MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

ANALYSIS OF REAL VEHICLE TRACES AND ITS USE IN OPTIMIZATIONS OF 5G CELLULAR NETWORK RESOURCES

MUHAMMED NUR AVCİL

Ph.D. THESIS

Department of Computer Engineering

Thesis Supervisor

Assoc. Prof. Müjdat SOYTÜRK

ISTANBUL, 2024

MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

ANALYSIS OF REAL VEHICLE TRACES AND ITS USE IN OPTIMIZATIONS OF 5G CELLULAR NETWORK RESOURCES

MUHAMMED NUR AVCİL

(724115701)

Ph.D. THESIS

Department of Computer Engineering

Thesis Supervisor

Assoc. Prof. Müjdat SOYTÜRK

ISTANBUL, 2024

ACKNOWLEDGMENT

I would like to thank my academic supervisor, Dr. Müjdat SOYTÜRK, for his encouragement, kindness, support, patience and valuable guidance throughout this study.

Many thanks to my colleagues in the Computer Science and Engineering Department for their sincere friendship and making my time spent at the Marmara University an enjoyable experience. Especially the head of the department, I would like to thank Prof. Dr. Haluk Rahmi TOPCUOĞLU for his support.

Also, I would like to thank Dr. Burak KANTARCI from Ottawa University for all his support and valuable time.

To my beloved wife, Ayşe, and my children Nil and Hasan Ali, and my parents, many thanks for their continuous support and understanding.

May, 2024 **Muhammed Nur AVCİL**

TABLE OF CONTENTS

PAGE

ACKNOWLEDGMENT i

TABLE OF CONTENTS ii

ÖZET v

ABSTRACT vii

CLAIM FOR ORIGINALITY ix

SYMBOLS x

ABBREVIATIONS xi

LIST OF FIGURES xiv

LIST OF TABLES xvi

1. INTRODUCTION 1

1.1. Contribution of the Thesis 3

1.2. Structure of the Thesis 4

2. LITERATURE REVIEW 5

2.1. Test & Simulation Environment 5

2.2. Centralized/Distributed Data Offloading 6

2.3. Selected Vehicle Based Data Offloading 8

3. PERFORMANCE EVALUATION OF V2X COMMUNICATIONS AND SERVICES IN CELLULAR NETWORK WITH A REALISTIC SIMULATION ENVIRONMENT 11

3.1. Preliminary Information About V2X 14

3.1.1. Vehicle-to-Everything (V2X) Communication Modes 14

3.1.1.1. Vehicle-to-Vehicle (V2V) Communication 14

3.1.1.2. Vehicle-to-Infrastructure (V2I) Communication 15

3.1.1.3. Vehicle-to-Pedestrian (V2P) Communication 15

3.1.1.4. Vehicle-to-Network (V2N) Communication 15

3.1.2. Communication Protocols and Technologies 16

3.1.2.1. Dedicated Short-Range Communication (DSRC) 16

3.1.2.2. Cellular V2X (C-V2X) Communication 16

3.1.3. Key Concepts Used in Thesis 17

3.1.3.1. Offloading 17

3.1.3.2. Reliability/Efficiency 17
3.1.3.3. Fairness 18
3.1.3.4. Realistic Simulation 18
3.2. Methodology and The Framework 19
3.3. Modules, Simulation & Test Environment 19
3.3.1. Used Modules in Simulation 19
3.3.2. Used Simulators 21
3.3.2.1. OMNeT++ 21
3.3.2.2. SUMO 22
3.3.2.3. Veins 22
3.3.3. Simulation & Test Environment 23
3.4. Performance Metrics and Simulation Results 24
3.4.1. Used Performance Metrics 24
3.4.2. Results 25
3.5. Summary 32
4. FAIR AND EFFICIENT RESOURCE ALLOCATION VIA VEHICLE-EDGE COOPERATION IN 5G-ENABLED V2X NETWORKS 33
4.1. Background, Methodology and The Proposed Approach 36
4.1.1. Background and Communication Settings 38
4.1.2. Proposed Method 40
4.2. Performance Metrics & Results 44
4.2.1. State-of-the-art Solutions and Baselines 44
4.2.2. Performance Metrics 45
4.2.3. Simulation Settings 47
4.2.4. Performance Evaluation under Scenario-1 49
4.2.5. Performance Evaluation under Scenario-2 57
4.3. Summary 66
5. DATA TRAFFIC OFFLOADING WITH SELECTING RELAY NODE IN C-V2X NETWORKS 69
5.1. The Proposed Relay Node Selection Approach 70
5.2. Simulations and Performance Results 75
5.2.1. State-of-the-art Solutions and Baselines 75
5.2.2. Performance Metrics 76

