capabilities [150]. SDN's original idea is to move the control plane outside the network switches, known as the network's slicing and enable external control data through a logical software called SDN controller. SDN provides a pure abstraction to describe the components, the function they provide, and the protocols to manage the forwarding plane from a remote controller via a secure channel. However, NFV aims at realising network functions on high-performance servers/switches and storage devices using a standard virtualisation technology [151]. Network functions are modularised and connected by software interfaces. The network can be sliced by network virtualisation technology, and each slice can apply its network function combination.

The traffic patterns of mobile networks and cloud-based services are dynamic and unpredictable in nature. The present-day static and manually configured transport network are not flexible and dynamic enough to support vehicular networks [152]. Therefore, mobile and wireless networks have become primary and sole access methods for many application services. The mobile operators must support a high traffic volume to aid more sophisticated services and the vehicular networks' preferences due to its critical nature. SDN controls the network in a centralised, systematic and programmable manner by decoupling the forwarding function (data plane, i.e., user equipment) and network controls (control plane, i.e., SDN controller/server), thus improving the efficiency of vehicular networks by fulfilling the requirements of ADVs [153]. With the uses of NFV and software-based controllers, network operators are much more flexible in programming, modifying, manipulating and configuring communication protocols in a centralised way, which improves network functionalities in terms of resource allocation and handling immense network loads in vehicular networks. This dynamic network and resource allocation can be achieved by network management and orchestration module, i.e., MANO system [148].

4.3 Technical Requirements and System Design Specifications

This section discusses a communication architecture for ADVs based on SDN due to its suitability to meet future vehicular communication demands. We shall also set the design specifications and consider technical requirements and features of autonomous vehicles for V2X communication. As mentioned before, V2X communications refer to information exchange between a vehicle and various elements of the intelligent transportation system (ITS), including other vehicles, pedestrians, internet gateways, and transport infrastructures such as traffic lights and signs. From the vehicular network perspective, the development of communication architecture requires high flexibility, low latency communication, and efficient load balancing for data routing and handling the high capacity of vehicular nodes. In order to support extremely-dense-and-heterogeneous scenarios (EDHs) where multiple road users are connected by a robust, reliable and dynamic network, there is a need for fast data transmission with sub-millisecond latency [154].

The technical requirements for designing V2X communication architecture for autonomous vehicles are listed below:

- **End-to-end latency for automated overtaking in milliseconds $(\mathbf{ms})$:** Maximum tolerable elapsed time from the instant, a data packet is generated at the source application (ADVs) to the instant it is received by the destination application (Vehicular Network) should be approximately 10 ms to create the necessary gap in time to avoid a collision with an oncoming vehicle [14].
- **Reliability $(\mathbf{10^{-x}})$:** Maximum tolerable packet loss rate at the application layer will be, 10^{-5} within the maximum tolerable latency [14].
- **Data rate $(\mathbf{Mbit/s})$:** Minimum required data rate for the multiple ADVs applications to function correctly is in a range of 3 to 27 Mbps for exchanging Basic Safety Message (BSM), which contains information on GPS location, speed, direction, and vehicle-related information [15].
- **Communication range in meters $(\mathbf{m})$:** Maximum distance between source and destination(s) of a radio transmission within which the application should achieve the specified reliability. The typical range will be 100 to 300 meters [14].
- **Node mobility $(\mathbf{Km/hr})$:** Maximum relative speed under which the specified reliability should be achieved, considering minimum 25 km/hr and 120 km/hr maximum [155, 156].
- **Network density $(\mathbf{Vehicles/Km^2})$:** A maximum number of vehicles per unit area under which the specified reliability should be achieved. The saturation point per square kilometre is 2000 vehicles [14].

In our proposed architecture in the next section, we consider ADVs communicate and share status information with the nearest RSU, depending on their local knowledge of the surrounding environment. The SDN controller creates dynamic policies and rules according to the requirements of ADVs and share them with the RSUs, allocates resources, and provides information to ADVs for their operational requirements. These data from RSUs are sent to data centres through SDN controllers for further processing. Beacon messages are broadcasted periodically to maintain and update the network topology of ADVs, allowing vehicles to know their neighbours' location. These messages also include traffic data, such as route map, position, speed and vehicle's sensor data. To demonstrate this, we also proposed a four-lane road infrastructure with multiple clusters consists of several ADVs and SDN-based communication architecture to evaluate data requirements using sensors and vehicle safety requirement.

For ADVs, it is essential to acquire and communicate information related to the position, acceleration, deceleration, speed, steering tilt angle, separation between the vehicles and object tracking. The following objectives are achieved with multiple sensors, including Accelerometer, Radar System, Vehicle Dynamics Control (VDC), Differential Global Positioning System (DGPS) and Digital Steering Angle System (DSAS). Specifications of the selected sensors, along with their values, sampling rate and the data bits requirement for communication, are listed in Table 4.1. These sensors also define the data requirements for an individual vehicle which can be linearised to more extensive networks. These sensors serve five crucial aspects of autonomous driving: Localisation, Perception, Planning, Vehicle Control and System Management [13].

We also considered breaking the strategy for vehicles' safety requirement; each vehicle must maintain a safe following distance (3 seconds rule) from the vehicle in front and back. These requirements can significantly change with weather conditions (rain, fog, snow and lightning), traffic and road conditions. Therefore, in an inclement situation such as bad weather conditions, a 6 to 9 seconds distance margin should be maintained [157]. The vehicles' speed and knowledge about its stopping time and distance can be quickly evaluated while maintaining a safe following distance. For different speeds or velocity, the stopping distance and perception time/distance are calculated and presented in Table 4.2. The average driver would take one-half to three-quarters of a second to perceive a need to brake and another three-quarter of a second to move their foot from the gas to the brake pedal. This perception and reaction time in autonomous vehicles are critical, and appropriate information must be communicated to take suitable actions within due time. It is also worth noting that the autonomous vehicle system must respond within the same time duration for good weather conditions, as well as critical. The safe braking strategy can be ensured by following the recommended separation distance between vehicles, as represented in Table 4.2. The time separation is represented in seconds as a general convention, and it applies to a broader range of speeds and different weather conditions [158].

Table 4. 1. Sensor Data

Sensor Type	**Reference**	**Manufacturer**	**Bits/ Sample**	**Sample/s**	**Sampling Rate (Hz)**
Accelerometer [159, 160]	SCA3100-D04	VTI Tech	36	2000	2000
	MM5.10	Bosch	36	1000	2000
Mid-Range Radar (MRR) [161]	Front	Bosch	-	-	-
	Rear	Bosch	-	-	-
LiDAR System [162]	LUX	IBEO	14	50	50
VDC [163]	SMB 225	Bosch	16	100	57/ 180
Roll-over [164]	SMB 200	Bosch	10	-	52
DGPS [165]	DSM132	Trimble	-	-	1,2,5, 10
Steering angle [166]	6002	Bourns	8	100	200

Table 4. 2. Safe Breaking and Following Distance [155, 158]

Speed (mph, ft./sec)	**Perception distance (ft.)**	**Overall Stopping Distance (ft.)**	**Safe following distance**	
			Good (ft.)	**Marginal (ft.)**
(25,37)	37	74.16	111	222
(35,52)	52	103.83	166	312
(45,66)	66	133.497	198	396
(55,81)	81	163.163	243	486
(65 ,96)	96	192.829	288	576
(75,111)	111	222.495	333	666
The time separation between the vehicles (3 Seconds/Good weather), (6 Seconds/Critical weather)				

4.4. Proposed Communication Architecture & Four Lane Road Infrastructure for ADVs

The proposed cellular-enabled vehicular network has an SDN architecture for system management and control. The proposed architecture for V2X communication is shown in Figure 4.1, where the low-level cellular infrastructure (as represented in Figure 4.2) is integrated with the higher hierarchy of the network model. ADVs act as dynamic nodes in the proposed architecture, installed with wireless On-Board Units (OBUs) for communicating with other ADVs and infrastructure. The OBUs communicate in vehicular network with the help of RSUs. The ADVs are equipped with multiple sensors such as pre-crash collision sensors, adaptive cruise control sensors, blind-spot detection sensors and rear-crash collision sensor. These sensors provide vehicles with a complete perspective of road infrastructure and any objects in their proximity to facilitate smooth and safe driving.

The proposed architecture is implemented using SDN and cellular structure to facilitate frequency reuse and accommodate many ADVs and related applications. The cellular base station (eNB) is under the SDN controller's control and facilitates the local vehicular network. Multiple RSUs are connected to the RSU controller and are responsible for forwarding data, storing local road information and performing emergency services.

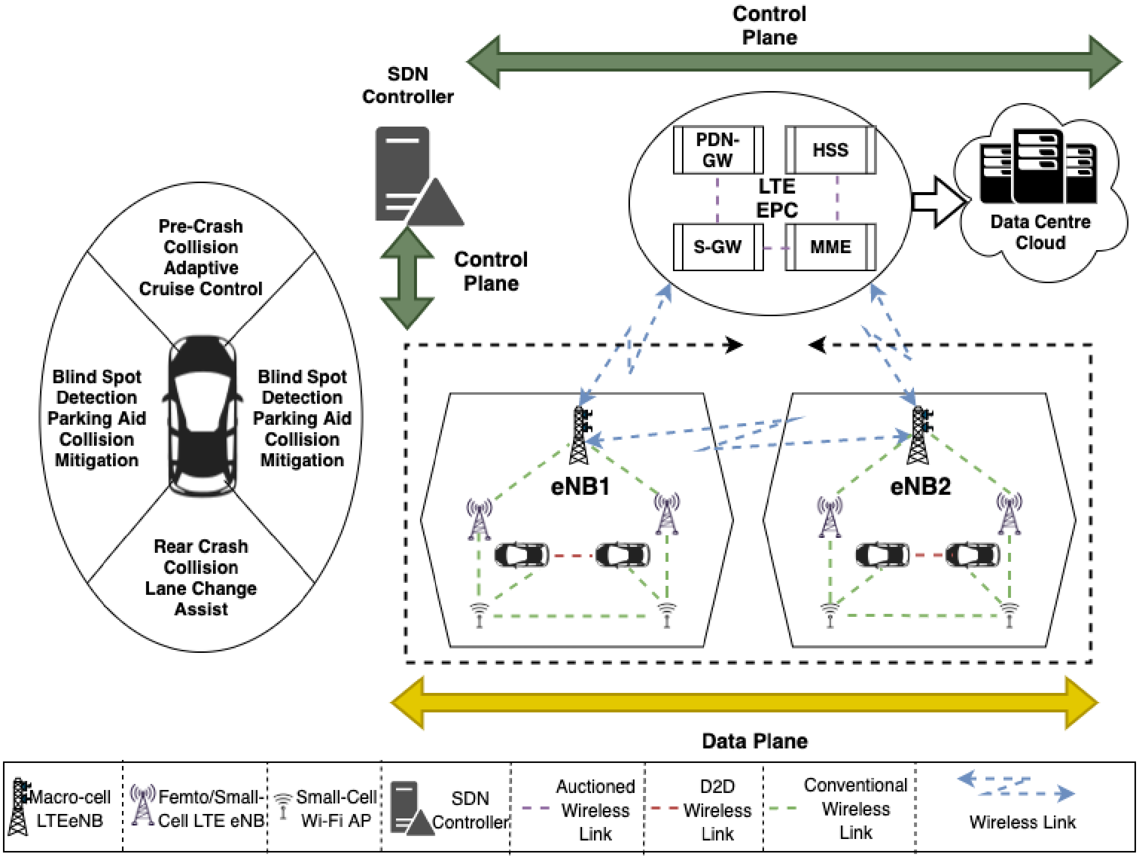

Figure 4. 1. Proposed SDN Communication Architecture for ADVs

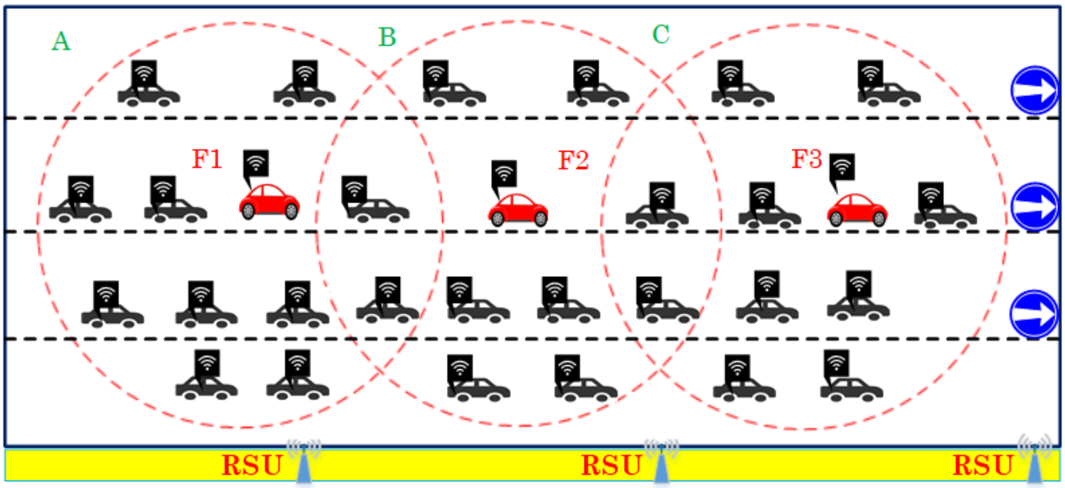

Figure 4. 2. Four Lane Road Infrastructure for ADVs

Figure 4.2 represents the four-lane road infrastructure for ADVs as an example scenario where three clusters are presented. The interference between the two clusters is mitigated by using a clustered structure with *n* frequency sets. The ADVs in a cluster exchange information with each other on a regular interval, whereas the RSUs execute the inter-cluster communication. Each cluster uses a dedicated frequency (*F1, F2, F3)* to mitigate inter-cluster interference. The cluster size can be extended to multiple hops where each additional hop adds more vehicles in front and back of the cluster, as represented in Figure 4.2.

The proposed SDN-based cellular architecture leveraging V2X and their components in Figure 4.1 are discussed as follows:

- **SDN Controller**: It is a global intelligence that controls all the SDN-based V2X system's network behaviour. It also plays as Fog orchestration and Resource management.
- **Wireless Nodes:** The vehicles act as the end-users and a forwarding element, equipped with On-Board Unit (OBU) operating on OpenFlow protocol. They are data plane elements.
- **Road Side Units (Small/Pico/Femtocells):** The RSUs running OpenFlow and controlled by the SDN Controller. It is a Fog device.
- **Road Side Unit Controller (LTE EPC):** A cluster of RSUs is connected to Roadside Unit Controller (RSUC) through a broadband connection before accessing SDN Controller. The RSUC is OpenFlow-based and controlled by SDN Controller. Besides the responsibility of forwarding data, RSUCs also store local road system information and perform emergency services. RSUCs are Fog devices under the orchestration of the SDN Controller.
- **Cellular Base Stations (eNB):** In the proposed architecture, the Base Station (BS) is not only carrying voice calls and conveying data but performs more sophisticated task under the control of the SDN Controller, running OpenFlow and delivering Fog services. Similar to RSUCs, BS is also a local intelligence, a Fog device under the control of the SDN Controller.

- **PDN-GW:** The PDN-GW (Packet Data Network - Gateway) is the connection between the Long-Term Evaluation (LTE) Evolved Packet Core (EPC) and the external IP network. These networks are called PDN; PDN-GW routes packets to and from the PDNs. The PDN-GW also performs various functions such as IP address/IP prefix allocation or policy control and charging. PDN-GW deals with the user plane.
- **S-GW:** The (S-GN) Serving Gateway is the point of interconnect between the radio-side and EPC. It transports IP data traffic between the User Equipment (UE) and external networks. It is an anchor point for the intra-LTE mobility (i.e., in the handover between eNodeBs) and between LTE and other access technology.
- **HSS:** The HSS (Home Subscriber Server) is a database that contains user-related and subscriber-related information. It also supports mobility management, call and session setup, user authentication and access authorisation.
- **MME:** The MME (Mobility Management Entity) deals with the control plane. It handles the signalling related to mobility and security for E-UTRAN access.

The RSUs are responsible for accumulating sensory data from ADVs. With the increase in cluster-size, or while facilitating multiple clusters, RSUs accumulate data from the affiliated ADVs. However, due to the large amount of data received from ADVs, the communication links from RSUs to RSU controller can saturate. Therefore, evaluation of management capabilities of the high-speed data link from RSUs to RSU controller is essential. Further to this, it is crucial that resources are efficiently managed and equally divided into multiple RSUs for effective operation.

Fog computing architecture is used to resolve the issue of resource management. It can be perceived both in large cloud systems and data structure, referring to the growing difficulties accessing information objectively. The edge devices will carry out a substantial amount of computation, storage and communication locally and routed over the internet backbone [167]. Fog networking consists of a control plane and a data plane. For example, on the data plane, Fog computing enables computing services to reside at the edge of the network instead of servers in the data-centre cloud. Compared to cloud computing, Fog computing emphasises proximity to end-users and client objectives (e.g., resource exploitations and security policies), dense geographical distribution and context-awareness for computation and Internet of Things (IoT) resources. It also aids latency reduction and backbone bandwidth savings to achieve better Quality of Service (QoS), resulting in superior user-experience and redundancy in case of communication link failure.

For V2V communication, Time Division Multiple Access (TDMA) based channel access mechanisms are used, allowing vehicles to communicate in dedicated time slots to reduce interference in that zone. The TDMA is a digital technique that divides a single channel or band into time slots. Each time slot is used to transmit one byte or another digital segment of each signal in a sequential serial data format. This technique works well with data signals but is also useful for compressed video and other high-speed data. The TDMA uses a single frequency band for both the transmitting and receiving end. The single band is shared by assigning alternating time slots for transmitting and receiving operation. Because of the high-speed nature of the data transmission in the vehicular network, these transmissions are concurrent rather than simultaneous.

Moreover, the alternating time slots are of the same duration or have the same downlink and uplink times. However, this system does not have to be 50/50 symmetrical; it can be asymmetrical as required. The clusters are needed in VANETs to achieve stability and channel utilisation [114]. The TDMA divides the signal into time frames, and it divides the time frame into time slots, where each vehicle is associated with a time slot in the frame [168]. Figure 4.3 shows the working of TDMA.

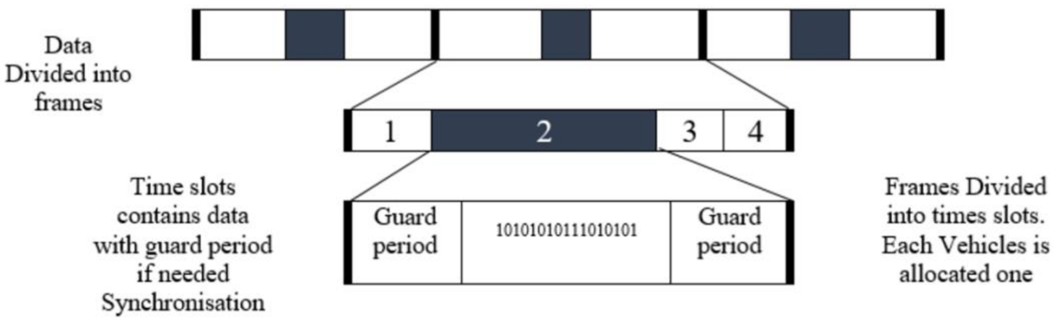

Figure 4. 3. Structure of TDMA Channel

4.5. System Design for Evaluating Network Efficiency

The proposed network design investigates the traditional Cisco and SDN network for throughput and network efficiency for an individual host (vehicle) and the entire system.