5.2.3. Simulation Settings 77
5.2.4. Performance Results 79
5.3. Summary 83
6. CONCLUSION AND FUTURE WORK 85
6.1. Conclusion 85
6.2. Future Work 86
REFERENCES 87

ÖZET

Gerçek Araç İzlerinin Analizi ve 5G Hücresel Ağ kaynaklarının Optimizasyonunda Kullanımı

5G standartları içindeki V2X iletişimi, araçların birbirine bağlanmasını ve hücresel hizmetlere her an her yerden erişmesini sağlayan önemli bir özelliktir. Değişken sayıda araç, uygulama/ağ hizmetleri, yol ağı altyapısı ve sistem performansını artırmak veya iyileştirmek için önerilen yeni çözüm yaklaşımları/yöntemleri dahil olmak üzere test edilen sistemin büyük ölçekli gösterimi için gerçekçi bir simülasyon ortamı oluşturmak esastır. Tezin ilk bölümünde bu amaçla geliştirilen simülasyon ortamı anlatılmakta ve ayrıca V2X iletişimi ve hücresel ağ tarafından sağlanan hizmetler değerlendirilmektedir. Sonuçlar, sistem performansı ve performansı iyileştirmeye yönelik sonraki çalışmalar hakkında bilgi sağlar.

Güvenlik riskleri ve operasyonel verimlilik sorunlarıyla başa çıkmak için, Bağlantılı ve Otonom Araçlarda yüksek veri hızlarının sağlanması ve gecikme gereksinimlerinin karşılanması son derece önemlidir. Bu tür ortamlardaki sorun iki yönlüdür: 1) Artan talepler nedeniyle ağ üzerindeki yoğun yük; 2) Belirli bölgelerdeki araç trafiği yoğunluğundaki farklılıklar nedeniyle kaynak dengesizliği. Bu iki olgunun sonuçları, araçlar arasında adil kaynak tahsisinin yanı sıra hizmet kesintilerine de yol açabilir. Tezin ikinci bölümünde, yüksek iş yükünün kenar düğümler arasında dağıtılmasını ve ağ kaynaklarının etkili ve adil bir şekilde tahsis edilmesini sağlayan bir kaynak tahsisi yöntemi öneriyoruz. Önerilen yöntemin performansı gerçekçi senaryolar altında değerlendirilmiş ve literatürdeki en son tekniklerle karşılaştırılmıştır. Tüm yöntemlerin belirli bölgelerdeki aşırı yüklenme koşullarında davranışları ve performansları analiz edilmiştir.

Hücresel Araçlar Arası Her Şey (C-V2X) iletişimi bağlamında, röle düğümlerinin seçimi, verimli ve güvenilir veri aktarımının sağlanmasında kritik bir rol oynar, bu da sürücü güvenliğini artırır ve genel sürüş deneyimine katkıda bulunur. C-V2X iletişimi, 3GPP Sürüm 17 tarafından desteklenen 5G protokollerini kullanır. C-V2X ağ topolojisinin dinamikliği ve 5G baz istasyonu'nun sınırlı kapasitesi göz önüne alındığında, gerekli veriler, veri boşaltma ile seçilen röle düğümü aracılığıyla etkili bir

şekilde iletilebilir. Tezin üçüncü bölümünde, düşük iş yüküne sahip 5G baz istasyonu kapasitesinden yararlanmak amacıyla röle düğümü seçimi için yeni bir veri boşaltma çözümü öneriyoruz. Bu seçme işlemi, aracın hem mesafesi hem de kanal kapasitesi dikkate alınarak 5G baz istasyonu tarafından gerçekleştirilir. Önerilen yöntem, performans sonuçlarını değerlendirmek için gerçekçi bir ağ senaryosunda son teknoloji algoritmalara uygulanmıştır.

Mayıs, 2024 **Muhammed Nur AVCİL**

ABSTRACT

ANALYSIS OF REAL VEHICLE TRACES AND ITS USE IN OPTIMIZATIONS OF 5G CELLULAR NETWORK RESOURCES

V2X communications is one key feature in the 5G standards that enables the vehicles to get connected and access the cellular services anywhere anytime. It is essential to build a realistic simulation environment for large scale demonstration of the system under test including varying number of vehicles, application/network services, road network infrastructure and new solution approaches/methods proposed to enhance or make improvements on the system performance. In the first part of the thesis I describe the simulation environment developed for this purpose and also evaluate the V2X communication and the services provided by the cellular network. The results provide insights on the system performance and the follow-up studies to improve the performance.

To cope with safety risks and operational efficiency problems, it is of paramount importance to ensure high data rates and meet the latency requirements in Connected and Autonomous Vehicles. The problem in such environments is two-fold: 1) Heavy load on the network due to increasing demands; 2) Resource imbalance, due to variations in the vehicular traffic density in certain regions. The consequences of these two phenomena may lead to service disruptions, as well as the fairness of resource allocation across vehicles. In the second part of the thesis, we propose a resource allocation method that distributes high workload among edge nodes and allocates network resources efficiently and fairly. The performance of the proposed method is evaluated under realistic scenarios, and compared to the state-of-the-art approaches in the literature. The behavior and performance of all methods in overload conditions in certain regions were analyzed.

In the context of Cellular Vehicle-to-Everything (C-V2X) communication, selection of relay nodes plays a critical role in ensuring efficient and reliable data transfer, which improves driver safety and contributes to the overall driving experience. C-V2X communication utilizes 5G protocols supported by 3GPP Release 17. Considering the dynamic nature of a C-V2X network topology and limited capacity of a gNodeB, the required data can be efficiently transmitted through the selected relay node with offloading. In the third part of the thesis, we propose a novel data offloading solution for relay node selection with the aim of utilizing the capacity of gNodeB's with low workloads. The selection is determined by the gNodeB, taking into account both the distance and the channel capacity of the vehicle. The proposed method is applied to state-of-the-art algorithms in a realistic network scenario to evaluate performance results.

May, 2024 **Muhammed Nur AVCİL**

CLAIM FOR ORIGINALITY

ANALYSIS OF REAL VEHICLE TRACES AND ITS USE IN OPTIMIZATIONS OF 5G CELLULAR NETWORK RESOURCES

The significant contributions of this thesis can be summarized as follows:

Firstly, a realistic test environment has been prepared to evaluate the performance of V2X communication services in 5G networks. This test environment will guide the proposed solution methods and improvements for 5G services.

Secondly, a novel data offloading solution for V2X communication in 5G networks has been proposed. We have proposed a mathematical linear programming model to balance the network workload and allocate vehicle requests more fairly among base stations. Additionally, we have evaluated this new method comprehensively by conducting tests based on various performance metrics commonly used in the literature.

Finally, we have proposed a new relay node selection solution method to utilize the existing base station resources of the 5G network more effectively and efficiently. When base station resources become available, the base station selects a relay node, thus unused resource is included in the use of the network's operations.

May, 2024 **Assoc. Prof. Müjdat SOYTÜRK** **Muhammed Nur AVCİL**

SYMBOLS

T_{slot}	:	time frame (*ms*)
N_{symb}^{slot}	:	number of OFDM symbol per slot
$N_{slot}^{subframe,\mu}$	:	number of slots per subframe
$N_{slot}^{frame,\mu}$	:	number of slots per frame
$\triangle f$	:	subcarrier spacing [*kHz*]
μ	:	subcarrier spacing configuration
M_{RB}	:	data size of the resource block
B_{RB}	:	resource block bandwidth
N_{RB}	:	number of resource blocks
$N_{Channel}$	:	number of channels
Q_m	:	frame modulation order
N_{SC}^{RB}	:	number of subcarriers per resource block
B	:	channel bandwidth
B_{guard}	:	guard interval
C	:	channel RB capacity
C_{AN}	:	edge node data capacity
N_{AN}	:	number of edge nodes
C_{System}	:	total data capacity of the system
α	:	ratio of the total RB requests
$\mathcal{J}$	:	Jain's fairness index value
S	:	List of the sub-cells