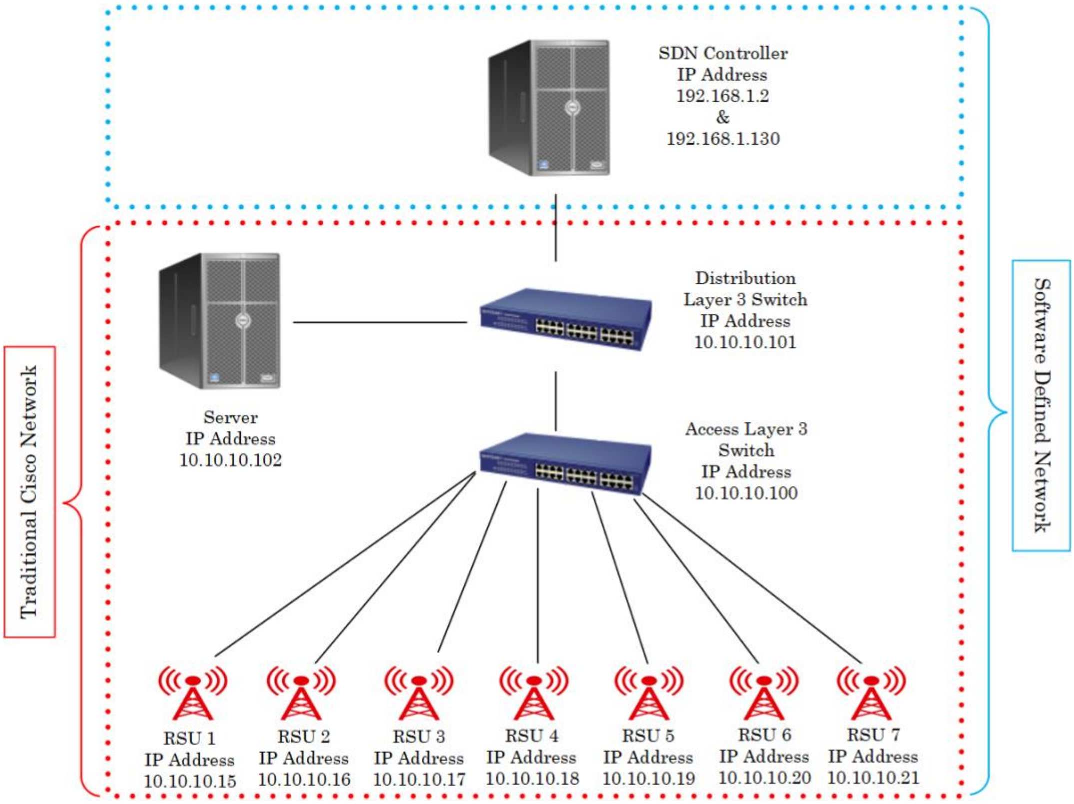

Figure 4. 4. Network Design for Throughput Test

In Figure 4.4, the SDN controller consists of a Network Operating System (NOS) running a collection of application modules, such as radio resource management, node mobility management, on-demand resource allocation, self-configuration, routing and self-organisation. The SDN helps enhance the ADVs system performance, including driving efficiency, safety and resource allocation. Therefore, the newer generation of cellular networks needs to be designed so that the separation of control plane functionalities fits well within its current architecture of the core and backhaul.

The design goal of the control plane and management plane can be summarised in the following steps:

- The control plane functionalities in all network entities of the LTE network need to be separated by slicing the network with SDN and NFV to achieve an efficient and optimal ADVs network.
- By creating a mathematical model and an optimisation algorithm, the future autonomous vehicles' network topology can be reconstructed considering heterogeneous environment to support multi-service.
- Implementation of the control plane functions as an SDN controller for ADVs use cases to develop a model for information processing and SDN optimisation for future autonomous vehicles.
- The traditional functions incorporated in the data plane (user equipment) of the LTE network, including mobility management and resource allocation, can be decoupled and ported to the control plane. However, lack of management intelligence requires an additional tier in the SDN architecture for intelligence management and orchestration (MANO). The MANO layer can be integrated with the SDN to increase the reliability and functionality of the network.
- The SDN controller can potentially have control over the number, placement and work-load assignment of instances of each function instantiated as Virtual Machine (VM); therefore, encapsulation of the management plane functions within individual VM can be made to interact with the SDN controller.

Our design has used an intelligent management plane in this approach, which introduces significant flexibility and programmability through a newly developed control plane. For the software data plane, the OpenvSwitch agent is installed in all devices, which a logically centralised SDN controller can control. In this SDN-based design, the control plane is decoupled from the data plane, and the control aspects are incorporated in a distributed SDN controller. The data plane is reduced to a set of SDN-enabled routers for the primary task of packet forwarding. In this decoupled architecture, the control plane handles all necessary signalling and manages user equipment (UE) mobility. The SDN is based on OpenFlow protocol, and the SDN controller will push the rules to all devices in a proactive manner to handle the large scale of subscribers.

Seamless communication between vehicles and infrastructure is a requirement of vehicular networks. Therefore, in this experiment, the efficiency and throughput of traditional core (Cisco) and SDN-based networks are evaluated. The test scenario is being created with Cisco devices and HP SDN compatible devices, where hosts act as an RSUs and the server acts as a core network with TCP based data traffic. Figure 4.4 shows the test network set up to conduct the throughput tests from hosts (RSUs) to the server (Core Network). Two network designs are proposed to test the Cisco and SDN network topologies. The devices with a similar configuration are being used, with parameters maintained the same for network testing tools, to investigate the difference between the practical throughputs from both test scenarios. The only difference between Cisco and SDN topology is the SDN controller's presence for SDN topology management. The SDN controller has a global view of all the devices, allowing it to manage networks more appropriately and efficiently. Thus, it is very convenient for network operators to decide how the traffic is routed and how to apply specific policies to route network traffic according to specific applications' dynamic needs.

4.5.1. Test Methodology

Table 4.3 summarises the list of equipment for the throughput test. The practical throughput of the Cisco traditional network is obtained and compared with the SDN network's practical throughput by transmitting continuous data streams by a number of hosts to the server and vice-versa.

For the network formation, two Cisco 3550 layer three switches with 12-fibre gigabit Ethernet and 2-copper, gigabit ports are used as a distribution and access layer for Cisco topology, while two HP switches with SDN (Open-Flow) compatibility are used for SDN topology. The Layer 2 trace-route functionality of these switches' eases troubleshooting by identifying the physical path that a packet takes from source to destination. The IP traffic generator is used on a server, which acts as a host, connected to the 1-gigabit port on the distribution switch. The host and server machines are running Windows 7 Enterprise, with an AMD processor and 8 GB of RAM. The SDN controller is running on Ubuntu 16.04 with VMware virtualisation desktop and used only for SDN topology. JPerf is a graphical interface open-source software used evaluating the network's throughput and performance by varying the parameters such as payload and protocol. It also accounts for parameters such as bandwidth, delay, and jitter, amongst others.

Table 4. 3. List of equipment used for setup [30, 31]

Hardware	**Cisco Catalyst** [169]	**HP ProCurve (SDN)** [170]
Distribution Layer Switch	WS-C3550-12G	HPE 3800-24G-2SPF+ Switch (J9575A)
Access Layer Switch	WS-C3550-12T	HPE 3800-24G-2SPF+ Switch (J9575A)
Hosts/Server	Windows 7 Enterprise Service Pack 1 64-bit with AMD A4-5300 APU with Radeon ™ HD Graphics 3.40 GHz with 8 GB RAM.	Windows 7 Enterprise Service Pack 1 64-bit with AMD A4-5300 APU with Radeon ™ HD Graphics 3.40 GHz with 8 GB RAM.
SDN Controller	N.A.	Ubuntu 16.04, 64-bit with AMD A4-5300 APU with Radeon ™ HD Graphics 3.40 GHz with 8 GB RAM.
Network Testing Tool	Jperf version 2.0.2	Jperf version 2.0.2

The hosts send a continuous stream of data to the server for a fixed period of 10 seconds, and the throughput is recorded at the receiving host. However, only one host transmitting a single stream of data does not reach the link saturation; hence multiple streams of data by several hosts are sent simultaneously to the server. The obtained result shows the maximum practical throughput generated by the TCP protocol in this experiment. Ten runs are recorded to get accurate results, and their averages are used as a final result.

4.6. Results and Discussion

4.6.1. Data rate requirement for ADVs

The proposed low-level cellular infrastructure in Figure 4.2 is a four-lane road scenario with 3 clusters labelled as A, B and C. Each cluster has a number of vehicles that the local vehicular network can handle. The data required for each cluster is dependent on the number of ADVs and the number of lanes (road). The data requirements vary with the lane traffic and different cluster sizes (for example, the cluster represented in figure 4.2 is extended to multi-hops communication).

For the communication in each cluster, data requirements can change drastically for different lanes and cluster sizes. Figure 4.5 presents the upper bound of data rate requirements in vehicular communication networks for three different cluster-sizes and a different number of lanes. The required data rate is evaluated using the sampling rate and quantisation levels for each sensor, which is mandatory for collecting sufficient information for ADVs. The susceptibility of packet loss in a wireless channel is also considered for evaluating the maximum data link requirements under given conditions. A TDMA based slotted channel access is implied where control information necessary to handle the network traffic is also included in the evaluation. Since the sensory data necessary to predict vehicle trajectory and movement is relatively low (~ 1 Kbyte), it can easily be handled with traditional wireless networks. The sensor data from the vehicles is communicated every 100 milliseconds to keep the network updated. The increase in cluster size allows more accommodation of ADVs, resulting in better network management. However, data requirements can change notably in a vehicular network.

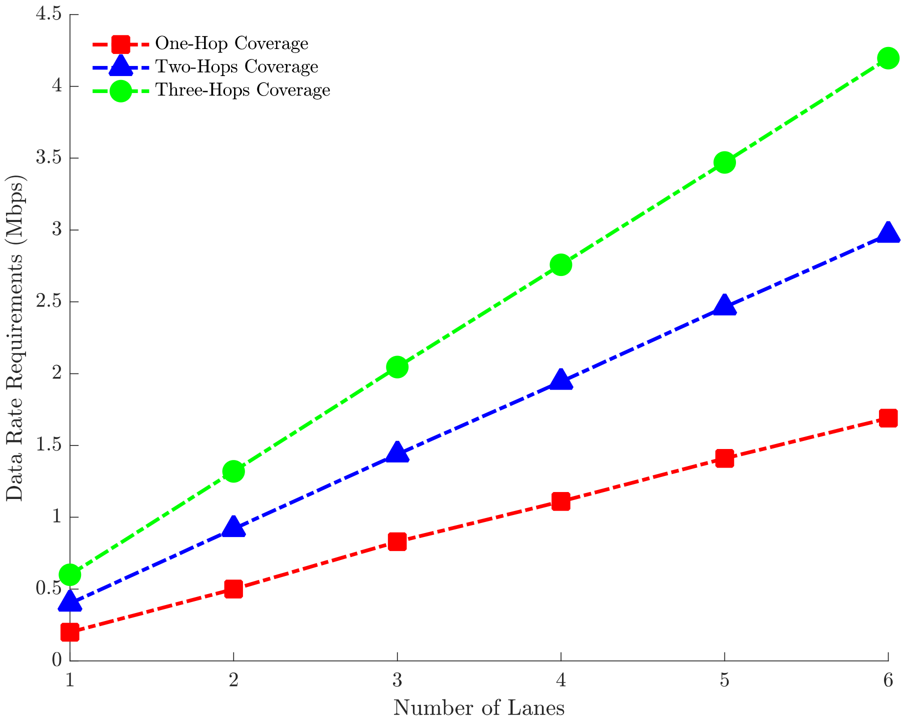

Figure 4. 5. Maximum Data Requirements for Different Number of lanes

4.6.2. Throughput and Efficiency Test

In the presented throughput test scenario, data rate throughput on Cisco and SDN networks are investigated using standard TCP protocols. Uniform environments and setup are ensured to compare the performance of SDN with the traditional Cisco networks. Both network scenarios (SDN and Cisco) are tested by increasing the number of parallel streams where the obtained results for Cisco and SDN based networks are presented in Table 4.4 and 4.5, respectively.

The data rate requirements plotted in Figure 4.5 indicate the throughput requirement of a single cluster with an increase in the number of lanes and cluster size. Each cluster is affiliated with a particular RSU, while multiple clusters can be associated with a single RSU. The data accumulated at the RSUs needs to be transmitted to the RSU controller and data centre; hence high-speed links are desirable in the core network, capable of handling multiple RSUs over a single link.

Table 4. 4. Cisco wired TCP

Runs	**Host 1 [Mbps]**	**Host 2 [Mbps]**	**Host 3 [Mbps]**	**Host 4 [Mbps]**	**Host 5 [Mbps]**	**Host 6 [Mbps]**	**Host 7 [Mbps]**
Run 1	738	924	927	882	916	926	933
Run 2	720	917	925	926	913	896	940
Run 3	703	913	921	920	922	897	929
Run 4	724	899	928	946	884	920	932
Run 5	704	907	927	924	883	897	937
Run 6	735	911	940	866	902	929	936
Run 7	697	920	932	917	903	911	929
Run 8	697	922	932	912	914	928	945
Run 9	711	919	927	929	924	932	936
Run 10	694	922	926	897	910	927	940
Average	713.1	915.4	928.5	911.8	907.1	916.3	935.7

Table 4. 5. SDN wired TCP

Runs	**Host 1 [Mbps]**	**Host 2 [Mbps]**	**Host 3 [Mbps]**	**Host 4 [Mbps]**	**Host 5 [Mbps]**	**Host 6 [Mbps]**	**Host 7 [Mbps]**
Run 1	877	920	929	957	943	956	957
Run 2	878	937	948	965	936	942	959
Run 3	882	936	948	940	946	950	952
Run 4	872	923	951	945	937	958	959
Run 5	900	936	932	958	949	957	966
Run 6	861	940	928	952	951	952	956
Run 7	867	930	940	955	959	964	958
Run 8	887	940	945	948	951	948	955
Run 9	878	941	931	947	949	961	953
Run 10	862	936	951	949	944	955	962
Average	867.4	933.9	940.3	951.6	946.5	954.3	957.7

The network topology presented in Figure 4.4 compares the throughput of networks and their effects on increasing host numbers. As per the data rate requirements presented in Figure 4.5and network topology presented in Figure 4.4, the SDN controller's maximum load capabilities can be evaluated. The core network efficiency is evaluated with up to seven RSUs, where each RSU can facilitate up to twenty-five 3-hop clusters.

The results show that one host of SDN performs better than Cisco. It is also observed that the throughput of the SDN-based network remains far more consistent than the Cisco network. The throughput comparison for both state-of-the-art Cisco and SDN-based networks is presented in Figure 4.6, where the SDN network's performance remains continuously better than that of the Cisco network. It can be seen that the average throughput achieved by the SDN topology is better than the Cisco topology, as, with two RSUs, the Cisco network only manages to achieve 915.7 Mbps while SDN achieves 933.9 Mbps, offering 2% improvement over the traditional network. Moreover, Figure 4.7 shows that the increase in the number of RSUs improved 4% efficiency in throughput and bandwidth on RSU 4 and 5. Since the 1 Gbps link is used for the setup, and the number of RSUs increases during the experiment, the link reached its saturation point, consequently affecting bandwidth between multiple RSUs operating on Cisco and SDN networks. The obtained results suggest that SDN effectively manages the increasing number of RSUs than the traditional Cisco network. Therefore, the overall efficiency of 5.19% achieved in terms of throughput in the SDN network over the Cisco network.

To compare all data rate, throughput and efficiency over every RSU and the entire system, we calculate their efficiency, E, by Equations 4.1 and 4.2 as follows:

$$D = RSU_{Average}\ (Cisco) - RSU_{Average}\ (SDN) \tag{4.1}$$

$$E = \left(\frac{D}{Cisco_{Average}}\right) \times 100 \tag{4.2}$$

where, D is the difference between average throughput obtained from Cisco RSUs and SDN RSUs over ten runs, and E denotes the improvement in the network's efficiency. The evaluated results suggest that SDN based network offers improved throughput and ensures bandwidth consistency in the network, allowing relatively lesser fluctuations in the system bandwidth with a change in circumstances. In the case of vehicular networks, SDN would offer better resource allocation by improving the utilisation of available bandwidth. To conclude with the TCP protocol test with a 1Gbps link, the SDN performs better than Cisco.

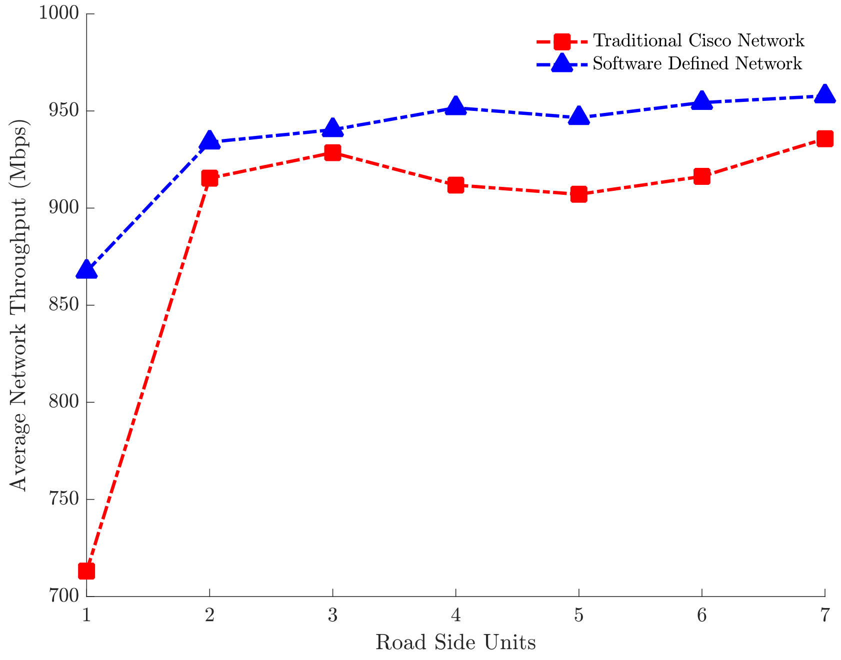

Figure 4. 6. Average throughput comparison of the network

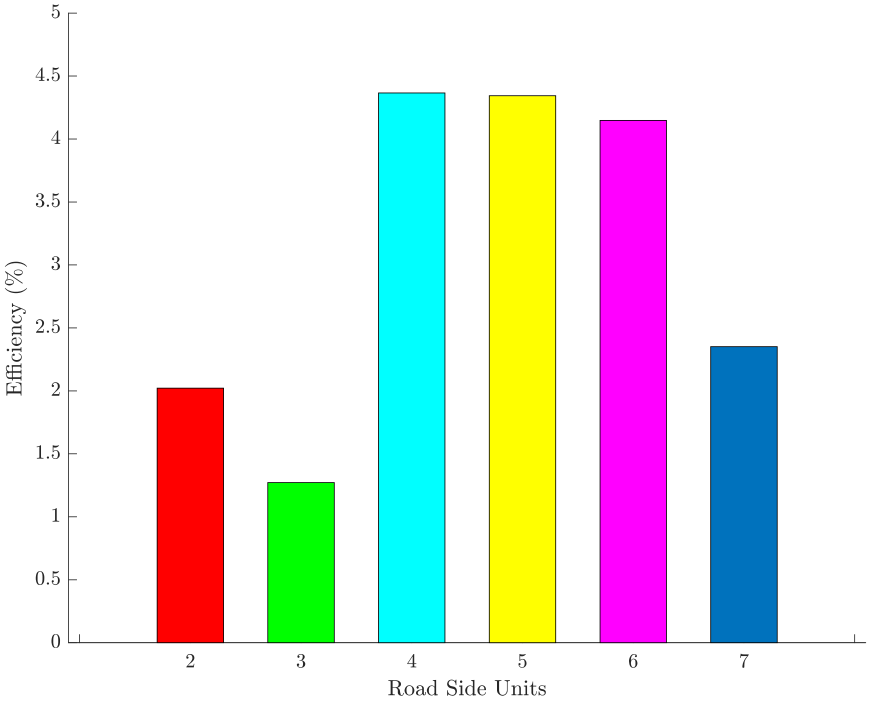

Figure 4. 7. The efficiency of the network

4.7. Chapter Summary

Autonomous driving technology can serve suitably for future vehicles. However, the autonomous driving system must be extended to network-level instead of a stand-alone solution to access the full benefits of communication technology and implement a secondary safety layer. In this chapter, an SDN based vehicular network was investigated to establish and ensure bandwidth requirement for a reliable link between the vehicles and the intelligent traffic control infrastructure. SDN's use offers improvements in overall throughput performance and resource management efficiency over conventional networks, and it manages bandwidth fluctuation effectively. This chapter lays the foundations for ADVs and network architecture; however, the vehicular networks' data requirements need to be further investigated for vehicular communication and SDN based network attributes.

SDN can offer optimised resource management in the vehicular networks, efficient use of bandwidth management and throughput performance improvement. However, the feasibility of Base Station (BS) and RSUs to cooperate with SDN controller for network knowledge to optimise the resource utilisation, service hosting, and migration need to be validated. Furthermore, a fallback/backup mechanism is required in case of unreliable connections or failure between RSUs and ADVs, while the SDN controller maintains the services, which must be carefully addressed. In conclusion, it is vital to simulate the proposed architecture, model, protocols and services using simulator platforms such as Matlab.

In the next chapter, we will develop a hybrid data-driven model by incorporating the IEEE 802.11p communication scheme with Car-Following models to demonstrate the working of V2I communication for autonomous driving vehicles' safety in a heterogeneous urban and highway traffic environment.