ABBREVIATIONS

3GPP	:	3rd Generation Partnership Project
AV	:	Autonomous Vehicles
BS	:	Base Station
CAV	:	Connected Autonomous Vehicles
CDF	:	Cumulative Distribution Function
C-V2X	:	Cellular Vehicle-to-Everything
DL	:	Downlink communication channel
EAS	:	Edge Application Servers
EDF	:	Earliest Deadline First
EES	:	Edge Enabler Servers
eNodeB	:	Evolved Node B (LTE Base Station)
EPC	:	Evolved Packet Core
FCFS	:	First Come-First Served
FIFO	:	First In First Out
gNodeB	:	Next-Generation Node B (5G Base Station)
GPS	:	Global Positioning System
GTP-U	:	Tunneling protocol for user plane
HSS	:	Home Subscriber Server
ILP	:	Integer Linear Programming
ITS	:	Intelligent Transportation Systems
LiDAR	:	Light Detection and Ranging
LTE	:	Long Term Evolution

MAC : Media Access Control

MAC : Media Access Control Address

MANET : Mobile Ad Hoc Network

MAX C/I : Maximum Carrier-to-Interference

MME : Mobility Management Entity

M-LWDF : Modified Largest Weighted Delay First

MT : Maximum Throughput

OFDM : Orthogonal Frequency Division Multiplexing

OMNET++ : Object-oriented Modular Discrete Event Network Simulation

PDN : Packet Data Network

PF : Proportional Fairness

PGW : Packet Data Network Gateway

PLR : Packet Lose Rate

PSO : Particle Swarm Optimization

QoS : Quality of Service

RADAR : Radio Detection And Ranging

RB : Resource Block

RMU : Resource Allocation Management Unit

RR : Round Robin

RSS : Received Signal Strength

SAE : Society of Automotive Engineers

SDN : Software Defined Networking

SGW : Serving Gateway

SINR : Signal to Interference plus & Noise Ratio

SONAR : Sound Navigation and Ranging

SUMO : Simulation of Urban Mobility

UDP : User Datagram Protocol

UE : User Equipment

UL : Uplink communication channel

V2I : Vehicle-to-Infrastructure

V2N : Vehicle-to-Network

V2P : Vehicle-to-Pedestrian

V2V : Vehicle-to-Vehicle

V2X : Vehicle-to-Everything

VANET : Vehicular Ad Hoc Network

Veins : Vehicles in Network Simulation

LIST OF FIGURES

Figure 2.1 Taxonomy of Workload Offloading in V2X. 6

Figure 3.1 V2X Services Demand from the Cellular Network [5] 12

Figure 3.2 LTE Architecture 20

Figure 3.3 MAC Scheduler 21

Figure 3.4 Architecture of the Veins Simulator [17] 23

Figure 3.5 Simulation topology 24

Figure 3.6 Average Number of Service Demands per Vehicle 27

Figure 3.7 Number of Acknowledged Service Demands 27

Figure 3.8 Number of Unsuccessful Service Demands 29

Figure 3.9 Number of Successful Service Demands 29

Figure 3.10 Number of Unsuccessful Packages 30

Figure 3.11 Delay on Service - Turnaround time 31

Figure 4.1 A high level illustration of C-V2X communication in 5G network. 33

Figure 4.2 5G Frame Structure in 3GPP Rel. 17 [10]. 36

Figure 4.3 Sequence Diagram for Data Offloading Decision. 43

Figure 4.4 Average Turnaround Time versus Number of Demands (Scenario-1). 49

Figure 4.5 Average Waiting Time versus Number of Demands (Scenario-1). 50

Figure 4.6 Jain's Fairness Index Value for Each Vehicle's Requests (Scenario-1). 51

Figure 4.7 Number of Unsuccessful Demands versus Number of Demands (Scenario-1). 52

Figure 4.8 Successful Demands Rate versus Number of Demands (Scenario-1) 53

Figure 4.9 Number of vehicles that experience resource starvation under varying number of vehicles in the network (Scenario-1). 54

Figure 4.10 Data offloading ratio with varying number of demands under the proposed method. By enabling offloading up to 30% of the demands, the proposed method can improve the turnaround and wait times with no starvation (Scenario-1). 56

Figure 4.11 Average Turnaround Time versus Number of Demands (Scenario-2). 57

Figure 4.12 Average Waiting Time versus Number of Demands (Scenario-2). 58

Figure 4.13 Number of Unsuccessful Demands versus Number of Demands (Scenario-2). 59