Chapter 5

Integrating Intelligent Driver Model (IDM) for Platoon of ADVs with Vehicle-to-Infrastructure (V2I) Communication

5.1. Introduction

In the previous chapter, we proposed an SDN network architecture for Autonomous Driving Vehicles (ADV) and validated data rate requirement for Vehicle to Infrastructure (V2I) communication. Moreover, we also tested the improvement in network efficiency between traditional Cisco and SDN networks. Following that, in this chapter, we propose a Vehicular-to-Everything (V2X) communication enabled Intelligent Driver Model (VX-IDM) focusing on a vehicle platoon's safety in urban and highway traffic environments. The future ADVs must have a precise knowledge of other vehicles' locations in the vicinity and should be able to determine how to reach the destination optimally without any human intervention [171, 172]. They should also comprehensively sense the surrounding environment for other road users and weather conditions to avoid collisions and accidents. Furthermore, they should detect road signs and other static road infrastructure details such as traffic lights, lanes, crosswalks and speed bumps. In existing technologies, for detecting surrounding environment in different driving conditions, the sensing systems use a range of cameras, radar, lidar, laser range finders and advanced autonomous driving algorithms [173].

Network and traffic simulators are employed for studying platooning scenarios to support the simulations for wireless communication and complex traffic scenarios. The effects of V2X communication on system performance, such as transmission delay, transmission coverage, and noise measurement, are studied theoretically and verified by numerical simulations [174-183]. However, none of these studies shows how wireless communication and system stability gains of implementing Cellular-V2X such as low latency communication and signal coverage would affect platoon performance. Moreover, there is no mention of mapping between these wireless technologies' performance with the achievable inter-vehicle distance or how the platoon would react and follow the policies enforced by the V2I communication in the literature. Therefore, our main objective is to integrate computing, control and communication by proposing a data-driven extension of the car-following model.

5.2. Problem Formulation

In this section, an overview of platoon-based vehicular communication and their implementation on vehicle platoon and implementation challenges are discussed and presented. Several empirical studies have been performed in the SARTRE project from 2009–2012 to evaluate and demonstrate vehicle platooning’s performance by implementing IEEE 802.11p-based communication systems [174]. They successfully deployed a platoon of two trucks and three cars driven autonomously at a speed of 90 km/h with approximately 5–7 m inter-vehicular gap. In Japan’s national ITS project named Energy ITS, three fully autonomous trucks were successfully tested on an expressway at 80 km/h with 10 m of an inter-vehicular gap. They used 76 GHz radar and lidar to control longitudinal manoeuvres, while inter-vehicular communication is facilitated by the 5.8 GHz DSRC. For the European Truck Platooning Challenge, several major truck vendors such as DAF, MAN, and Daimler drove their trucks in platoons on public roads from various European Cities to Rotterdam in the Netherlands [175]. The published work from these vendors indicates that they used IEEE 802.11p communication modules for inter-vehicular communication. Another study, called the PATH program, led by UC Berkeley and Volvo, successfully demonstrated the platoon of three IEEE 802.11p-equipped trucks driving on the busy 110 Interstate Freeway in Los Angeles with a 15 m inter-vehicular gap [184].

These field trials certainly provide valuable information with a thorough analysis of platooning performance under a realistic radio propagation environment for V2X communication with actual vehicle dynamics. However, they do not account for emergency scenarios where the platoons on the highway would require more information about traffic, accidents, weather conditions further away from them on the road as they would not know how to refrain themselves from such an emergency situation if their information database only consists of the local driving environment rather than global driving environment. Therefore, V2I communication is necessary along with platooning, and therefore simulations are an essential tool to study the ability of different V2I technologies to meet the requirements of the ITS applications. A comprehensive simulation framework to investigate the Adaptive Cruise Control (ACC) performance in noisy communication conditions is presented by [176]. The results show that the ACC algorithm’s performance significantly depends on the broadcast frequency and loss ratio of the CAM messages.

In [177], a consensus-based study on platoon with multiple wireless control communication topologies are proposed in the presence of interference, delay and fading conditions. The results show the improvement in comfort level and safety of platoon drivers. Another study to investigate the inter platoon communication facilitated by IEEE 802.11p on control, safety, and dedicated service channels is proposed by [178]. The results show that the guarantee of timely channel access for all packets within a specified deadline is achieved while still providing reasonable dissemination delay. The multiple adaptive CAM beaconing schemes are implemented in IEEE 802.11p for the ACC to manage and maintain the platoons on a freeway is evaluated in [179]. The results show that this system met the stringent requirement regarding update frequency and communication reliability for ACC.

Furthermore, few more studies that evaluate ACC's performance implemented with IEEE 802.11p are provided in [180]. The Block Error Rate (BER) versus Signal-to-Noise Ratio (SNR) for wireless communication link and Packet Reception Rate (PRR) versus Distance for the system stability performances for Cellular-Vehicle-to-Everything (C-V2X) and IEEE 802.11p are compared and evaluated [181]. To achieve the 10% BER target, the C-V2X provides 4–5 dB and 1.3 dB SNR gains over IEEE 802.11p in Line-of-Sight (LOS) condition and Non-Line-of-Sight (NLOS) condition, respectively. To achieve the 90% PRR target, the C-V2X provides a 95% and 55% gain in coverage over IEEE 802.11p in highway and urban scenarios, respectively [182].

Similar models investigating the ACC performance in terms of complex traffic scenarios with V2V and V2I communication are suggested in the studies [183]. They designed a suitable vehicle driving strategy and proposed an improved consensus-based control algorithm for the Cooperative Driving System considering V2X communications for CF models. The main contributions of this chapter can be summarised as follows:

1) Firstly, a channel estimation model for V2X communication is investigated and developed to optimise signal level and alter physical layer parameters settings.
2) Secondly, an extension of the intelligent driver model is derived, considering Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication.
3) Thirdly, four case studies are designed to integrate and demonstrate vehicular communication-centric coordination within different on-road vehicles in the platoon.
4) Finally, the performance of VX-IDM is assessed and compared with the state-of-the-art models considering standard vehicular parameter settings and metrics.

5.3. Channel estimation model for V2X Communication

In this section, we investigated and proposed a channel estimation model for V2I communication. We employ the IEEE 802.11p vehicular standard and calculated path loss, packet error rate, and throughput between transmitter and receiver end. The technical specification of 802.11p is mentioned in Section 2.3.5 in Chapter 2. In a wireless communication system, the signal propagates through the air from a transmitter to the receiver via multiple paths. This propagation of wireless signal involves reflection, refraction, and diffraction, which results in signal strength attenuation. Due to the different attenuation factors, the delay and phase-shift echoes are experienced at the receiver's end. This dynamic change in network topologies is due to non-stationary transmitter and receiver. For V2V and V2I communication scenarios, the distance between vehicles and the Infrastructures with LOS and NLOS is considered the most critical performance factor.

The packet loss in vehicular communication leads to a loss in data throughput at the receivers' end, and these errors in wireless communication influence the performance degradation of V2V and V2I communication channels. The average PER is a function of packet loss due to transmission errors on the wireless channel. The three major deterioration factors affecting packet loss on wireless channels are path-loss, shadowing and small-scale fading. The DSRC and IDM enabled vehicle will broadcast Basic Safety Messages (BSM)/Wave Short Messages (WSM) every 10 seconds, dynamically informing other vehicles and RSUs about their latitude, longitude, velocity, heading, brake status, throttle position, vehicle size, Global Positioning System (GPS) information [185]. In vehicular communication, the vehicles and RSUs act as a transmitter, receiver and vice-versa. The communication between transmitter and receiver experiences fading realisation.

In the transmitter, PLCP Service Data Units (PSDUs) are created and encoded to create a single packet waveform. The waveform is passed through the V2I channel with different channel realisations for each transmitted packet. The Additive White Gaussian Noise (AWGN) is added to the received waveform to create the desired average SNR per sub-carrier after OFDM demodulation. The AWGN channel is configured to provide the correct SNR. The configuration accounts for normalisation within the channel by the number of receive antennas and the noise power in an unused sub-carrier removed during the OFDM modulation.

The per-packet processing includes packet detection, coarse carrier frequency offset estimation and correction, symbol timing and fine carrier frequency offset estimation and correction. The non-High Throughput (NHT) Data Field is extracted from the synchronised received waveform. The PSDU is recovered using the extracted data field with the channel estimates and noise power estimate. The recovered PSDUs are then compared with the transmitted signal to determine the Packet Errors. For each packet, packet detection, timing synchronisation, carrier frequency offset correction and phase tracking are performed at the receiver. For channel tracking, decision-directed channel estimation is used to compensate for the high Doppler spread.

The link quality is characterised by the Bit Error Rate (BER) and Packet Error Rate (PER), where the Markov model is widely used for analysing Bit errors and packetisation of errors. The BER of 10^{-5} is acceptable for the wireless LANs, while PER values depend on the various transmission parameters such as transmission power, the modulation scheme (transmission rate) used and packet size [186]. The BER is computed only from the received packet (Correct or Corrupted), while PER is computed from the received packet and packet loss due to interference and noise on the wireless channel. The wireless channel condition attributed to random bit errors and various other reasons, but the number of consecutive bits or packet loss errors indicates poor connectivity between source and destination due to severe fading [187].

The BER and PER affect the data rate and throughput received on the wireless channel. If BER and PER value is more than the threshold value, the transmitter and receiver cannot establish the connectivity. In IEEE 802.11 wireless standards, the transmitter transmits multiple bits, and they are grouped into packets to share the transmitting medium. The receiver then receives these packets using the checksum in every packet to detect and discard the packets with any bit-errors.

We obtain the packet error loss at the receiver end. This packet error loss reduces the net data rate (Throughput) obtained at the receiver. This resulting throughput B_{th} of the wireless channel can be estimated by

$$B_{th} = \frac{(1-PER)B_r}{n_{rec}} \tag{5.1}$$

In the above equation, PER is the packet-error rate and B_r is the bit rate of the modulation scheme. The throughput obtained at each receiver will also depend on the number of receivers (n_{rec}) in communication with the RSU. Due to a non-zero data packet size (P_s) that is transmitted between the receiver and the transmitter and the finite throughput value, there will be a slight communication lag (t_c) between the transmitter and the receiver, which can be obtained by

$$t_c = \frac{P_s}{B_{th}} \tag{5.2}$$

The attenuation of radio signal during propagation is termed as *path loss*, and it includes the propagation losses due to the free space, absorption and diffraction. The path loss model considers the effect of the signal's path loss during transmission from the transmitter (RSU) and the receiver (platoon leader). The path loss is one of the widely adopted statistical channel metrics and is considered the most crucial quantity for any wireless channel.

The path loss is a function of the surrounding environment and the distance between the transmitter and the receiver (d), given by d^{γ}, where γ is the path loss exponent, which depends on the surrounding environment. An increase in the path loss leads to attenuation of Signal-to-Noise Ratio (SNR), limiting the transmission range and data rates of the wireless channel between the receiver and the transmitter. Therefore, in our model, the path loss will determine the transmission range of the RSUs. We estimate the path loss using the free-space path loss model, given by the Equation 5.3 below.

$$PL(d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\gamma\log_{10}(d) \tag{5.3}$$

where, $PL(d)$ is the Path Loss at distance d, λ is the free space wavelength defined as the ratio of the velocity of radio signal c to the carrier frequency f of the radio signal. The SNR, without considering fading, can be calculated using equation:

$$SNR = P_t + G_t + G_r - PL(d) - N_{Power} - I_m \tag{5.4}$$

where, P_t is the transmitted power, G_t is the antenna gain at the transmitter, G_r is the antenna gain at receiver, N_{Power} is the noise power and $I_m$is the implementation noise. N_{Power} is the additional power attenuation per meter and is given by

$$N_{Power} = 10\log_{10}(KTB) + N_{Figure} \tag{5.5}$$

where k is the Boltzmann constant, T is the noise temperature, B is the bandwidth and N_{Figure} is the Noise Figure. In our model, we consider an SNR of 15 dB obtained at the maximum distance between transmitter and receiver at which transmission occurs. Therefore, the transmission range of the RSU (denoted as RSU_{range}) is identified from (5.3) and (5.4) for a threshold SNR of 15 dB. Also, Equations 5.3 and 5.4 are used to obtain the SNR at each of value of distance d from the transmitter.

As the transmitter's signal strength weakens depending on the distance, a packet loss is probable during transmission. Therefore, we model the receiver's internal working to identify the packet error from the SNR values obtained from the path loss model. Table 5.1 and 5.2 details the values of all the parameters used to calculate the path loss and SNR at a certain distance over the V2I channel.

The 802.11p transmitter and receiver model is shown in Figure 5.1, it calculates the PER and SNR at the receiver, while the throughput model calculates the time lag between instances where the platoon leader enters the RSU range and communication is established, and data is transferred between leader and RSUs.

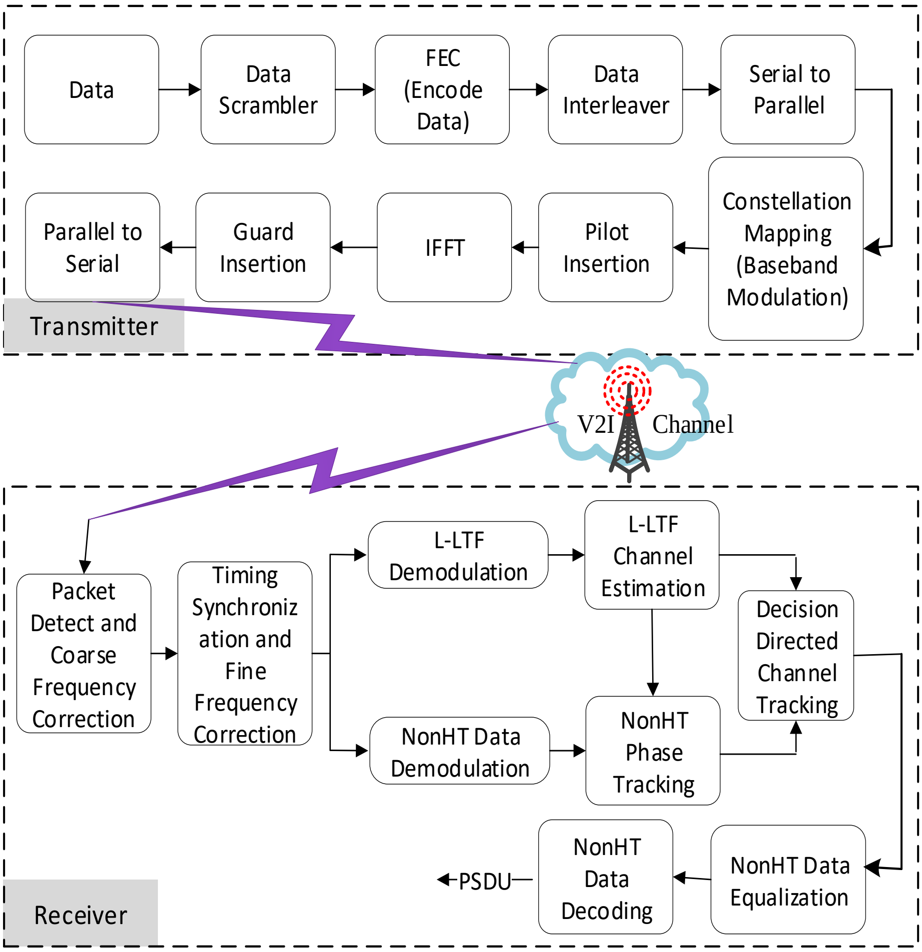

Figure 5. 1. Transmitter and Receiver design of IEEE 802.11p for Vehicle-to-Infrastructure (V2I) communication.

Table 5. 1. Parameters to calculate Path Loss of Wireless Channel for V2I Communication [188, 189]

Parameters	**Vehicle-to-Infrastructure**
Channel Bandwidth	10 MHz
Channel Frequency	5.860 GHz
Transmit Power	24 dBm
Transmit Antenna Gain	9 dBi
Transmit EIRP	33 dBm
Receive Antenna Gain	5 dBi
Average Path Loss	2 – 3
Noise Power	10 dB
Implementation Margin	5 dB

Table 5. 2. Communication Parameters of 802.11p PHY Layer [190]

Parameters	**Notations**	**IEEE 802.11p**
Channel width	$OFDM_{bw}$	10 MHz
Symbol Duration	T_{Symbol}	8 µs
Guard Time	T_g	1.6 µs
Signal Field Duration	T_{Signal}	8 µs
Sub-carrier Spacing	Δ_f	0.15625 MHz
Frequency Range	F_{range}	USA: 5.86 − 5.92 GHz EU: 5.87 − 5.92 GHz
Maximum EIRP	$EIRP_{max}$	USA: 30 W (44.8 dBm) EU: 2 W (33 dBm)

5.4. Intelligent Driver Model (IDM)

The IDM is a deterministic, autonomous and microscopic CF model from the family of Optimal Velocity Model (OVM) [191]. This traffic flow model is used for the simulation of the highway and urban traffic scenarios. The IDM considers the quadratic relation between the vehicles' speed and braking distance and considers the relative velocity $\Delta\dot{x}_n$ between the preceding and the following vehicle, which makes it accident-free.

The IDM uses two microscopic measures viz., safe time gap or distance headway T and actual distance (gap) s_n to calculate the longitudinal spacing between the vehicles, which depends on the vehicle's length and the actual gap between the vehicles.

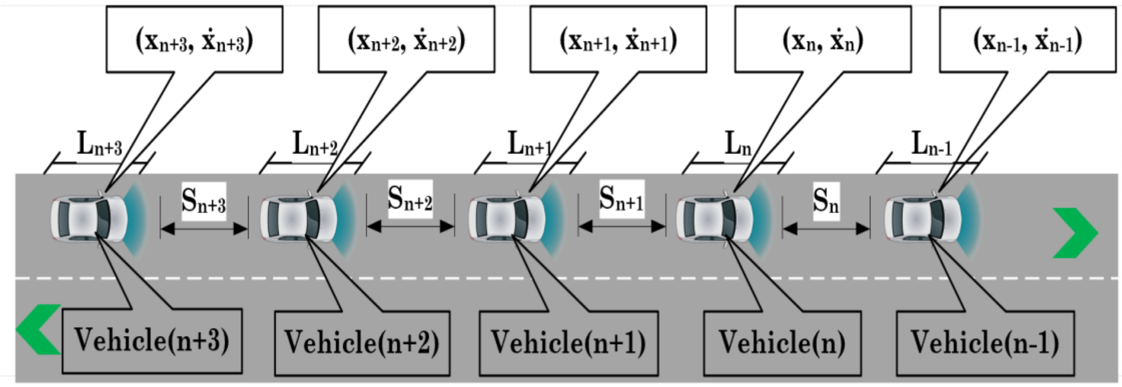

Figure 5. 2. The working of the Intelligent Driver Model in physical world environments, incorporating Vehicle-to-Vehicle (V2V) communication

Table 5. 3. Summary of Parameters used for IDM [192]

Notation	Description	Realistic Bound	Realistic Values
$\dot{x}_{0,n}$	Desired velocity	[0,50]	33.33 m/s
T	Safe Time Headway	[1,3]	1.6 m/s
a	Maximum Acceleration	[0.5,2]	2 $\mathrm{m/s^2}$
b	Comfortable Deceleration*	[0.5,2]	2 $\mathrm{m/s^2}$
δ	Acceleration Exponent	-	4 m/s
l	Length of Vehicle	[5,10]	5 m
s_0	Linear Jam Distance	[0,5]	2 m

Figure 5.2 depicts the general layout of IDM Platoon with their notations as below and Table 5.3 lists the parameters used to determine the velocity and displacement profile for the vehicle platoon:

- The vehicles in a platoon are marked with an index $n \in N$, where $n-1$ represents the first vehicle (leader) in the platoon, followed by vehicle n. Thus, the leader vehicle's position and velocity at time t are denoted by $x_{n-1}(t)$ and $\dot{x}_{n-1}(t)$ respectively.
- The actual distance (gap) between two vehicles is, denoted by s_n at time t. Due to the presence of the safe time gap T and considering the length of the vehicle l_n, the actual gap between vehicles is expressed by:

$$s_n = x_{n-1} - x_n - l_n \tag{5.6}$$

- The relative velocity $\Delta\dot{x}_n$ for the vehicle n can be expressed as

$$\Delta\dot{x}_n = \dot{x}_n - \dot{x}_{n-1} \tag{5.7}$$

- With this definition, the acceleration equation of IDM for any vehicle n is expressed as

$$\ddot{x}_n(s_n, \dot{x}_n, \Delta\dot{x}_n) = a\left[1 - \left(\frac{\dot{x}_n}{\dot{x}_{0,n}}\right)^{\delta} - \left(\frac{s^*\ (\dot{x}_{n,}\ \Delta\dot{x}_n)}{s_n}\right)^2\right] \tag{5.8}$$

where the desired gap s^* is determined by

$$s^{*}(\dot{x}_{n,}\Delta\dot{x}_{n}) = s_{0,n} + T\dot{x}_{n} + \frac{(\dot{x}_{n}\Delta\dot{x}_{n})}{2\sqrt{ab}} \tag{5.9}$$

In the above Equation 5.8, the free road acceleration strategy of the vehicle n on the road within IDM is defined as $\left[a\left(1-\left(\frac{\dot{x}_{n}}{\dot{x}_{0,n}}\right)\right)^{\delta}\right]$ with some acceleration exponent (δ). The term $\left[-a\left(\frac{s^{*}(\dot{x}_{n,}\Delta\dot{x}_{n})}{s_{n}}\right)\right]^{2}$ represents the deceleration strategy which is only effective if the actual gap s_n between vehicles is not significantly larger than the desired gap s^{*}. The follower vehicle's acceleration is reduced from initial acceleration a to zero when vehicle n is approaching the leader vehicle $n-1$ with the desired velocity $\dot{x}_{0,n}$. The desired velocity, $\dot{x}_{0,n}$ for all the vehicles is kept constant as given in Table 5.3.