Figure 4.14 Successful Demands Rate versus Number of Demands (Scenario-2). 60

Figure 4.15 Jain's Fairness Index Value for Edge Nodes (Scenario-2). 62

Figure 4.16 Jain's Fairness Index Value for All Demands Throughout The Simulation

(Scenario-2). 62

Figure 4.17 Jain's Fairness Index Value for Each Vehicle's Requests (Scenario-2). 63

Figure 4.18 Number of vehicles that experience resource starvation under varying number of vehicles in the network (Scenario-2). 64

Figure 4.19 Data offloading ratio with varying number of demands under the proposed method. By enabling offloading an average of 44% of the demands, the proposed method can improve the turnaround and wait times with no starvation (Scenario-2).... 66

Figure 5.1 5G Frame Structure in 3GPP Rel. 17 [10] 71

Figure 5.2 Illustration of the proposed model a) urban area b) highway area............... 72

Figure 5.3 Offloading rate per number of demands 80

Figure 5.4 Total assigned demands size per number of demands 81

Figure 5.5 Successful demands rate per number of demands....................................... 82

LIST OF TABLES

Table 3.1 V2X Service requirement defined by 3GPP [5] 11

Table 3.2 LTE vs 5G Physical channels and modulation defined by 3GPP................. 13

Table 3.3 Simulation Parameters 26

Table 4.1 Notation table.. 37

Table 4.2 Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix 38

Table 4.3 Frame Modulation order (*Qm*).. 39

Table 4.4 Simulation and C-V2X Communication Parameters.................................... 47

Table 4.5 Percentage of responded demands by MAX C/I and our proposed method under varying number of demands under Scenario-1.. 55

Table 4.6 Percentage of responded demands by MAX C/I and our proposed method under varying number of demands under Scenario-2.. 60

Table 5.1 Algorithm 1: Update Vehicle List 73

Table 5.2 Algorithm 2: Candidate Relay Node Selection 73

Table 5.3 Algorithm 3: Relay Node Selection... 74

Table 5.4 Simulation Parameters 78

Table 5.5 Average gNodeB load ratio according to varying vehicle data request (%) . 78

1. INTRODUCTION

Vehicular Ad-hoc Network (VANET) is a special kind of network that enables vehicles communicate between each other via wireless communication [1]. VANET primarily focuses on inter-vehicle communication within a localized network, while vehicle-to-everything (V2X) extends this capability to include communication with surrounding infrastructure, which is including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P) and vehicle-to-network (V2N) interactions. This advancement significantly improves road safety, traffic efficiency, and the availability of infotainment services [2].

3GPP (3rd Generation Partnership Project) [3] is a collaborative project established to develop and manage mobile communication standards. The goal of 3GPP is to develop universally accepted standards to enable seamless communication among users across different devices and networks. 3GPP defined the standards for V2X services for LTE and 5G, included in Release 15 [4] and Release 16 [5] (Release 17 [10] is in progress). With 3GPP Release 15, the V2X functionality has been extended to support 5G [11]. V2X communication model uses cellular network and in Release 15 is called Cellular V2X (C-V2X). The C-V2X was designed to include both direct communication of between vehicles (V2V) and cellular network. The requirements for services such as platooning, advanced driving, extended sensors, and remote driving have been defined with the inclusion of 5G. This definition covers parameters such as latency, reliability, message size, frequency, range, speed, and security requirements [12]. Thus, the C-V2X standards specify the transmission of data required by vehicles through the cellular network in accordance with these defined service requirements.

Connected car is another term used for communicating vehicles with the use of V2X communications. According to the [13], 77 million connected cars will be ship to the market in 2025 and it is estimated that all shipped will account for 82% of the vehicles. Only when mobile data is considered, according to Cisco's forecast [14], global mobile data traffic increase sevenfold between 2018 and 2023. Chen et al. [15] indicates that a connected car generates 25GB/h of data from equipped sensors, while for online activities use approximately 1GB/h of data. For autonomous vehicles (AV), data plays an even more crucial role, as continuous data transfer is required for navigation and hazard detection. Autonomous vehicles require sensory data from various devices/sensors such as cameras, RADAR, SONAR, LiDAR, GPS, and others to ensure safe driving. According to [15], a single autonomous vehicle may require 20-40 MB of camera data, 10-100 KB of RADAR and SONAR data, 10-70 MB of LiDAR data, and 50 KB of GPS data per second. According to these values, one autonomous vehicle can consume up to 500 GB of data per an hour. This huge data requests will create a critical load on the edge node. As the number of autonomous vehicles increases, vehicle data requests are expected to rise significantly over time.