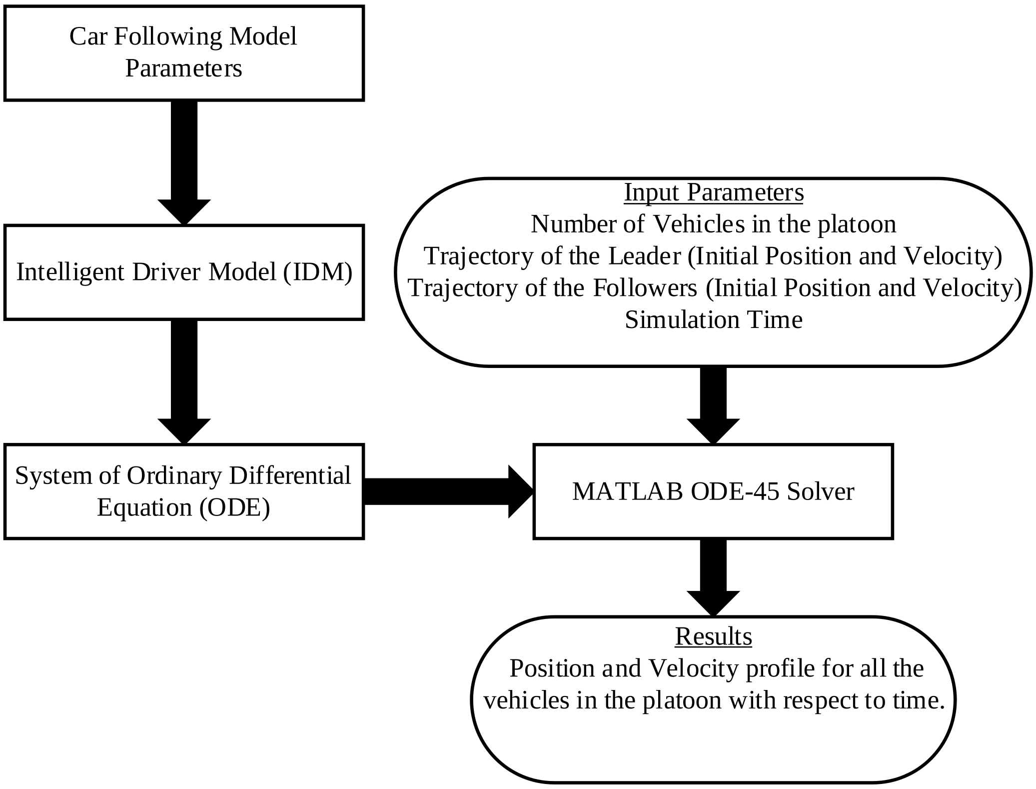

Figure 5. 3. The integration of the Intelligent Driver Model in Matlab

The computed acceleration from Equation 5.8 generates the velocity and displacement profile of the following vehicles at time t based on the platoon leader's velocity and displacement at time t. In our presented model, the platoon initially leader moves with a constant velocity. After initialisation of all vehicle's positions and velocities (including the platoon leader) in the platoon, the second-order IDM equations are solved using an ODE-45 solver for the acceleration, displacement and velocity of all vehicles. Figure 5.3 shows the IDM integration with Matlab.

5.5. Development of V2X enabled IDM Model

This section integrates the above discussed platoon-based car-following model and the V2I communication scheme between the platoon leader and an RSU. By integrating these two models, we demonstrate how a V2I communication scheme can control a platoon vehicle's motion while communicating only with a leader vehicle. The presence of a car following scheme within the platoon ensures the vehicles' safety in the platoon at all times. This, in turn, reduces the data and decision-making load on the RSU and provides an extra layer of control and safety. The V2I communication enables the transmission of periodic safety information, such as weather changes, traffic information and accident knowledge, to an entire platoon, while the IDM ensures that vehicles within a platoon are safe.

The proposed data-driven Hybrid model integrates the 802.11p V2I communication channel with the Intelligent Driver Model (IDM). The V2I communication is facilitated with the help of RSUs, and the RSUs transmit periodic information about traffic, weather conditions to the platoon leader of ADVs. Therefore, the vehicle's driving behaviour is controlled by the RSUs for V2I communication. However, when the vehicle is not in the communication range of the RSUs, the IDM plays a vital role to govern the safety of the vehicle platoon. Although both models work independently with their own limitations, their integration will facilitate the efficient and simultaneous operation of V2V and V2I communication for ADVs. Here, we identify the key parameters that interlink these two models and how effectively they work together to govern the safety of ADVs. The depiction of interlinking this data-driven model is shown in Figure 5.4.

The IDM controls the longitudinal motion of ADVs with sensors' help and controls the acceleration, deceleration, safety time headway, and inter-distance (safety gap) between the ADVs. The IDM determines all platoon vehicles' initial positions and velocities in the proposed model, along with their fixed safety gap (environment dependent) and maximum velocities (road type dependent) for all ADVs. The ADVs follow each other safely, maintaining the safety gap between them and adopting the platoon leader's behaviour. To simulate the platoon of ADVs driving safely, without colliding with each other, the IDM uses the system of Ordinary Differential Equations, generating/predicting the Positions, Velocities and Acceleration profile for the entire platoon in real-time.

The simplified modelling of the path loss, shown in section 5.2, is very accurate and suitable for the vehicular environment. The path loss and SNR threshold will define the efficient range of the nearest available RSU. The proposed model calculates the average path loss between ADVs and Road Side Unit (RSU) in real-time for every distance instant from the IDM position profile data. It also determines if the ADVs are in the communication range of the RSU.

The V2I wireless channel is configured using time and frequency selective multipath Rayleigh fading channel specified in [188]. The created channel object filters the real and complex input signal through the multipath V2I wireless channel to obtain the channel-impaired signal. For each SNR point, multiple packets (1000) of 1000 bytes are transmitted through the V2I channel, with the BPSK modulated Scheme, MCS 2. The V2I parameters (RMS delay spread, Average path gains and RMS Doppler spread) for different driving conditions are adopted from the real-world field trials mentioned in [193]. The V2I channel estimation is evaluated using SNR ranges from SNR threshold of 15 decibels (dB) to Maximum SNR of 60 dB. For every SNR point, a PSDU is created and encoded to create a single packet waveform.

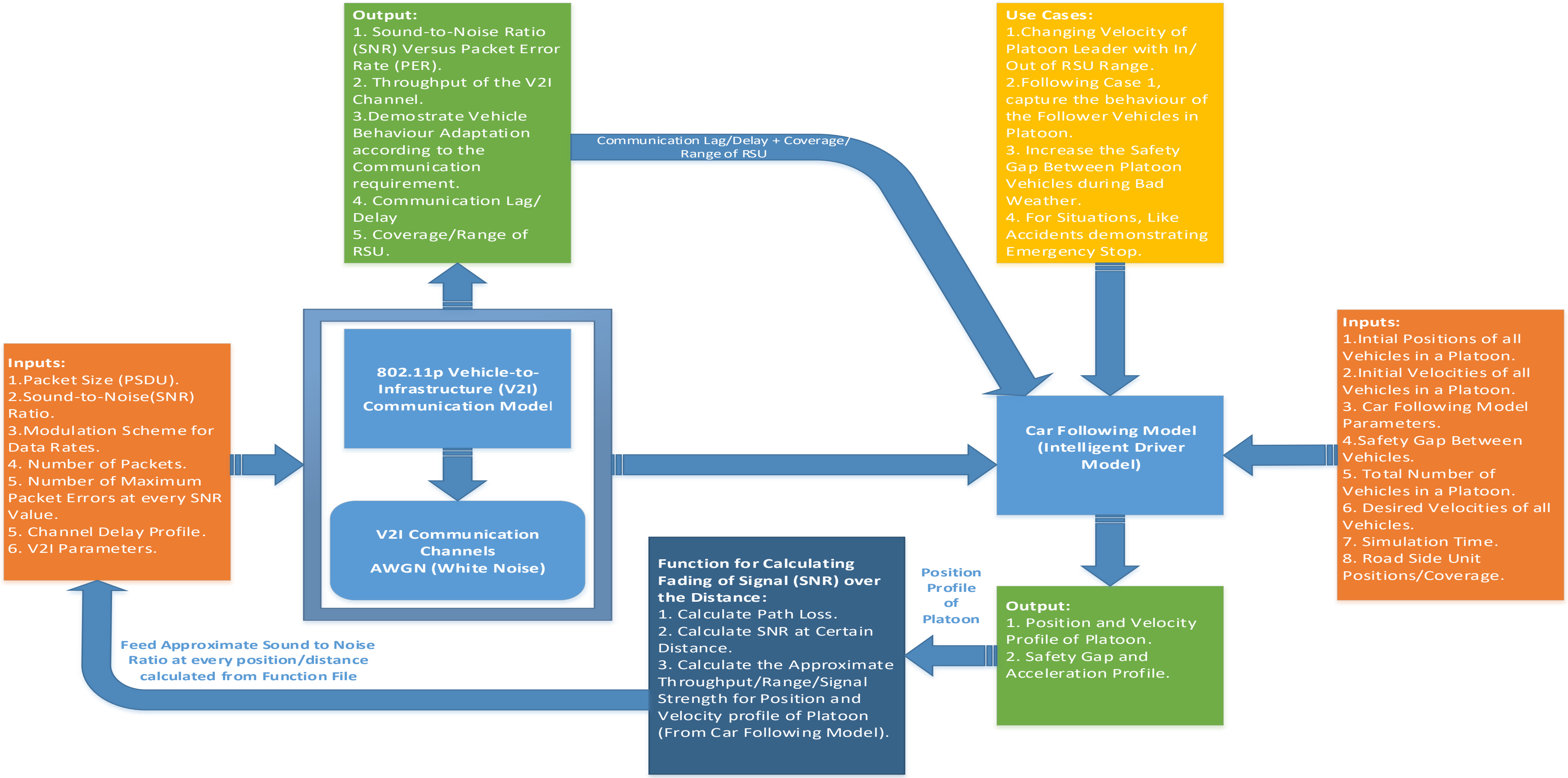

Figure 5. 4. The integration of the Intelligent Driver Model and V2I in Matlab

5.6. Case Studies for V2X Centric Communication in Vehicles

The simulation layout of our integrated model is shown in Figure 5.5. Here, we consider a road of length $L_{road} = 15$ km with 3 RSUs' arranged at equal distances, where their transmission range also depicted in Figure 5.5. We consider a platoon consisting of 5 vehicles (including the leader) to be present on the road with given initial positions and velocities. As the platoon leader enters the transmission range of any RSU, a communication is established between the platoon leader and the RSU after a certain time lag (t_c), whereby the leader relays information regarding the platoon, and the RSU (as an observer) provides new control parameters for the car-following model to the platoon leader. Presently, the distance between the RSUs is kept such that their transmission ranges do not overlap. This is done primarily to avoid the problem of deciding between the controls of RSU when the platoon leader is in the overlap region.

The general control layout of the integrated communication and IDM model is shown in Figure 5.6. In the current model, the platoon leader is given a constant velocity, controlled by the RSU's. The other vehicles follow the platoon leader based on IDM, as discussed in Section 5.3. As the platoon leader moves, the model compares the platoon leader's position with the communication range of each RSU; the path loss model detailed in Section 5.2 is used to approximate the range of RSUs. When the platoon leader enters the communication range, the RSU detects the platoon leader's presence; however, message transmission is not established instantly. There is a marginal communication lag depending on the available data rate and the amount of data to be transferred, provided by the channel estimation and VX-IDM models discussed in Section 5.2 and 5.4, respectively.

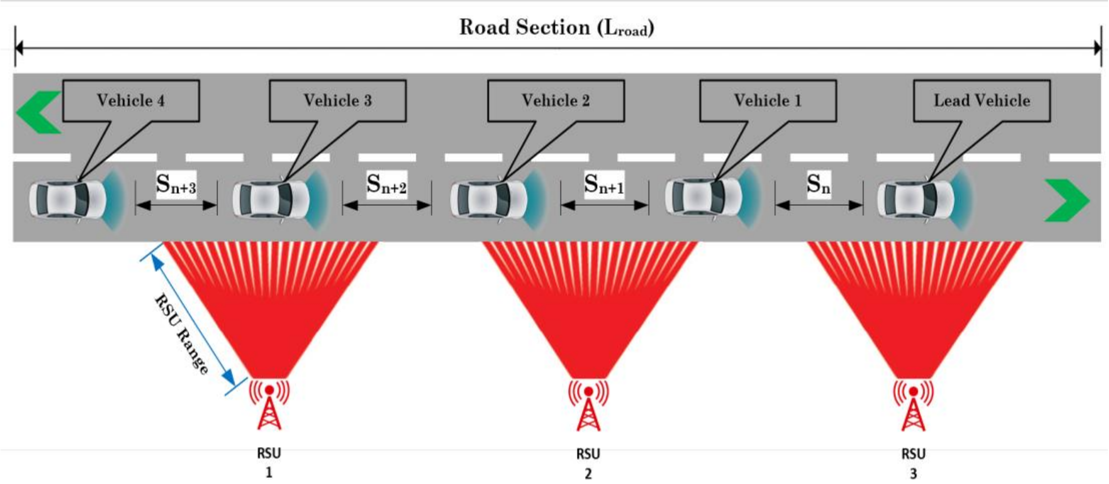

Figure 5. 5. V2X enabled Platoon Vehicles in physical world environments

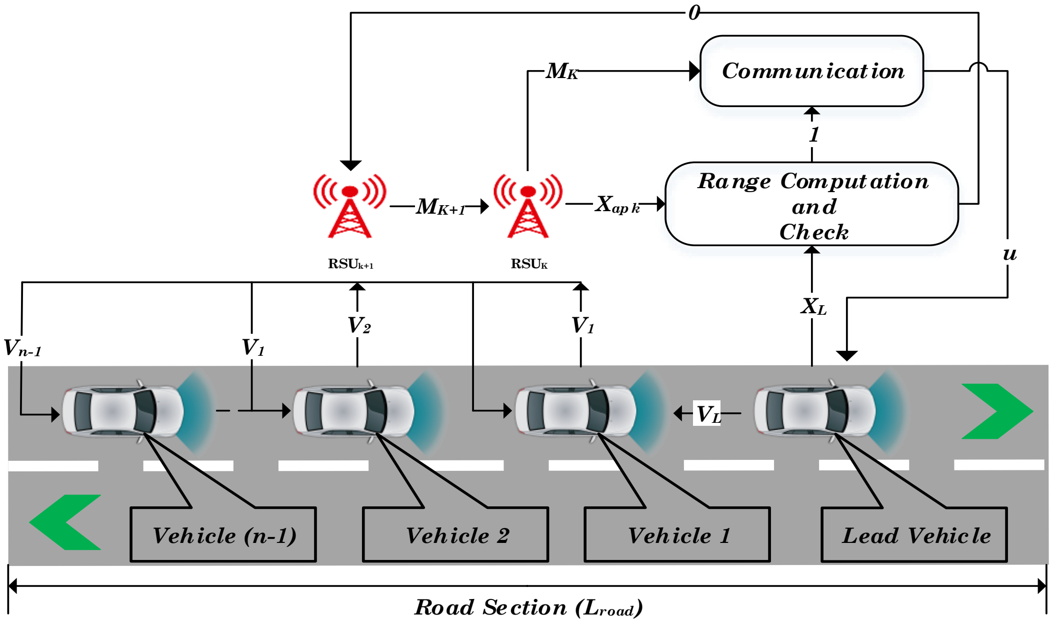

Figure 5. 6. V2X oriented Intelligent Driver Model

When a message transmission is established, the RSU provides new instructions to the platoon leader to control the vehicles' behaviour in the platoon following IDM. These instructions comprise controlling the velocity, safety gap, platoon length, and car acceleration based on the current safety information relayed to the RSU's from the ITS Controller. The data shared by the platoon leader comprise information such as the number of vehicles in the platoon, position and velocity of each vehicle in the platoon, condition of each vehicle, and emergency messages from other vehicles. The RSU's periodically update this information which is relayed to the platoon leader while remaining in the range of the RSU. Once the platoon leader leaves the RSU range, it retains the driving instructions provided by the preceding RSU, while the code compares their positions with the next RSU range. During this entire time, IDM controls the position of the other vehicles in the platoon. Therefore, the RSU's communicate only with the platoon leader, while IDM controls the other vehicles' trajectory in the platoon. To demonstrate the working of this integrated communication and car-following model, we designed Six test cases simulating a few different driving scenarios, which are described hereafter. Table 5.4 summarises the parameters that are directly affected and altered in all the corresponding cases.

1) **Case I – response to multiple RSUs instructions:** In this case, controlling the vehicles platoon's velocities by multiple RSU's is demonstrated. Each RSU enforces a different driving velocity on the platoon leader; the out-of-range velocity and the RSU imposed velocities are given in Table 5.4. The platoon is in Highway LOS condition; therefore, the communication parameters, such as average path gains, Doppler shift, and path loss exponent (gamma), are used mentioned in Table 5.5.
2) **Case II – sensitivity to an emergency:** This case simulates the scenario of how a platoon reacts to a dynamic change in instruction from RSU's, such as in an emergency of an accident. At 400 seconds, the RSU broadcast an emergency safety message reporting about an accident ahead on the road and instructs all platoon leaders to reduce their velocities. Additionally, the RSU's broadcast another message at 450 seconds, relaying that the road is cleared and instructs the platoon leader to increase the speed again.
3) **Case III – performance under the loss of communication:** In this case, we show the effect of a change in LOS condition between RSU and the platoon leader due to an obstacle's appearance. At 800 seconds, we consider that a truck blocks the direct view

between the platoon leader and RSU, affecting communication. The change in this condition from Highway LOS to Highway NLOS changes the path loss exponent, which would alter the transmission range (as per discussion in section 5.2 and 5.4).

4) **Case IV – performance under changing environmental conditions:** In this case, we simulate a change in the driving environment of the platoon, considering the scenario where the platoon enters into a city. In this case, the RSU 1, as shown in Figure 5.5, is considered to be in a Highway LOS environment while handling only a single platoon. The environment around the RSU 3 is considered to be a city with high traffic density, where the RSU handles 1000 platoons. Other communications parameters such as Path Loss Exponent, Average Path Gains, Channel Delay Profile, and Doppler Spread also change in this Urban LOS environment. RSU 2 is considered to be in Highway LOS environment handling 100 platoons.
5) **Case V – sensitivity to single large perturbation:** The stable traffic flow wherein all vehicles drive at the same constant speed $25\ m/s$. The single large perturbation where the leading vehicle first experiences a deceleration phase with $4\ m/s^2$ from $25\ m/s$ to $5\ m/s$, then maintains the lower speed of $5\ m/s$ for a time of 160s, and finally accelerates with $2\ m/s^2$ from $5\ m/s$ to $25\ m/s$.
6) **Case VI - sensitivity to inter-vehicular gap:** The platoon leader starts with a speed of $27.78\ m/s$. The platoon's leader's speed is changed to 25 and $30\ m/s$ at time 200 and 400 seconds, respectively. In addition, after 60 s, a command to increase the inter-vehicular gap is sent to all vehicles in the platoon. The default time headway is set to 0.5 seconds. After receiving the "increase gap" command, the controllers then modify the gap parameter to 20 metres and time headway to 1 second.

Table 5. 4. Test Cases used for Simulation

Case No.	Changing Parameters	Parameters Value (Before)	Parameters Value (After)
1.	v_1 [m/s] γ	33.33 [m/s] 2.02	$13.88; 6.94; 5.55$ [m/s] $No\ Change$
2.	v_1[m/s] γ	33.33 [m/s] 2.02	$27.77; 27.77; 27.77$ [m/s] $No\ Change$
3.	v_1 [m/s] γ	33.33 [m/s] 2.02	$13.88; 9.25; 6.94$ [m/s] 2.96
4.	v_1 [m/s] γ n	33.33 [m/s] 2.02 1	$27.77; 27.77; 27.77$ [m/s] 2.56 $1; 10; 100$
5.	v_1 [m/s] γ n	25 [m/s] 2.02 1	$27.77; 27.77; 27.77$ [m/s] 2.56 $1; 10; 100$
6.	v_1 [m/s] γ n	27.78 [m/s] 2.02 1	$25; 30; 30$ [m/s] 2.56 $1; 10; 100$

Table 5. 5. Parameters for Channel delay Profile [187]

Channel Delay Profile	Values
Highway LOS	Path Delays $[0\ 100\ 167\ 500] * 1e-9$ (s) Avg. Path Gains $[0\ \ -10\ \ -15\ \ -20]$ (dB) Doppler Shifts $[0\ \ 689\ \ -492\ \ 886]$ (Hz)
Highway NLOS	Path Delays $[0\ 200\ 433\ 700] * 1e-9$ (s) Avg. Path Gains $[0\ \ -2\ \ -5\ \ -7]$ (dB) Doppler Shifts $[0\ \ 689\ \ -492\ \ 886]$ (Hz)
Urban NLOS	Path Delays $[0\ 267\ 400\ 533] * 1e-9$ (s) Avg. Path Gains $[0\ \ -3\ \ -5\ \ -10]$ (dB) Doppler Shifts $[0\ \ 295\ \ -98\ \ 591]$ (Hz)

5.7. Empirical Results and Discussions

The results of the six test cases for the integrated model, proposed in the previous section, are discussed in this section. The test cases were initially compiled, projecting onto future technologies; however, they are adapted from existing transportation requirements and functionalities.

Case I - Figure 5.7 illustrates a basic control test conducted to show the effect of an RSU control over a vehicle platoon's position and velocity, adhering to a car-following model. As detailed in the previous section, as the platoon leader starts communicating with an RSU, the RSU relays a message that changes the platoon leader's speed. This velocity change forces the follower cars to adjust their motion under the influence of the ever-present car-following IDM model, as shown in Fig. 5.7 (a) and (b). It can be seen from Figure 5.7 (a) (i), the follower vehicles adopt the behaviour of the platoon leader while maintaining a safe gap determined by the IDM.

Each RSU imposes a different speed condition on the platoon leader (values given in Table 5.4). The lightly shaded red regions represent instances when the leader vehicle is in an RSU's coverage. Similarly, Figure 5.7 (b) (i) and (ii) shows the velocity profile of the vehicles in the platoon with respect to time, reflecting their car-following model behaviour. It is also visible that the platoon retains the driving conditions imposed by the respective RSU as it leaves their coverage area. The communication lag obtained at each RSU is about 0.0135 seconds, which is relatively insignificant in this case's driving conditions. This pilot case shows the basic functioning of the V2I communication while controlling the movement of a platoon of vehicles as it moves in and out of the coverage range of RSUs. The following cases in this section will demonstrate some simple exemplary scenarios of how and where such an integrated V2I communication and car-following model can be used.

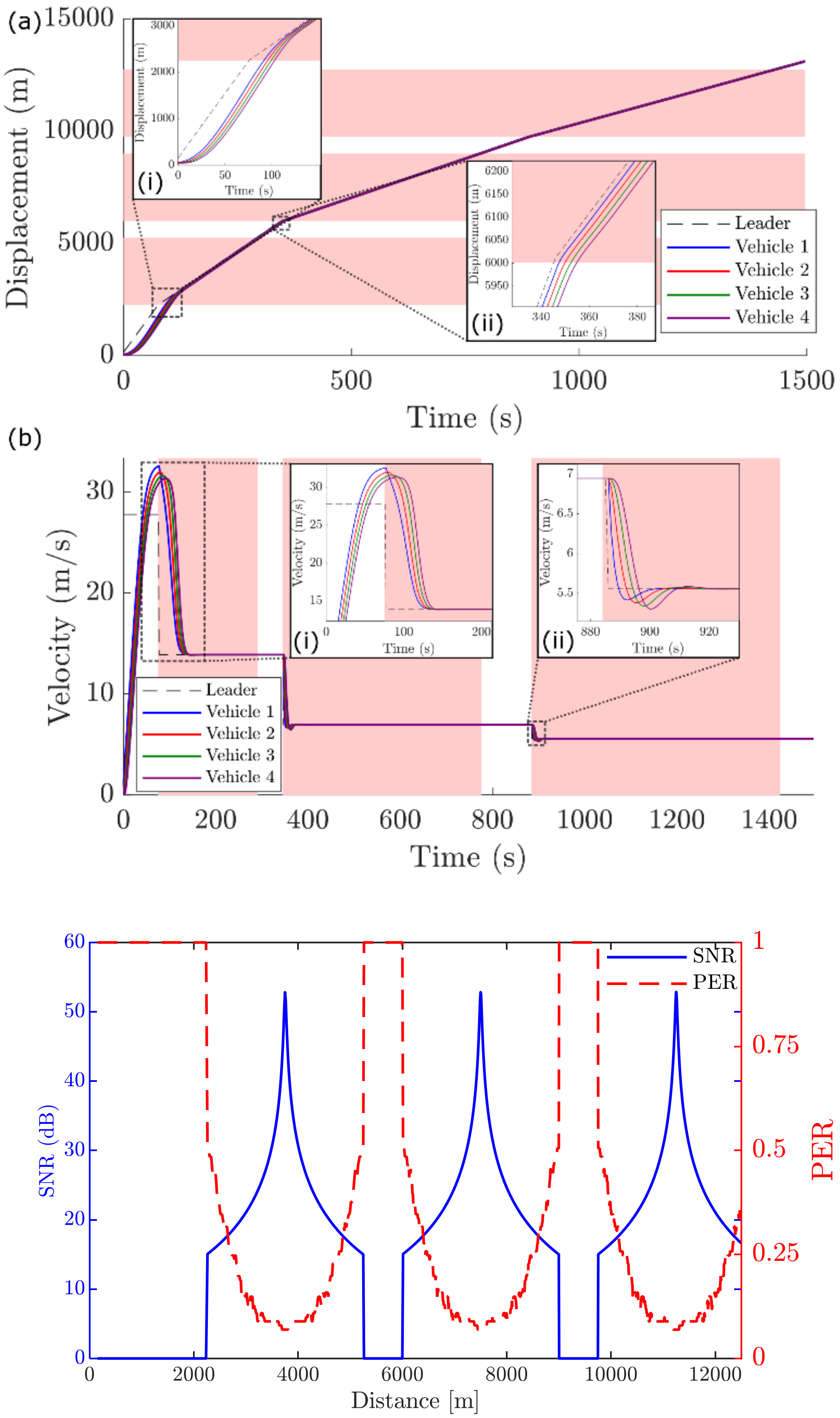

Figure 5. 7. Case-I vehicle platoon motion, as described in Section 5.5. (a) Displacement of the vehicles over the simulation time. The inset shows a magnified image of the car movement as the platoon enters the RSU coverage. (b) The velocity of the vehicles over the simulation time. The inset shows a magnified image of the car velocities as the platoon enters the RSU coverage. (c) Variation of SNR and PER as the platoon moves along the road. Leader is the platoon vehicle leader.

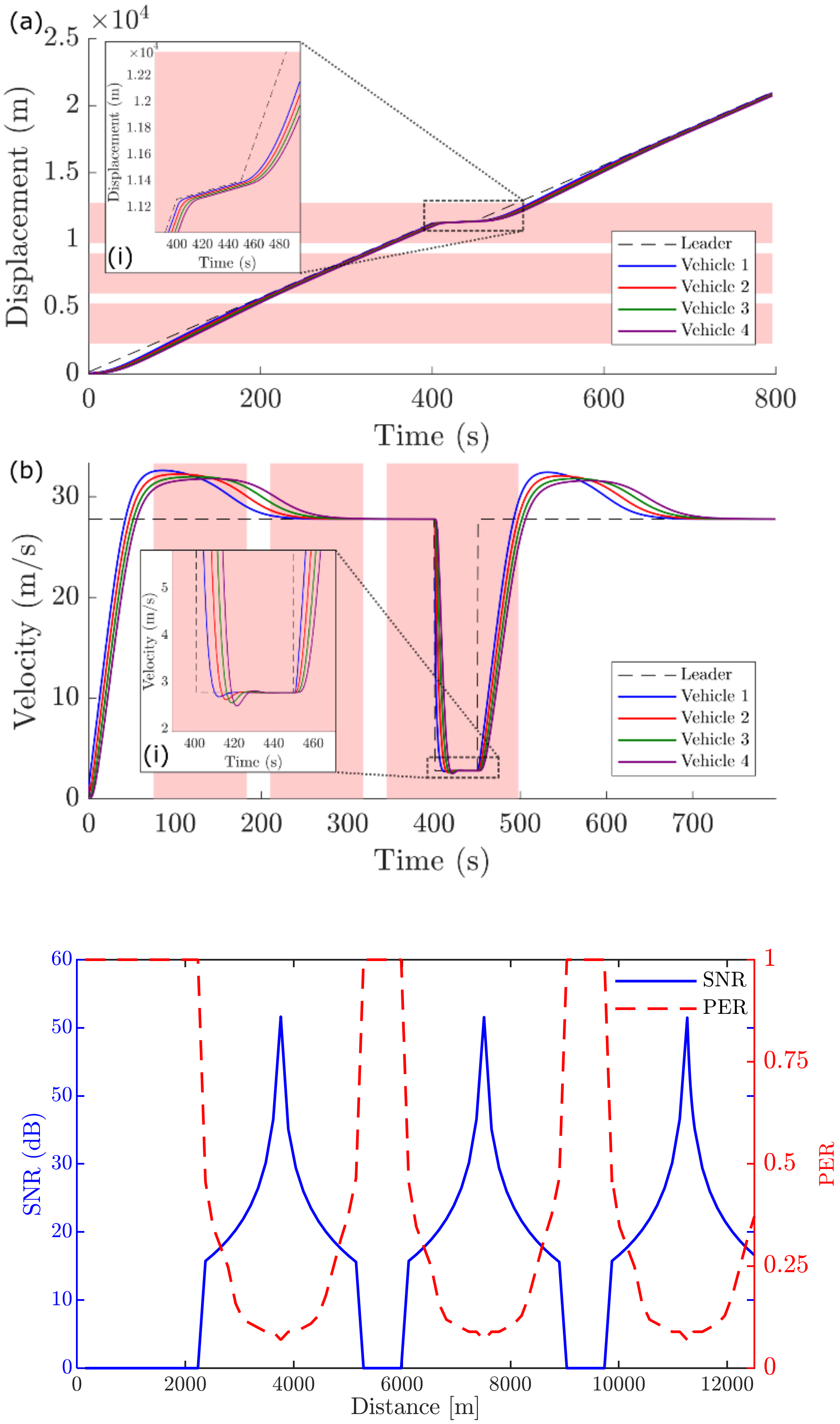

Figure 5. 8. Case-II vehicle platoon motion, as described in Section 5.5. (a) Displacement of the vehicles over the simulation time. The inset shows a magnified image of the car displacements as the platoon encounters a dynamic message from the RSU's. (b) The velocity of the vehicles over the simulation time. The inset shows a magnified image of the car velocities as the platoon encounters a dynamic message from the RSU's. (c) Variation of SNR and PER as the platoon moves along the road. Leader is the platoon leader.

Case II - Figure 5.8 illustrates the vehicle platoon's functioning with V2I communication in an emergency situation, like an accident. We imitate an accident scenario by simulating that a message is relayed by all the RSU's to the platoon leaders in their coverage range to reduce their velocities. In our model, this instruction is provided at 400 seconds. As shown in Figure 5.8 (b), at this time, the platoon is in the range of RSU 3 when the platoon leader suddenly decreases the velocity, and the follower vehicles adapt accordingly. To further demonstrate the dynamic functioning of the V2I communication with car behaviour, we relay another message at 450 seconds, simulating that the road is clear, to instruct the leader vehicle to increase its velocity. The follower vehicles again adapt and increase their velocities while adhering to the IDM. Due to this dynamic message relay, the platoon leader and the following vehicles have a displacement of only 29 meters during this emergency. Therefore, this case shows that the platoon motion can react and adopt different driving conditions by responding to dynamic instructions from the RSU's.

Case III- Figure 5.9 illustrates the vehicle platoon's functioning with V2I communication when an obstacle such as a truck or trailer blocks the direct LOS path between the platoon leader and the RSUs. We imitate the scenario by considering an obstacle that blocks the direct LOS path between RSU 3 and platoon leader at 800 seconds of simulation time. As seen in Figure 5.9 (a) and (b), the platoon enters the coverage range of the RSU 3 at 750 seconds, till which point the platoon was traversing under the LOS conditions. Under these conditions, the communication range of the RSU's was about 3000 meters. As the obstacle blocks the line of sight between the RSU and the platoon leader (at 800 seconds), there is an increase in the transmitted signal's path loss. This path loss is observed as a decrease in the RSU's communication range, which depletes its range to 1500 meters.

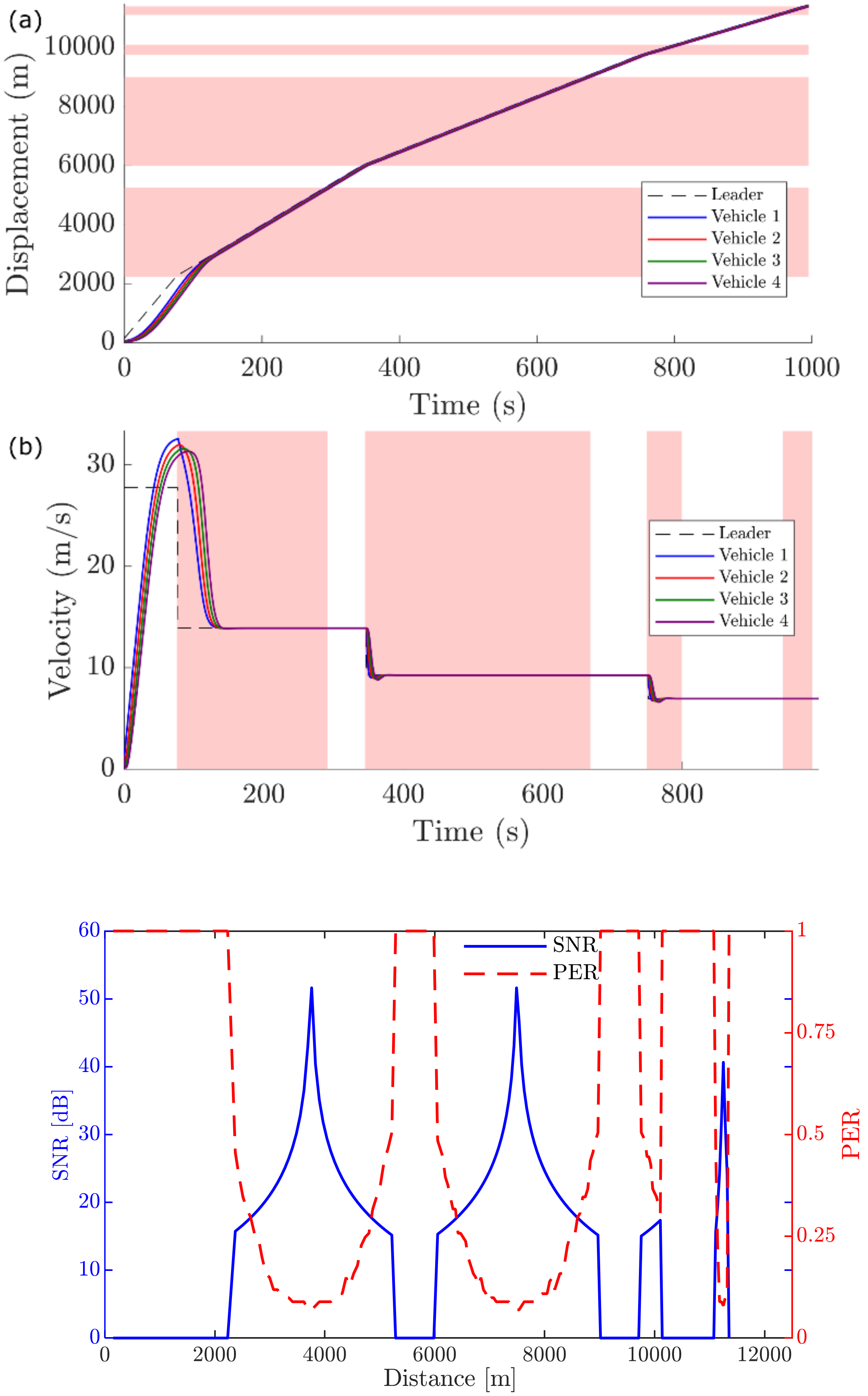

Figure 5. 9. Case-III vehicle platoon motion, as described in Section 5.5. (a) Displacement of the vehicles over the simulation time. (b) The velocity of the vehicles over the simulation time. (c) Variation of SNR and PER as the platoon moves along the road. Leader is the platoon leader.

In this NLOS condition, the platoon leader falls out of range of the RSU and has to travel more distance to re-connect with the RSU; at around 1000 seconds can be seen in Figure 5.9 (a). Although, in this case, we assumed the line of sight between the platoon leader and the RSU 3 to be consistently blocked after 800 seconds, the example shows the ability of this model to predict how a platoon would react to dynamic changes in signal attenuation due to the environment and surrounding obstacles. This simple example can also be expanded to a more complex scenario of intermittent changes in the line-of-sight due to multiple trucks overtaking the platoon.

Case IV- In Figure 5.10, we simulate our integrated model's working in a scenario where a vehicle platoon enters an urban environment from a highway environment. Here, we show the effect of multiple isolated vehicle platoons communicating with the RSU's in driving environments changing from a Highway LOS to Urban LOS. As mentioned in section 5.5, RSU 1 and RSU 2 are considered to be in a highway environment, and RSU 3 coverage is considered an urban environment. All the RSU's are assumed to handle a different number of platoons, as mentioned in Table 5.4; we simulate only one platoon's motion, assuming all platoons are isolated. We imitate the scenario where the platoon crosses the RSU 2's coverage (Highway LOS condition) and follows the slip road into the city (Urban LOS condition). The RSU 3 is in an Urban LOS condition and due to multiple scatters in this environment, path loss exponent changes, that reduces the RSU range (3000 meters) as opposed to that on the highway (640 meters), shown in Figure 5.10 (a), (b) and (c).

Additionally, we assume that due to a high car density in the urban environment, the number of platoons in communication with the RSU increases, decreasing the data throughput received by each platoon leader. This decreasing throughput increases the communication lag as a platoon enters the RSU range; the communication or time lag t_{lag} of 0.01, 0.02 and 0.031 seconds is observed at RSU 1, RSU2 and RSU 3, respectively.

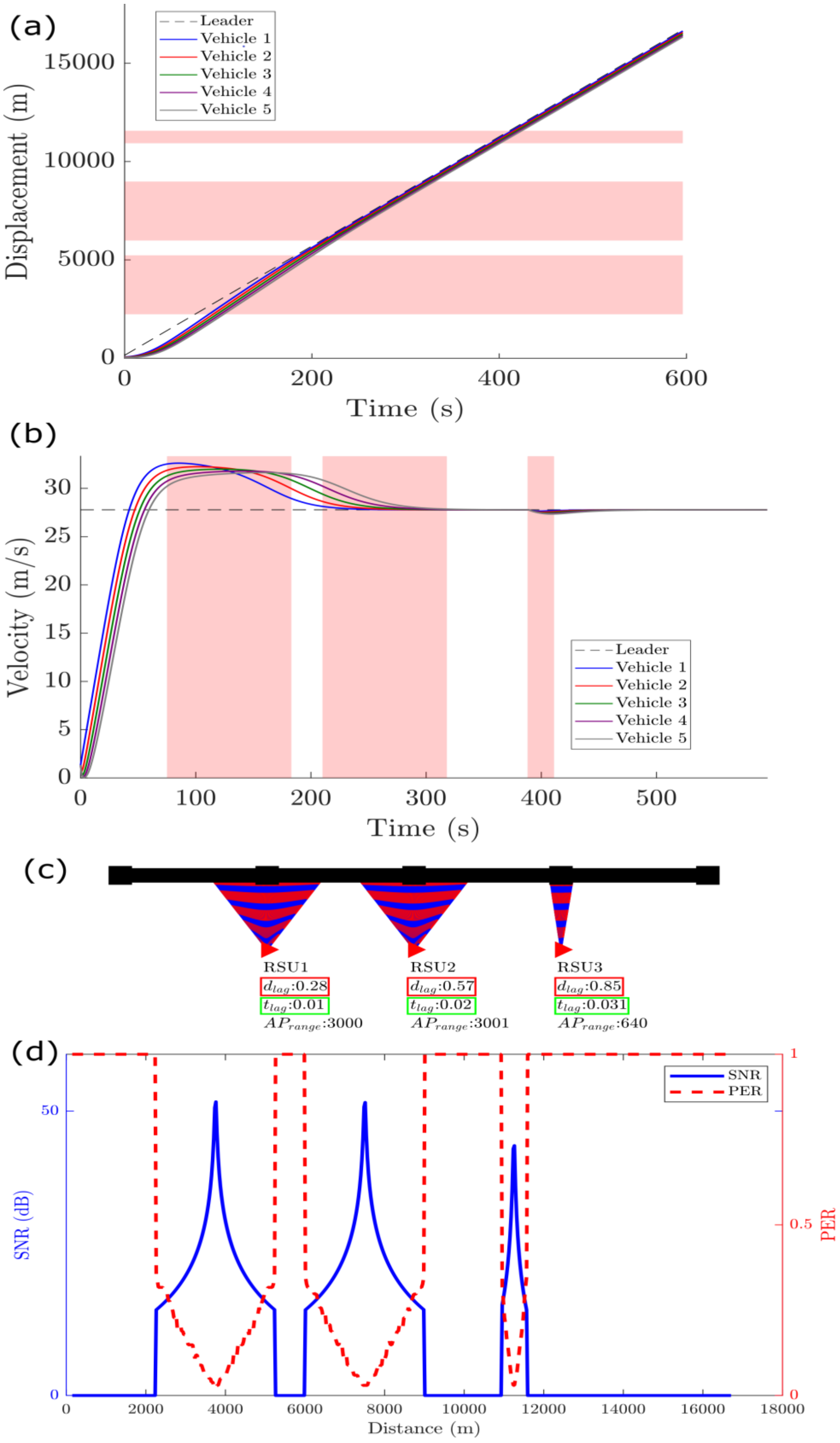

Figure 5. 10. Case-IV vehicle platoon motion for case IV, as described in Section 5.5 (a) Displacement of the vehicles over the simulation time. (b) The velocity of the vehicles over the simulation time. (c) Depiction of the coverage range of RSU's (red) and the range during which the car communicates with the RSU (blue). The distance lag (red), time lag (green) and the RSU range are also mentioned. (d) Variation of SNR and PER as the platoon moves along the road. Leader is the platoon leader.

This communication lag implies that, for any instance, even though the platoon leader is in the coverage range of an RSU 3, there is no effective communication established, and it moved 0.85 meters, termed as the distance lag d_{lag} in Figure 5.10 (c). This distance lag may become necessary for relaying safety messages in conditions when the coverage range of an RSU changes dynamically and is of a similar order of magnitude to the distance lag. Therefore, this parameter can be essential in designing an appropriate RSU layout given any environment condition. This case shows that the coupled system works dynamically and shows the vehicle platoon can adapt to changes in range and communication ability of RSUs in a LOS and NLOS condition on the highway and urban environment. This shows the effect of traffic density on the communication lag, and it helps RSUs implementation design in a transition from a highway to an urban environment. Another aspect that can be included in communication is changing in path losses due to weather change. We found no concrete evidence of weather change significantly affecting path loss exponent, which changes at frequencies below 10 GHz. However, this integrated scheme can be used to simulate path loss changes due to weather alterations at other frequency schemes as well. Corresponding changes in vehicular movement such as speed decrease, safety gap increase, maximum acceleration and deceleration exponents can be adapted and included as shown above, accordingly.

Case V and VI- These two cases are discussed separately in the following section, as they are mainly employed for comparison purposes with existing methods.

5.8. Comparison with state-of-the-art models

We implemented two state-of-the-art models for cooperative intelligent transport systems, including [183] and [37], shown in Figures 5.11 and 5.12 as Case-V and Case-VI, respectively and our VX-IDM model depicted as Case-IV in Figure 5.10. The test cases used for simulation from literature are compared with our model test cases depicted in Table 5.4. The relevant results are compared in terms of speed and gap between the platoons. Figure 5.10 shows the VX-IDM model where a platoon's behaviour is captured in terms of their displacement and velocity in urban and highway driving conditions. Moreover, the distance lag (d_{lag}), time lag (t_{lag}) and AP range are also calculated from RSU to Vehicle Platoon communication.

In comparison to the models in [183] and [37], the d_{lag}in Figure 5.10(C), at RSU 1, 2 and 3 are 0.28m, 0.57m and 0.85m, respectively. While in Figure 5.11(C), the d_{lag}at RSU 1, 2 and 3 are 0.38m, 0.15m and 1.13m, respectively. In Figure 5.12(C), the d_{lag}at RSU 1, 2 and 3 are 0.34m, 0.67m and 0.91m, respectively. The distance lag d_{lag} in all the three cases are compared and can be seen that our model performs better than the compared model, where the distance lag (Longitudinal Spacing) is more compared to our model.

Moreover, the t_{lag}, calculates the time lag between instances where the platoon leader enters the RSU range and establishes data communication. Figure 5.10(C) shows that the time lag at RSU 1, 2 and 3 are 0.01s, 0.02s and 0.031s, respectively. While in Figure 5.11(C) it is, 0.015s, 0.03s and 0.045s respectively. In addition, the Figure 5.12(C) depicts 0.012s, 0.024s and 0.036s. VX-IDM model shows that the time lag required to establish communication with the roadside unit is substantially lower than the compared model.

Overall, the results clearly illustrate that incorporating an Intelligent Driver Model (IDM) with Vehicle-to-Infrastructure (V2I) communication improves model fidelity. Moreover, our model shows consistent improvement in terms of distance and time lag compared with other existing frameworks. These results are heavily focused on the value of spacing between the platoon vehicles and time delay for establishing reliable communication. Moreover, these interesting variable values are considered very important for several applications, such as safety consideration, wireless network connectivity, and various traffic systems. Accurate simulation of the spacing and time lag is essential for all other physical attributes for platoon vehicles' position, velocity and acceleration.

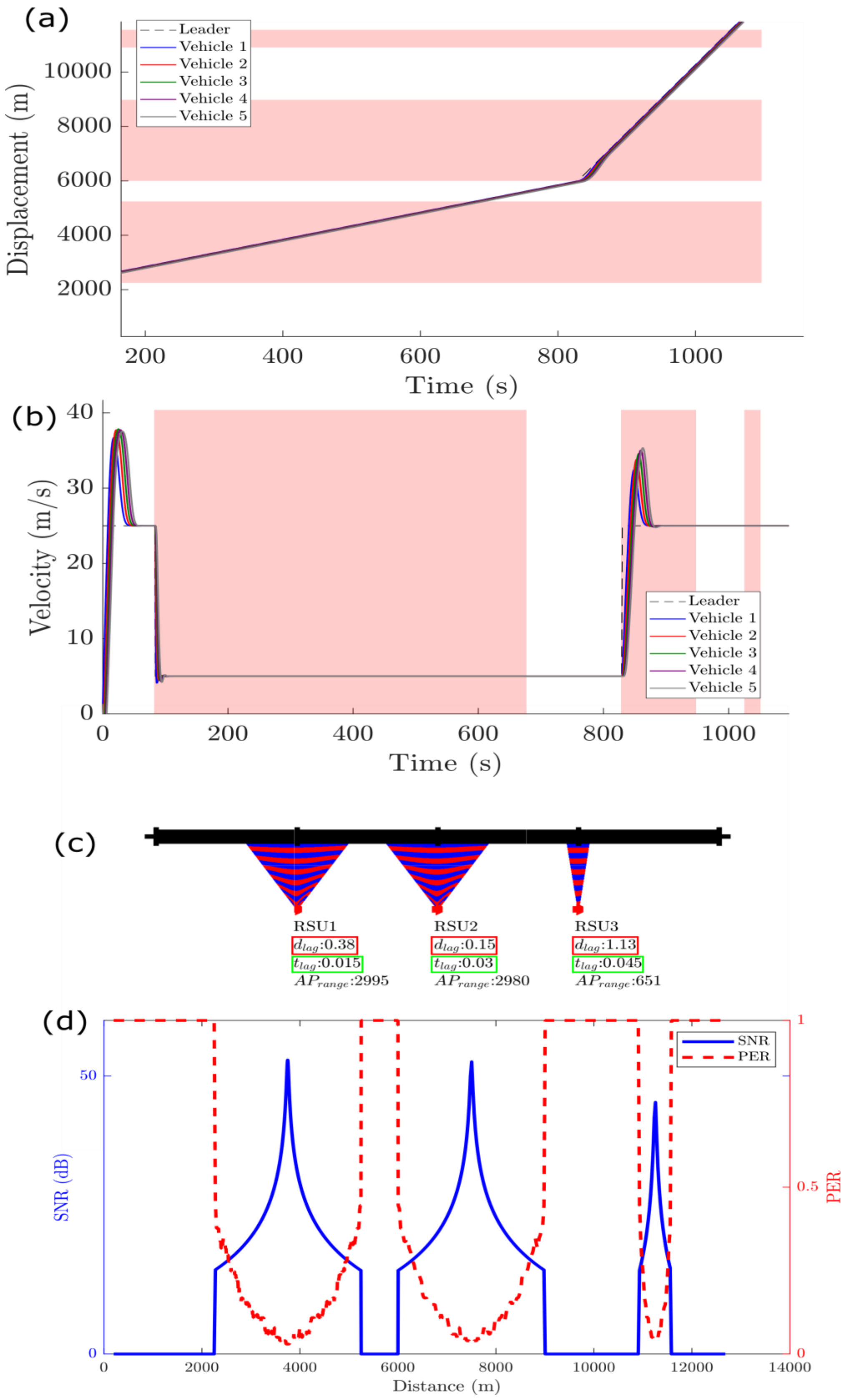

Figure 5. 11. Case-V vehicle platoon motion, as described in Section 5.5 (a) Displacement of the vehicles over the simulation time. (b) The velocity of the vehicles over the simulation time. (c) Depiction of the coverage range of RSU's (red) and the range during which the car communicates with the RSU (blue). The distance lag (red), time lag (green) and the RSU range are also mentioned. (d) Variation of SNR and PER as the platoon moves along the road. Leader is the platoon leader.

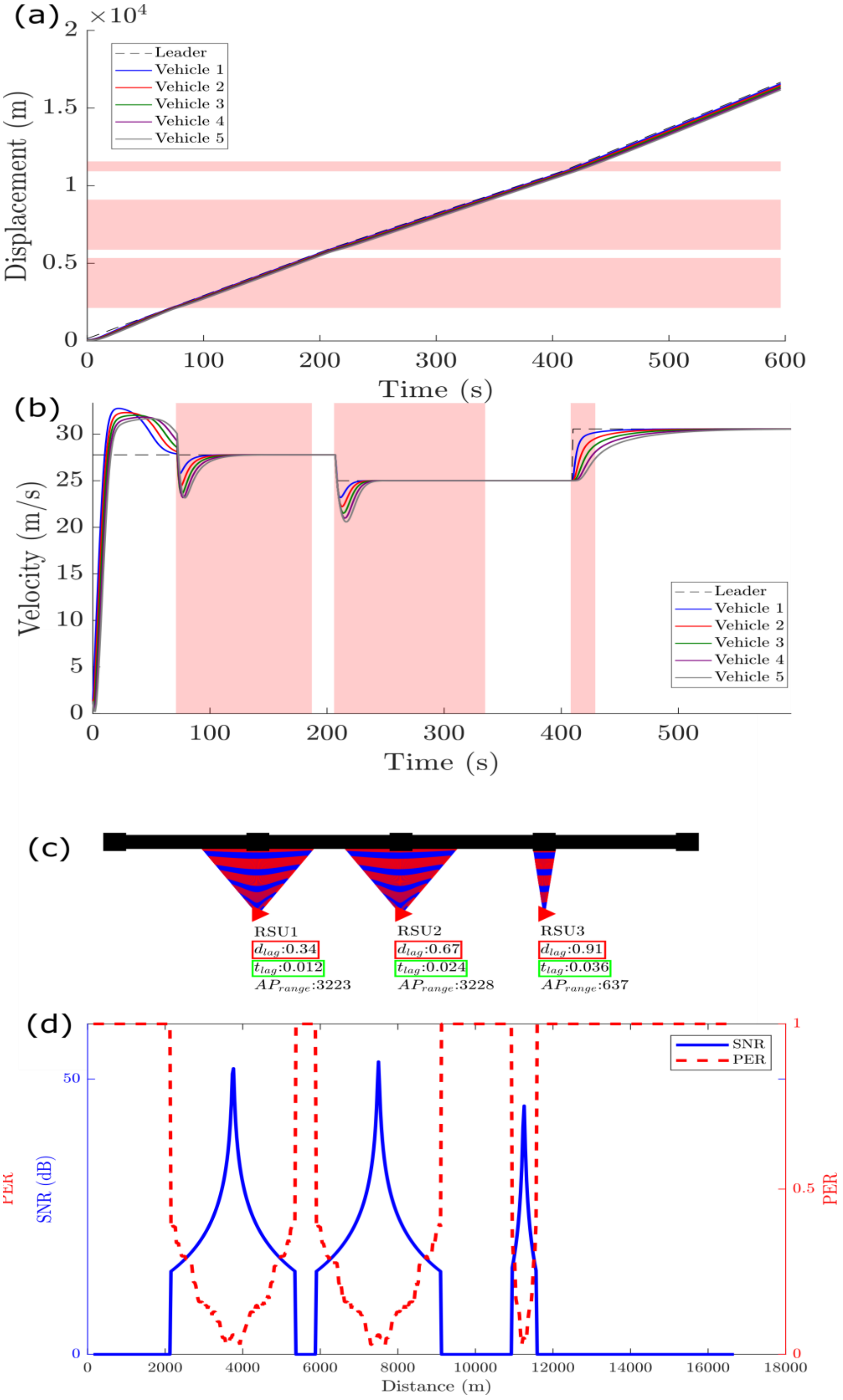

Figure 5. 12. Case-VI vehicle platoon motion described in Section 5.5 (a) Displacement of the vehicles over the simulation time. (b) The velocity of the vehicles over the simulation time. (c) Depiction of the coverage range of RSU's (red) and the range during which the car communicates with the RSU (blue). The distance lag (red), time lag (green) and the RSU range are also mentioned. (d) Variation of SNR and PER as the platoon moves along the road. Leader is the platoon leader.

5.9. Chapter Summary

This chapter presents a vehicular communication (V2X) enabled Intelligent Driver Model (VX-IDM), focusing on a vehicle platoon's safety in urban and highway traffic environments. The platoon stability is an essential requirement for the design of vehicle following control system that aims for the safety and comfortable driving of future vehicles. However, a commonly used approach for analysing platoon stability with vehicular communication requires an already defined communication topology. Towards this end, we have demonstrated some aspects of platoon-based driving with vehicular network architecture and their effects on platoon dynamics and control. This involves a car following controller jointly operating and adapting dynamically with 802.11p communication architecture.

We have provided a clear insight into the communication topology's effects on the controller performance to define the platoon vehicles' control strategy. We have also systematically elaborated the effect of cooperative platoon driving and platoon based vehicular communication. Simulation results show the effectiveness of the implemented control architecture in its sensitivity to an emergency, inter-vehicular gap, large perturbation, and the loss of communication and changing driving environment. Moreover, the proposed simulation platform proves that it can integrate any CF or consensus control model with any communication system. The model is collision-free for an infinite length of platoon string on a single road-driving environment. It can also work during lack of communication ability, where the platoon vehicles can make their decision with the help of their sensors. The road network's integration of traffic history with the V2X enabled autonomous vehicles will be explored considering big traffic data analytics in the future work.

Chapter 6

Conclusions and Future Work

6.1. Conclusions

This thesis has investigated different aspects of wireless access technologies for vehicular communication in Autonomous Driving Vehicles (ADVs). Firstly, we have presented a comprehensive overview of wireless communication technologies, Vehicular ad hoc network (VANET), Software Defined Networks (SDN), and Car Following (CF) models. Moreover, various wireless and vehicular communication technologies and theoretical analysis of IEEE standards were discussed for vehicular communication. Secondly, the wireless transmission of IEEE 802.11 standards has been investigated for their performance and backward compatibility with other IEEE 802.11 standards, mainly IEEE 802.11a, 802.11n and 802.11ac in an indoor line of sight environment in 5 GHz frequency spectrum. Moreover, the performance stats were compared with the analytical path loss model to attest to a suitable migration strategy for successful enterprise wireless network deployment. Third, a novel communication architecture was proposed for ADV's using Software-Defined Networks (SDN) for resource management and to analyse network latency requirements for vehicular networks comparing with the traditional core network deployment.

For wireless communication testing, the protocols' improvements in practical data rates, range, and interoperability have been tested in an indoor Line-of-Sight (LOS) environment at Northumbria University City Campus. The throughputs of tested protocols (IEEE 802.11a/n/ac) are measured on TCP and UDP, where the findings show these protocols could only achieve 50% and 60% of the advertised data throughput. The short guard interval of 400ns is used during the test improved the tested protocols' data rate by 8-12%. Moreover, the effective operational practical range of 30-35 meters is recorded for 802.11n and 802.11ac protocols, and they achieved the highest data rate in this range while maintaining connectivity with the host. The test results attest to seamless roaming within all the tested protocols. Similar test result may be achieved in outdoor environment as the IEEE 802.11 protocol standard’s performance are generally dependent on the RSSI values, transmit power, and modulation scheme and it remains same or can be adapted according to their operational environment i.e., indoor, or outdoor. However, their performance can be affected due to noise, interference, and obstacles.

In addition, to support Software Defined Network (SDN) for Vehicular Communication, a novel communication architecture was proposed. The communication architecture exploits the benefits of SDN over a Cisco traditional networking. For this, firstly, ADV's data rate requirements were evaluated using the vehicle sensor data for vehicular communication. The results attest that SDN offers approximately 5.19% throughput efficiency over the traditional networking approach while providing flexibility and granularity of the network and data plane.

Finally, a data-driven model has been developed and investigated for a vehicle to infrastructure (V2I) communication using a Car-Following (CF) model and IEEE 802.11p communication architecture. Six case studies were proposed and explored with a different driving condition in Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) scenarios by varying physical layer communication parameters. We compared our model with two other models with respect to their communication delay and displacement lag (longitudinal spacing) in our data-driven hybrid model. The results attested that the compared models' longitudinal spacing between the vehicles in motion is much higher than our model, restricting relaying safety-related messages in a dynamically changing communication topology in real-time. Moreover, in our model, the communication delay (time lag), essential for vehicles to establish communication with the infrastructures and starts relaying safety-related messages, was substantially lower than a compared model. This makes the VX-IDM model collision-free for a platoon of vehicles on a single road highway and urban driving environment.

To conclude, Software-defined networking and a novel hybrid data-driven model (VX-IDM) could be suitable for the future generations of ADVs as these technologies can enhance inter and intra vehicular communication and support ADVs in densely populated traffic much better than existing technologies for seamless operation on any kind of traffic condition.

This research's primary motivation was to present and numerically implement a novel data-driven hybrid model for autonomous driving vehicles' various driving conditions while considering physical vehicular parameters and wireless communications' channel estimation metrics.

6.2. Future Works

The proposed research was conducted within a limited time frame and under restrictive conditions such as some network and IT resources' unavailability. Moreover, the IEEE 802.11 wireless protocol and SDN testing are conducted in an indoor environment and on a wired network, respectively. This is due to the unavailability of equipment's configured with vehicular protocols. Therefore, there is ample scope for future investigations in this research area, and some of which are detailed hereafter.

1. **Extending SDN controller for vehicular communication on RSUs and BS**

The issue of loss of connectivity between ADVs and SDN controllers, routing in mobile (edge) cloud computing, and managing network efficiency is one of the challenges that need addressing. Moreover, the challenges related to data privacy and IP communication can be addressed for the vehicular environment. For this, an SDN-based MIPv6 Protocol should be investigated since most existing MIPv6 Protocols are designed based on traditional network architecture and have a series of limitations. A more flexible and lightweight, secure IP communication scheme in the high-mobility scenario should be proposed to replace IP Security (IPsec) with some inherent shortcomings. Finally, the cross-layer authentication for privacy issue mainly occurs above the physical layer (e.g., Layer 2 and Layer 3). Therefore, a more efficient cross-layer authentication mechanism involving the physical layer could be proposed for reducing the handover authentication latency.

2. **The Need for better communication scheme integrating with different CF model**

This thesis investigated the IDM model and IEEE 802.11p to mimic vehicle communication in a single lane road scenario with a single platoon and does not consider lane changing and multi-platoon communication. In the future, the lane-changing strategies will be considered along with various platoons on a multi-lane road driving environment. The communication within the lane changing vehicles and their association with the other platoons must be exploited using the Vehicle-to-Infrastructure communication employing Software-defined networking. Moreover, it must also include the data collected from real traffic system, which will consider the platoon behaviour in very dense traffic situation such as rush hours on weekdays and weekend traffic scenarios.

3. **Privacy and Security issue of Sensor data collected in vehicular communication**

Data collection, privacy and security, are some of the most significant challenges in vehicular communication. The vehicular data collected on the wireless network should be handled carefully, and the encryption system should be deployed for it. The current vehicular standards IEEE 1609.4 protocol uses a multi-channel communication system to avoid collisions between different vehicular applications. However, this results in poor utilisation of the channel resources due to the presence of only a single-radio transceiver employed in the IEEE 1609.4 standard/protocol suite. Moreover, synchronous channel switching affects the message delay and delivery ratio, consequently affecting the dissemination of safety broadcast message over multi-channel VANETs. A new safety message delivery system is required to address this issue, which provides faster dissemination of safety message in IEEE 1609.4 based VANETs with backward compatibility with existing WAVE standards.

In terms of protocols being used for vehicular communication, it is worth studying the wireless protocols for vehicular communication operating in the different frequency spectrum to evaluate their signal strength and explore compatibility with each other. It would be interesting to see how the hand-off process occurs between these protocols at different criteria in a dense heterogeneous vehicular environment. This comparison can be made in terms of range and compatibility with legacy/existing protocols. Moreover, this opens the door to another research area where these protocols can be tested in terms of power consumption due to the use of multiple radio/antennas on transmitter and receiver and observing the effect of channel bonding and multiple spatial streams.

References

[1] K. Jo, J. Kim, D. Kim, C. Jang, and M. Sunwoo, "Development of autonomous car—Part II: A case study on the implementation of an autonomous driving system based on distributed architecture," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 8, pp. 5119-5132, 2015.

[2] J. M. Anderson, K. Nidhi, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, *Autonomous vehicle technology: A guide for policymakers*. Rand Corporation, 2014.

[3] S. A. Bagloee, M. Tavana, M. Asadi, and T. Oliver, "Autonomous vehicles: challenges, opportunities, and future implications for transportation policies," *Journal of Modern Transportation,* vol. 24, no. 4, pp. 284-303, 2016/12/01 2016, doi: 10.1007/s40534-016-0117-3.

[4] C. Urmson *et al.*, "Autonomous driving in urban environments: Boss and the urban challenge," *Journal of Field Robotics,* vol. 25, no. 8, pp. 425-466, 2008.

[5] V. Vukadinovic *et al.*, "3GPP C-V2X and IEEE 802.11 p for Vehicle-to-Vehicle communications in highway platooning scenarios," *Ad Hoc Networks,* vol. 74, pp. 17-29, 2018.

[6] N. E. Bezai, B. Medjdoub, A. Al-Habaibeh, M. L. Chalal, and F. Fadli, "Future cities and autonomous vehicles: analysis of the barriers to full adoption," *Energy and Built Environment,* vol. 2, no. 1, pp. 65-81, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.enbenv.2020.05.002.

[7] J. Bierstedt, A. Gooze, C. Gray, J. Peterman, L. Raykin, and J. Walters, "Effects of next-generation vehicles on travel demand and highway capacity," *FP Think Working Group,* vol. 8, pp. 10-1, 2014.

[8] J. Choi *et al.*, "Environment-detection-and-mapping algorithm for autonomous driving in rural or off-road environment," *IEEE Transactions on Intelligent Transportation Systems,* vol. 13, no. 2, pp. 974-982, 2012.

[9] R. Yu, J. Ding, X. Huang, M.-T. Zhou, S. Gjessing, and Y. Zhang, "Optimal resource sharing in 5G-enabled vehicular networks: A matrix game approach," *IEEE Transactions on Vehicular Technology,* vol. 65, no. 10, pp. 7844-7856, 2016.

[10] N. Jahanshahi and R. M. Ferrari, "Attack detection and estimation in cooperative vehicles platoons: A sliding mode observer approach," *IFAC-PapersOnLine,* vol. 51, no. 23, pp. 212-217, 2018.

[11] A. Ulahannan *et al.*, "User expectations of partial driving automation capabilities and their effect on information design preferences in the vehicle," *Applied Ergonomics,* vol. 82, p. 102969, 2020/01/01/ 2020, doi: https://doi.org/10.1016/j.apergo.2019.102969.

[12] S. Gong and L. Du, "Cooperative platoon control for a mixed traffic flow including human drive vehicles and connected and autonomous vehicles," *Transportation research part B: methodological,* vol. 116, pp. 25-61, 2018.

[13] R. Coppola and M. Morisio, "Connected car: technologies, issues, future trends," *ACM Computing Surveys (CSUR),* vol. 49, no. 3, pp. 1-36, 2016.

[14] E. U. a. G. Ertico. "5G Automotive Vision." https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White-Paper-on-Automotive-Vertical-Sectors.pdf (accessed 10 January, 2021).

[15] L. Frenzel. "Major Wireless Developments Driving 2017 Agendas." https://www.electronicdesign.com/technologies/wireless/article/21802083/major-wireless-developments-driving-2017-agendas (accessed 10 January, 2019).

[16] L. Hobert, A. Festag, I. Llatser, L. Altomare, F. Visintainer, and A. Kovacs, "Enhancements of V2X communication in support of cooperative autonomous driving," *IEEE communications magazine,* vol. 53, no. 12, pp. 64-70, 2015.

[17] K. Sasaki, N. Suzuki, S. Makido, and A. Nakao, "Vehicle control system coordinated between cloud and mobile edge computing," in *2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE),* 2016: IEEE, pp. 1122-1127.

[18] A. Choudhury, T. Maszczyk, C. B. Math, H. Li, and J. Dauwels, "An integrated simulation environment for testing V2X protocols and applications," *Procedia Computer Science,* vol. 80, pp. 2042-2052, 2016.

[19] J. Zhang, W. Xie, and F. Yang, "An architecture for 5G mobile network based on SDN and NFV," 2015.

[20] A. Festag, "Cooperative intelligent transport systems standards in Europe," *IEEE communications magazine,* vol. 52, no. 12, pp. 166-172, 2014.

[21] L. Lei, Y. Zhang, X. S. Shen, C. Lin, and Z. Zhong, "Performance analysis of device-to-device communications with dynamic interference using stochastic Petri nets," *IEEE transactions on wireless communications,* vol. 12, no. 12, pp. 6121-6141, 2013.

[22] H. Oh, C. Yae, D. Ahn, and H. Cho, "5.8 GHz DSRC packet communication system for ITS services," in *Gateway to 21st Century Communications Village. VTC 1999-Fall. IEEE VTS 50th Vehicular Technology Conference (Cat. No. 99CH36324)*, 1999, vol. 4: IEEE, pp. 2223-2227.

[23] X. Shen, X. Cheng, R. Zhang, B. Jiao, and Y. Yang, "Distributed congestion control approaches for the IEEE 802.11 p vehicular networks," *IEEE intelligent transportation systems magazine,* vol. 5, no. 4, pp. 50-61, 2013.

[24] A. Vinel, "3GPP LTE versus IEEE 802.11 p/WAVE: Which technology is able to support cooperative vehicular safety applications?," *IEEE Wireless Communications Letters,* vol. 1, no. 2, pp. 125-128, 2012.

[25] J. Calabuig, J. F. Monserrat, D. Gozalvez, and O. Klemp, "Safety on the roads: LTE alternatives for sending ITS messages," *IEEE Vehicular Technology Magazine,* vol. 9, no. 4, pp. 61-70, 2014.

[26] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: a survey," *IEEE communications magazine,* vol. 51, no. 5, pp. 148-157, 2013.

[27] V. C. Borges, K. V. Cardoso, E. Cerqueira, M. Nogueira, and A. Santos, "Aspirations, challenges, and open issues for software-based 5G networks in extremely dense and heterogeneous scenarios," *EURASIP Journal on Wireless Communications and Networking,* vol. 2015, no. 1, pp. 1-13, 2015.

[28] R. Vilalta, A. Mayoral, R. Casellas, R. Martínez, and R. Muñoz, "Experimental demonstration of distributed multi-tenant cloud/fog and heterogeneous SDN/NFV orchestration for 5G services," in *2016 European Conference on Networks and Communications (EuCNC)*, 2016: IEEE, pp. 52-56.

[29] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE internet of things journal,* vol. 1, no. 4, pp. 289-299, 2014.

[30] R. Coppola and M. Morisio, "Connected Car: Technologies, Issues, Future Trends," *ACM Comput. Surv.,* vol. 49, no. 3, p. Article 46, 2016, doi: 10.1145/2971482.

[31] Q. Corporation. "How Honda's V2V and V2P Technology Uses Smartphones to Save Lives?" https://quartsoft.com/blog/201404/honda-v2v-v2p-technology-smartphones#:~:text=The%20DSRC%20operates%20on%20a,especially%20designed%20for%20the%20purpose (accessed 07/09, 2020).

[32] P. Resende, E. Pollard, H. Li, and F. Nashashibi, "ABV-A Low Speed Automation Project to Study the Technical Feasibility of Fully Automated Driving," 2013.

[33] V. Kumar, S. Mishra, and N. Chand, "Applications of VANETs: present & future," *Communications and Network,* vol. 5, no. 01, p. 12, 2013.

[34] E. Ndashimye, S. K. Ray, N. I. Sarkar, and J. A. Gutiérrez, "Vehicle-to-infrastructure communication over multi-tier heterogeneous networks: A survey," *Computer Networks,* vol. 112, pp. 144-166, 2017/01/15/ 2017, doi: https://doi.org/10.1016/j.comnet.2016.11.008.

[35] C.-M. Chou, C.-Y. Li, W.-M. Chien, and K.-c. Lan, "A feasibility study on vehicle-to-infrastructure communication: WiFi vs. WiMAX," in *2009 tenth international conference on mobile data management: systems, services and middleware*, 2009: IEEE, pp. 397-398.

[36] K. Prasanth, D. K. Duraiswamy, K. Jayasudha, and D. C. Chandrasekar, "Improved packet forwarding approach in Vehicular ad hoc networks using RDGR algorithm," *arXiv preprint arXiv:1003.5437,* 2010.

[37] D. Jia and D. Ngoduy, "Enhanced cooperative car-following traffic model with the combination of V2V and V2I communication," *Transportation Research Part B: Methodological*, vol. 90, pp. 172-191, 2016.

[38] A. A. Saleh and R. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE Journal on selected areas in communications*, vol. 5, no. 2, pp. 128-137, 1987.

[39] N. Seddon and T. Bearpark, "Observation of the inverse Doppler effect," *Science*, vol. 302, no. 5650, pp. 1537-1540, 2003.

[40] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless personal communications*, vol. 6, no. 3, pp. 311-335, 1998.

[41] S. Report. "Smart Home in United Kingdom." https://www.statista.com/outlook/279/156/smart-home/united-kingdom (accessed 7/10, 2020).

[42] Y. Jeong, H. Joo, G. Hong, D. Shin, and S. Lee, "AVIoT: Web-based interactive authoring and visualization of indoor internet of things," *IEEE Transactions on Consumer Electronics*, vol. 61, no. 3, pp. 295-301, 2015.

[43] S. Popli, R. K. Jha, and S. Jain, "A survey on energy efficient narrowband internet of things (NBIoT): architecture, application and challenges," *IEEE Access*, vol. 7, pp. 16739-16776, 2018.

[44] A. Ö. Kaya and D. Calin, "On the wireless channel characteristics of outdoor-to-indoor LTE small cells," *IEEE Transactions on Wireless Communications*, vol. 15, no. 8, pp. 5453-5466, 2016.

[45] G. M. R. D. T. Carpenter, G. Moerschel, and R. Dreger, "CWSP Certified Wireless Security Professional: Official Study Guide exam PWO-200," 2006.

[46] J. Geier, *Designing and deploying 802.11 n wireless networks*. Pearson Education, 2010.

[47] F. Siddiqui, S. Zeadally, and K. Salah, "Gigabit wireless networking with IEEE 802.11 ac: technical overview and challenges," *Journal of networks*, vol. 10, no. 3, p. 164, 2015.

[48] A. Osseiran *et al.*, "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," *IEEE communications magazine*, vol. 52, no. 5, pp. 26-35, 2014.

[49] Y. Xiao and J. Rosdahl, "Throughput and delay limits of IEEE 802.11," *IEEE Communications letters*, vol. 6, no. 8, pp. 355-357, 2002.

[50] L. Huang and T.-H. Lai, "On the scalability of IEEE 802.11 ad hoc networks," in *Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing*, 2002, pp. 173-182.

[51] O. Bejarano, E. W. Knightly, and M. Park, "IEEE 802.11 ac: from channelization to multi-user MIMO," *IEEE Communications Magazine*, vol. 51, no. 10, pp. 84-90, 2013.

[52] B. Bellalta, J. Barcelo, D. Staehle, A. Vinel, and M. Oliver, "On the performance of packet aggregation in IEEE 802.11 ac MU-MIMO WLANs," *IEEE Communications Letters*, vol. 16, no. 10, pp. 1588-1591, 2012.

[53] E. Perahia and R. Stacey, *Next generation wireless LANs: 802.11 n and 802.11 ac*. Cambridge university press, 2013.

[54] *European profile standard for the physical and medium access control layer of intelligent transport systems operating in the 5 Ghz frequency band*, E. T. S. I. (ETSI), 2009.

[55] A. Bazzi, B. M. Masini, A. Zanella, and I. Thibault, "On the performance of IEEE 802.11 p and LTE-V2V for the cooperative awareness of connected vehicles," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10419-10432, 2017.

[56] A. Van Zelst, "Per-antenna-coded schemes for MIMO OFDM," in *IEEE International Conference on Communications, 2003. ICC'03.*, 2003, vol. 4: IEEE, pp. 2832-2836.

[57] J. DasGupta, K. Ziri-Castro, and H. Suzuki, "Capacity analysis of MIMO-OFDM broadband channels in populated indoor environments," in *2007 International Symposium on Communications and Information Technologies*, 2007: IEEE, pp. 273-278.

[58] S. Dravida, J. R. Walton, S. Nanda, and S. K. Surineni, "Methods and devices for interworking of wireless wide area networks and wireless local area networks or wireless personal area networks," ed: Google Patents, 2013.

[59] R. Prasad, *OFDM for wireless communications systems*. Artech House, 2004.

[60] A. Holt and C.-Y. Huang, *802.11 wireless networks: security and analysis*. Springer Science & Business Media, 2010.

[61] A. N. M. Abdullah, H. Moinudeen, and W. Al-Khateeb, "Scalability and performance analysis of IEEE 802.11 a," in *Canadian Conference on Electrical and Computer Engineering, 2005.*, 2005: IEEE, pp. 1626-1629.

[62] T. Paul and T. Ogunfunmi, "Wireless LAN comes of age: Understanding the IEEE 802.11 n amendment," *IEEE Circuits and Systems Magazine*, vol. 8, no. 1, pp. 28-54, 2008.

[63] C. Inc. "802.11ac: The Fifth Generation of Wi-Fi." Cisco Inc. https://www.cisco.com/c/dam/en/us/products/collateral/wireless/aironet-3600-series/white-paper-c11-713103.pdf (accessed 15/10, 2020).

[64] T. Selvam and S. Srikanth, "A frame aggregation scheduler for IEEE 802.11 n," in *2010 National Conference On Communications (NCC)*, 2010: IEEE, pp. 1-5.

[65] C.-Y. Wang and H.-Y. Wei, "IEEE 802.11 n MAC enhancement and performance evaluation," *Mobile Networks and Applications*, vol. 14, no. 6, p. 760, 2009.

[66] D. Haider. "How Stuff Works - 802.11n and Short Guard Intevals." https://wifijedi.com/2009/02/11/how-stuff-works-short-guard-interval/ (accessed 15/10, 2020).

[67] J. Jansons and T. Dorins, "Analyzing IEEE 802.11 n standard: outdoor performanace," in *2012 Second International Conference on Digital Information Processing and Communications (ICDIPC)*, 2012: IEEE, pp. 26-30.

[68] C. Inc. "Advanced Settings 802.11n " https://www.cisco.com/assets/sol/sb/AP541N_Emulators/AP541N_Emulator_v1.9.2/help_Advanced_Settings.htm (accessed 15/10, 2020).

[69] C. Inc. "Cisco Aironet 2600 Series Access Points Data Sheet." https://www.cisco.com/c/en/us/products/collateral/wireless/aironet-2600-series/data_sheet_c78-709514.html (accessed 17/6, 2019).

[70] *Reliable and Available Wirless Technologies*, I. a. E. Cisco Systems, 18/05/2020 2020. [Online]. Available: https://tools.ietf.org/html/draft-thubert-raw-technologies-05

[71] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "Intelligent channel bonding in 802.11 n WLANs," *IEEE Transactions on Mobile Computing*, vol. 13, no. 6, pp. 1242-1255, 2013.

[72] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "The impact of channel bonding on 802.11n network management," presented at the Proceedings of the Seventh COnference on emerging Networking EXperiments and Technologies, Tokyo, Japan, 2011. [Online]. Available: https://doi.org/10.1145/2079296.2079307.

[73] R. Van Nee, V. Jones, G. Awater, A. Van Zelst, J. Gardner, and G. Steele, "The 802.11 n MIMO-OFDM standard for wireless LAN and beyond," *Wireless Personal Communications*, vol. 37, no. 3-4, pp. 445-453, 2006.

[74] D. D. Coleman and D. A. Westcott, *Cwna: certified wireless network administrator official study guide: exam Pw0-105*. John Wiley & Sons, 2012.

[75] R. W. Davis, "Compensation of propagation delays of wireless signals," ed: Google Patents, 2012.

[76] Digitalair. "802.11n Transmit Beamforming TxBF - Explained." https://www.digitalairwireless.com/articles/blog/802-11n-transmit-beamforming-txbf-explained (accessed 08/08, 2020).

[77] I. Pefkianakis, C. Li, and S. Lu, "What is wrong/right with IEEE 802.11n Spatial Multiplexing Power Save feature?," in *2011 19th IEEE International Conference on Network Protocols*, 17-20 Oct. 2011 2011, pp. 186-195, doi: 10.1109/ICNP.2011.6089050.

[78] P. Estrada. "Using Spectrum Wisely with Band Steering." Cisco and Miraki. https://meraki.cisco.com/blog/2011/04/using-spectrum-wisely-with-band-steering/ (accessed 10/5, 2020).

[79] S. Laroche, C. T. Hoang, and G. Moineau, "Band steering," ed: Google Patents, 2014.

[80] E. H. Ong, J. Kneckt, O. Alanen, Z. Chang, T. Huovinen, and T. Nihtilä, "IEEE 802.11 ac: Enhancements for very high throughput WLANs," in *2011 IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications*, 2011: IEEE, pp. 849-853.

[81] M. X. Gong, B. Hart, and S. Mao, "Advanced wireless LAN technologies: IEEE 802.11 ac and beyond," *GetMobile: mobile computing and communications*, vol. 18, no. 4, pp. 48-52, 2015.

[82] M. Inamullah and B. Raman, "Frame Aggregation in 802.11ac: Need for Modified Block ACK," presented at the Proceedings of the 10th on Wireless of the Students, by the Students, and for the Students Workshop, New Delhi, India, 2018. [Online]. Available: https://doi.org/10.1145/3264877.3264879.

[83] E. Perahia and M. X. Gong, "Gigabit wireless LANs: an overview of IEEE 802.11 ac and 802.11 ad," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 15, no. 3, pp. 23-33, 2011.

[84] R. Van Nee, "Breaking the gigabit-per-second barrier with 802.11 ac," *IEEE Wireless Communications*, vol. 18, no. 2, pp. 4-4, 2011.

[85] I. C. S. L. M. S. Committee, "IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11^*, 2007.

[86] G. Redieteab, L. Cariou, P. Christin, and J.-F. Hélard, "SU/MU-MIMO in IEEE 802.11 ac: PHY+ MAC performance comparison for single antenna stations," in *Wireless Telecommunications Symposium 2012*, 2012: IEEE, pp. 1-5.

[87] D. Gesbert, M. Kountouris, R. W. Heath, C.-B. Chae, and T. Salzer, "Shifting the MIMO paradigm," *IEEE signal processing magazine*, vol. 24, no. 5, pp. 36-46, 2007.

[88] M. X. Gong, B. Hart, and S. Mao, "Advanced Wireless LAN Technologies: IEEE 802.11AC and Beyond," *GetMobile: Mobile Comp. and Comm.*, vol. 18, no. 4, pp. 48–52, 2015, doi: 10.1145/2721914.2721933.

[89] N. S. Ravindranath, I. Singh, A. Prasad, and V. S. Rao, "Study of performance of transmit beamforming and MU-MIMO mechanisms in IEEE 802.11ac WLANs," in *2017 International Conference on Inventive Communication and Computational Technologies (ICICCT)*, 10-11 March 2017 2017, pp. 419-429, doi: 10.1109/ICICCT.2017.7975233.

[90] M. H. Cheong, H. J. Kwon, J. S. Lee, and S. K. Lee, "Channel sounding method in wireless LAN system and device for supporting same," ed: Google Patents, 2019.

[91] H. Hartenstein and K. Laberteaux, *VANET: vehicular applications and inter-networking technologies*. John Wiley & Sons, 2009.

[92] T. Kosch, I. Kulp, M. Bechler, M. Strassberger, B. Weyl, and R. Lasowski, "Communication architecture for cooperative systems in Europe," *IEEE Communications Magazine*, vol. 47, no. 5, pp. 116-125, 2009, doi: 10.1109/MCOM.2009.4939287.

[93] I. S. Association, "IEEE standard for local and metropolitan area networks-specific requirements: Part 11 (IEEE 802.11-2007)," *http://standards. ieee. org/*, 2007.

[94] E. ITS, "G5 standard—Final draft ETSI ES 202 663 V1. 1.0, Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band," Technical report ETSI, 2011.

[95] S. Biswas, R. Tatchikou, and F. Dion, "Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety," *IEEE Communications Magazine*, vol. 44, no. 1, pp. 74-82, 2006, doi: 10.1109/MCOM.2006.1580935.

[96] A. M. Abdelgader and W. Le-nan, "The Physical Layer of the IEEE 802.11p WAVE Communication Standard: The Specifications and Challenges," 2014.

[97] J. B. Kenney, "Dedicated Short-Range Communications (DSRC) Standards in the United States," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1162-1182, 2011, doi: 10.1109/JPROC.2011.2132790.

[98] U. F. C. Commission, "FCC Report and Order 03-324: Amendment of the Commission's Rules Regarding Dedicated Short--Range Communication Services in the 5.850-5.925 GHz Band," ed: December, 2003.

[99] Y. Li, "An Overview of the DSRC/WAVE Technology," Berlin, Heidelberg, 2012: Springer Berlin Heidelberg, in Quality, Reliability, Security and Robustness in Heterogeneous Networks, pp. 544-558.

[100] W. Vandenberghe, I. Moerman, and P. Demeester, "Approximation of the IEEE 802.11p standard using commercial off-the-shelf IEEE 802.11a hardware," in *2011 11th*

International Conference on ITS Telecommunications, 23-25 Aug. 2011 2011, pp. 21-26, doi: 10.1109/ITST.2011.6060057.

[101] K. Sjoberg, P. Andres, T. Buburuzan, and A. Brakemeier, "Cooperative Intelligent Transport Systems in Europe: Current Deployment Status and Outlook," *IEEE Vehicular Technology Magazine*, vol. 12, no. 2, pp. 89-97, 2017, doi: 10.1109/MVT.2017.2670018.

[102] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Communications Magazine*, vol. 51, no. 2, pp. 114-119, 2013, doi: 10.1109/MCOM.2013.6461195.

[103] L. Qiang, J. Li, Y. Ji, and C. Huang, "A novel software-defined networking approach for vertical handoff in heterogeneous wireless networks," *Wireless Communications and Mobile Computing*, vol. 16, no. 15, pp. 2374-2389, 2016, doi: https://doi.org/10.1002/wcm.2690.

[104] S. Agarwal, M. Kodialam, and T. V. Lakshman, "Traffic engineering in software defined networks," in *2013 Proceedings IEEE INFOCOM*, 14-19 April 2013 2013, pp. 2211-2219, doi: 10.1109/INFCOM.2013.6567024.

[105] *SDNi: A Message Exchange Protocol for Software Defined Networks (SDNS) across Multiple Domains*, Internet-Draft draft-yin-sdn-sdni-00, I. E. T. Force, 26/June/2012 2012. [Online]. Available: https://datatracker.ietf.org/doc/html/draft-yin-sdn-sdni-00

[106] R. D. R. Fontes, C. Campolo, C. E. Rothenberg, and A. Molinaro, "From Theory to Experimental Evaluation: Resource Management in Software-Defined Vehicular Networks," *IEEE Access*, vol. 5, pp. 3069-3076, 2017, doi: 10.1109/ACCESS.2017.2671030.

[107] K. Zheng, L. Hou, H. Meng, Q. Zheng, N. Lu, and L. Lei, "Soft-defined heterogeneous vehicular network: architecture and challenges," *IEEE Network*, vol. 30, no. 4, pp. 72-80, 2016, doi: 10.1109/MNET.2016.7513867.

[108] I. Ku, Y. Lu, M. Gerla, R. L. Gomes, F. Ongaro, and E. Cerqueira, "Towards software-defined VANET: Architecture and services," in *2014 13th annual Mediterranean ad hoc networking workshop (MED-HOC-NET)*, 2014: IEEE, pp. 103-110.

[109] M. A. Salahuddin, A. Al-Fuqaha, and M. Guizani, "Software-Defined Networking for RSU Clouds in Support of the Internet of Vehicles," *IEEE Internet of Things Journal*, vol. 2, no. 2, pp. 133-144, 2015, doi: 10.1109/JIOT.2014.2368356.

[110] Z. He, J. Cao, and X. Liu, "SDVN: Enabling rapid network innovation for heterogeneous vehicular communication," *IEEE network*, vol. 30, no. 4, pp. 10-15, 2016.

[111] H. Ali-Ahmad *et al.*, "An SDN-based network architecture for extremely dense wireless networks," in *2013 IEEE SDN for Future Networks and Services (SDN4FNS)*, 2013: IEEE, pp. 1-7.

[112] C. Campolo, A. Molinaro, and R. Scopigno, "From today's VANETs to tomorrow's planning and the bets for the day after," *Vehicular Communications*, vol. 2, no. 3, pp. 158-171, 2015/07/01/ 2015, doi: https://doi.org/10.1016/j.vehcom.2015.06.002.

[113] A. Pressas, Z. Sheng, F. Ali, D. Tian, and M. Nekovee, "Contention-based learning MAC protocol for broadcast vehicle-to-vehicle communication," in *2017 IEEE Vehicular Networking Conference (VNC)*, 27-29 Nov. 2017 2017, pp. 263-270, doi: 10.1109/VNC.2017.8275614.

[114] K. M. A. Alheeti, M. S. Al-Ani, and K. McDonald-Maier, "A hierarchical detection method in external communication for self-driving vehicles based on TDMA," *PloS one*, vol. 13, no. 1, p. e0188760, 2018.

[115] L. A. Pipes, "An operational analysis of traffic dynamics," *Journal of applied physics*, vol. 24, no. 3, pp. 274-281, 1953.

[116] A. Reuschel, "Fahrzeugbewegungen in der Kolonne," *Osterreichisches Ingenieur Archiv*, vol. 4, pp. 193-215, 1950.

[117] M. Brackstone and M. McDonald, "Car-following: a historical review," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 2, no. 4, pp. 181-196, 1999.

[118] R. E. Chandler, R. Herman, and E. W. Montroll, "Traffic dynamics: studies in car following," *Operations research*, vol. 6, no. 2, pp. 165-184, 1958.

[119] R. Herman, E. W. Montroll, R. B. Potts, and R. W. Rothery, "Traffic dynamics: analysis of stability in car following," *Operations research*, vol. 7, no. 1, pp. 86-106, 1959.

[120] D. C. Gazis, R. Herman, and R. W. Rothery, "Nonlinear follow-the-leader models of traffic flow," *Operations research,* vol. 9, no. 4, pp. 545-567, 1961.

[121] G. F. Newell, "Nonlinear effects in the dynamics of car following," *Operations research,* vol. 9, no. 2, pp. 209-229, 1961.

[122] M. Bando, K. Hasebe, A. Nakayama, A. Shibata, and Y. Sugiyama, "Dynamical model of traffic congestion and numerical simulation," *Physical review E,* vol. 51, no. 2, p. 1035, 1995.

[123] D. Helbing and B. Tilch, "Generalized force model of traffic dynamics," *Physical review E,* vol. 58, no. 1, p. 133, 1998.

[124] R. Jiang, Q. Wu, and Z. Zhu, "Full velocity difference model for a car-following theory," *Physical Review E,* vol. 64, no. 1, p. 017101, 2001.

[125] M. Saifuzzaman and Z. Zheng, "Incorporating human-factors in car-following models: A review of recent developments and research needs," *Transportation Research Part C: Emerging Technologies,* vol. 48, pp. 379-403, 2014/11/01/ 2014, doi: https://doi.org/10.1016/j.trc.2014.09.008.

[126] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Physical review E,* vol. 62, no. 2, p. 1805, 2000.

[127] D. Helbing, A. Hennecke, V. Shvetsov, and M. Treiber, "Micro-and macro-simulation of freeway traffic," *Mathematical and computer modelling,* vol. 35, no. 5-6, pp. 517-547, 2002.

[128] D. Jia, D. Ngoduy, and H. L. Vu, "A multiclass microscopic model for heterogeneous platoon with vehicle-to-vehicle communication," *Transportmetrica B: Transport Dynamics,* 2018.

[129] M. García-Pineda, S. Felici-Castell, and J. Segura-García, "Do Current Domestic Gigabit Wireless Technologies Fulfill User Requirements for Ultra High Definition Videos?," in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2017: IEEE, pp. 8-13.

[130] R.-S. Cheng, "Performance evaluation of stream control transport protocol over IEEE 802.11 ac networks," in *2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2015: IEEE, pp. 97-102.

[131] C.-Y. Chang, H.-C. Yen, C.-C. Lin, and D.-J. Deng, "QoS/QoE support for H. 264/AVC video stream in IEEE 802.11 ac WLANs," *IEEE Systems Journal,* vol. 11, no. 4, pp. 2546-2555, 2015.

[132] S. M. Bellovin, D. D. Clark, A. Perrig, and D. Song, "A clean-slate design for the next-generation secure internet," 2006.

[133] I. Aruba Network, "Migration Guide 802.11ac," 2000. [Online]. Available: https://www.arubanetworks.com/pdf/technology/MG_80211ac.pdf

[134] C. Mathias. "Deploying 802.11ac: Notes from the Field." https://www.networkworld.com/article/2226849/deploying-802-11ac--notes-from-the-field.html (accessed 8 July, 2018).

[135] Motorola, "802.11n: Look Before You Leap: Key considerations for moving to 802.11n," 2009.

[136] I. Brocade Communications System, "Deployment Strategies for 802.11n: Key Considerations for the Next Generation of Wireless Networking ", 2009. [Online]. Available: http://docs.media.bitpipe.com/io_10x/io_102560/item_479611/80211n_WLANS_WP_00.pdf

[137] N. Prasad and A. Prasad, *802.11 WLANs and IP networking: security, QoS, and mobility*. Artech House, 2005.

[138] D. D. Coleman and D. A. Westcott, *CWNA: Certified Wireless Network Administrator Official Study Guide: Exam CWNA-106*. John Wiley & Sons, 2014.

[139] T. Carpenter, *CWTS™ Certified Wireless Technology Specialist Study Guide*. McGraw-Hill, 2010.

[140] S. M. Jackman, M. Swartz, M. Burton, and T. W. Head, *CWDP Certified Wireless Design Professional Official Study Guide: Exam PW0-250*. John Wiley & Sons, 2011.

[141] M.-D. Dianu, J. Riihijärvi, and M. Petrova, "Measurement-based study of the performance of IEEE 802.11 ac in an indoor environment," in *2014 IEEE International Conference on Communications (ICC)*, 2014: IEEE, pp. 5771-5776.

[142] T. S. Rappaport, *Wireless communications: principles and practice*. prentice hall PTR New Jersey, 1996.

[143] F. Qin, X. Dai, and J. E. Mitchell, "Effective-SNR estimation for wireless sensor network using Kalman filter," *Ad Hoc Networks*, vol. 11, no. 3, pp. 944-958, 2013.

[144] S. S. Ghassemzadeh, R. Jana, C. W. Rice, W. Turin, and V. Tarokh, "A statistical path loss model for in-home UWB channels," in *2002 IEEE Conference on Ultra Wideband Systems and Technologies (IEEE Cat. No. 02EX580)*, 2002: IEEE, pp. 59-64.

[145] K. L. Blackard, T. S. Rappaport, and C. W. Bostian, "Measurements and models of radio frequency impulsive noise for indoor wireless communications," *IEEE Journal on selected areas in communications*, vol. 11, no. 7, pp. 991-1001, 1993.

[146] H. Hartenstein and L. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Communications magazine*, vol. 46, no. 6, pp. 164-171, 2008.

[147] O. N. F. (ONF), "Software-Defined Networking: The New Norm for Networks," 2013. [Online]. Available: http://opennetworking.wpengine.com/wp-content/uploads/2011/09/wp-sdn-newnorm.pdf

[148] F. Yang, H. Wang, C. Mei, J. Zhang, and M. Wang, "A flexible three clouds 5G mobile network architecture based on NFV & SDN," *China Communications*, vol. 12, no. Supplement, pp. 121-131, 2015.

[149] O. N. Foundation, "SDN in the Campus Environment," 2013. [Online]. Available: https://opennetworking.org/wp-content/uploads/2013/03/sb-enterprise-campus.pdf

[150] O. N. Foundation, "OpenFlow™-Enabled Mobile and Wireless Networks," 2013. [Online]. Available: https://opennetworking.org/wp-content/uploads/2013/03/sb-wireless-mobile.pdf

[151] B. Han, V. Gopalakrishnan, L. Ji, and S. Lee, "Network function virtualization: Challenges and opportunities for innovations," *IEEE Communications Magazine*, vol. 53, no. 2, pp. 90-97, 2015.

[152] O. N. Foundation, "OpenFlow-enabled Transport SDN," 2014. [Online]. Available: https://opennetworking.org/wp-content/uploads/2013/05/sb-of-enabled-transport-sdn.pdf

[153] N. B. Truong, G. M. Lee, and Y. Ghamri-Doudane, "Software defined networking-based vehicular adhoc network with fog computing," in *2015 IFIP/IEEE International Symposium on Integrated Network Management (IM)*, 2015: Ieee, pp. 1202-1207.

[154] G. I. Association, "The 5G Infrastructure Public Private Partnership: the next generation of communication networks and services. 2015," ed.

[155] S. Motorist. "What Is A Safe Following Distance? (3 Second Rule)." https://www.smartmotorist.com/safe-following-distance (accessed 9 March, 2018).

[156] D. N. Lee, "A theory of visual control of braking based on information about time-to-collision," *Perception*, vol. 5, no. 4, pp. 437-459, 1976.

[157] J. Conlon, "A Missouri Citizen's Guide to Red Light Cameras," *Mo. L. Rev.*, vol. 80, p. 197, 2015.

[158] M. Saffarian, R. Happee, and J. d. Winter, "Why do drivers maintain short headways in fog? A driving-simulator study evaluating feeling of risk and lateral control during automated and manual car following," *Ergonomics*, vol. 55, no. 9, pp. 971-985, 2012.

[159] V. Technologies, "SCA3100-D04 3-Axis High Performance Accelerometer with Digital SPI Interface Datasheet," 2015.

[160] Bosch, "Acceleration Sensor MM5.10 Datasheet," 2016.

[161] Bosch, "Mid-Range Radar Sensor (MRR) for Front and Rear Application Datasheet," 2016.

[162] IBEO, "LUX Lidar Sensor Datasheet," 2010.

[163] Bosch, "Low-g accelerometer for vehicle dynamics control SMB225 Datasheet," 2013.

[164] Bosch, "Low-g Accelerometer for Rollover Applications SMB200 Datasheet," 2013.

[165] Trimble, "DSM132 DGPS Receiver Datasheet," 2005.

[166] Bourns, "Non-Contacting Steering Angle Sensor Type 6002 Datasheet," 2013.

[167] Y. Rekhter, "Edge devices for providing a transparent LAN segment service and configuration such edge devices," United States, 2011.

[168] P. Djukic and P. Mohapatra, "Soft-TDMAC: A software TDMA-based MAC over commodity 802.11 hardware," in *IEEE INFOCOM 2009*, 2009: IEEE, pp. 1836-1844.

[169] C. Inc., "Cisco Catalyst 3550 Series Intelligent Ethernet Switches Datasheet," 2017.

[170] H.-P. Inc., "HPE 3800 Switch Series Datasheet," 2016.

[171] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE communications surveys & tutorials*, vol. 18, no. 1, pp. 263-284, 2015.

[172] O. Kaiwartya *et al.*, "Internet of vehicles: Motivation, layered architecture, network model, challenges, and future aspects," *IEEE Access*, vol. 4, pp. 5356-5373, 2016.

[173] P. Dhawankar, M. Raza, H. Le Minh, and N. Aslam, "Software-defined approach for communication in autonomous transportation systems," *EAI Endorsed Transactions on Energy Web*, vol. 4, no. 12, p. 152924, 2017.

[174] E. Chan, "Overview of the sartre platooning project: technology leadership brief," SAE Technical Paper, 0148-7191, 2012.

[175] L. Aarts and G. Feddes, "European truck platooning challenge," in *Proceedings of the HVTT14: International Symposium on Heavy Vehicle Transport Technology, Rotorua, New Zealand*, 2016, pp. 15-18.

[176] C. Lei, E. Van Eenennaam, W. K. Wolterink, G. Karagiannis, G. Heijenk, and J. Ploeg, "Impact of packet loss on CACC string stability performance," in *2011 11th International Conference on ITS Telecommunications*, 2011: IEEE, pp. 381-386.

[177] S. Santini, A. Salvi, A. S. Valente, A. Pescapé, M. Segata, and R. L. Cigno, "A consensus-based approach for platooning with intervehicular communications and its validation in realistic scenarios," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 1985-1999, 2016.

[178] A. Böhm, M. Jonsson, and E. Uhlemann, "Performance comparison of a platooning application using the IEEE 802.11 p MAC on the control channel and a centralized MAC on a service channel," in *2013 IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2013: IEEE, pp. 545-552.

[179] M. Segata *et al.*, "Toward communication strategies for platooning: Simulative and experimental evaluation," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 12, pp. 5411-5423, 2015.

[180] A. Vinel, L. Lan, and N. Lyamin, "Vehicle-to-vehicle communication in C-ACC/platooning scenarios," *IEEE Communications Magazine*, vol. 53, no. 8, pp. 192-197, 2015.

[181] J. Hu *et al.*, "Link level performance comparison between LTE V2X and DSRC," *Journal of Communications and Information Networks*, vol. 2, no. 2, pp. 101-112, 2017.

[182] R. Blasco, H. Do, S. Shalmashi, S. Sorrentino, and Y. Zang, "3GPP LTE enhancements for V2V and comparison to IEEE 802.11 p," in *Proc. ITS Eur. Congr.*, 2016, pp. 1-10.

[183] M. Aramrattana, T. Larsson, J. Jansson, and A. Nåbo, "A simulation framework for cooperative intelligent transport systems testing and evaluation," *Transportation research part F: traffic psychology and behaviour*, vol. 61, pp. 268-280, 2019.

[184] V. Trucks. "Volvo Trucks successfully demonstrates on-highway truck platooning in California." Volvo. https://www.volvotrucks.us/news-and-stories/press-releases/2017/march/volvo-trucks-successfully-demonstrates-on-highway-truck-platooning-in-california/ (accessed 10 September, 2021).

[185] D. SAE, "J2735 Dedicated Short Range, Communications (DSRC) Message Set Dictionary, Jun. 12, 2006, 167 pages, The Engineering Society For Advancing Mobility Land Sea Air and Space International," *Society of Automotive Engineers, Inc. USA*.

[186] R. Purandare, S. Kshirsagar, and S. Koli, "Analysis of various parameters for link adaptation in wireless transmission," in *Innovations in computer science and engineering*: Springer, 2016, pp. 9-19.

[187] V. Shivaldova, A. Paier, D. Smely, and C. F. Mecklenbräuker, "On roadside unit antenna measurements for vehicle-to-infrastructure communications," in *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications-(PIMRC)*, 2012: IEEE, pp. 1295-1299.

[188] P. Alexander, D. Haley, and A. Grant, "Cooperative intelligent transport systems: 5.9-GHz field trials," *Proceedings of the IEEE,* vol. 99, no. 7, pp. 1213-1235, 2011.

[189] T. S. Rappaport, "Wireless Communications--Principles and Practice, (The Book End)," *Microwave Journal*, vol. 45, no. 12, pp. 128-129, 2002.

[190] W. Vandenberghe, I. Moerman, and P. Demeester, "Approximation of the IEEE 802.11 p standard using commercial off-the-shelf IEEE 802.11 a hardware," in *2011 11th International Conference on ITS Telecommunications*, 2011: IEEE, pp. 21-26.

[191] A. Kesting, M. Treiber, and D. Helbing, "Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 368, no. 1928, pp. 4585-4605, 2010.

[192] M. Zhou, X. Qu, and S. Jin, "On the impact of cooperative autonomous vehicles in improving freeway merging: a modified intelligent driver model-based approach," *IEEE Transactions on Intelligent Transportation Systems,* vol. 18, no. 6, pp. 1422-1428, 2016.

[193] L. Bernado, T. Zemen, F. Tufvesson, A. F. Molisch, and C. F. Mecklenbräuker, "Delay and Doppler spreads of nonstationary vehicular channels for safety-relevant scenarios," *IEEE Transactions on Vehicular Technology,* vol. 63, no. 1, pp. 82-93, 2013.