The excessive data demand of autonomous vehicles will create burden for the existing base stations, leading to potential disruptions in data access for vehicles. Hence, there arises a need for more efficient and effective utilization of existing base station resources. To address this, by balancing the network load among base stations, the network can be used more effectively while meeting more vehicle data demand. Upon reviewing the literature on offloading in C-V2X, it is noted that while there is considerable focus on computation offloading with using vehicle resources and sensor data collection which is generated by vehicles, studies specifically vehicle demanded data related data offloading studies are limited. With 3GPP Release 16 [12], frame structure, channel frequency, bandwidth and new services are defined with new specifications. Therefore, there is a need for data offloading-based methods that take new parameters and modulations into consideration.

In this thesis, novel data offloading methods for C-V2X networks in 5G are developed that take into account the new parameters and modulations standardized by 3GPP. In the first stage, the performance of V2X communications and 5G networks is evaluated in a realistic simulation environment. A simulation environment is created with varying densities and speeds of vehicles, containing vehicle data requests defined according to 3GPP standards. Through this environment, V2X communications and 5G networks are being tested, and the results obtained, including the utilization of network resource capacity, will serve as a basis for different solution methods to be proposed.

In the second stage, we evaluated the performance results obtained in the first stage and proposed a centralized data offloading method to enhance the efficient utilization of base station resources and achieve a balanced distribution of the network load across base stations. Our proposed method allocates vehicle requests to base stations considering both the size of vehicle data demands and the capacities of base station resources. Thus, while vehicle data requests are allocated fairly to base stations, the workloads of the base stations are also distributed in a balanced manner.

In the third stage, the resources of base stations are utilized to fulfill more vehicle requests by enabling selected relay vehicles to fulfill the data demands of other vehicles. Thus, it is aimed to enable data access for vehicles without access to the base station or do not have access to network resources due to the high workload of the base station they are accessing. By selecting relay nodes based on some criteria from base stations with available resource capacity, the method provides to satisfy more vehicle requests while utilizing unused network resources.

1.1. Contribution of the Thesis

The first contribution of the thesis involves the analysis of vehicles' ability to access C-V2X services over cellular networks. Initially, a realistic variable vehicle density model is created using SUMO [16]. Subsequently, the C-V2X environment is integrated into the Veins [17] model, enabling vehicles to access the required services over cellular networks. We conduct an observation and analysis of the network's performance and the quality of services provided to vehicles, taking into account the varying parameter values within the network. Using a realistic simulation environment, we analyze the performance of cellular network services with C-V2X communications.

The second contribution involves proposing an innovative 5G-based data offloading solution for centralized C-V2X networks. In this study, we aim to utilize unused edge node resources to meet more vehicle data demands. While assigning more vehicle demands, we also aim to achieve load balancing of the edge nodes. To this end, we create a mathematical integer linear programming model. This model is being evaluated by creating two different simulation environments and obtaining results based on various performance metrics that have been studied separately in the literature.

The third contribution is a novel relay node selection method for data offloading in C-V2X. The proposed method selects vehicles to act as relay nodes based on the load status of edge nodes, enabling the transfer of load from one edge node to another. This method determines distributed-based which vehicle will serve as a relay node.

1.2. Structure of the Thesis

The structure of this thesis is outlined as follows. In Chapter 2, a survey of centralized/distributed data offloading algorithms and relay node selection methods in the literature related to C-V2X is conducted. In Chapter 3, the performance of cellular network services with V2X communication is analyzed using a realistic simulation environment. In Chapter 4, a novel centralized data offloading method in C-V2X is proposed, and its performance is evaluated in various test environments. In Chapter 5, a new data offloading method based on distributed relay node selection is proposed, and its performance is evaluated by comparing it with different relay node selection methods. Finally, in Chapter 6 concludes the thesis document and presents future directions.

2. LITERATURE REVIEW

We provide an overview of relevant literature in three subsections. In the first subsection, test and simulation environments employed in studies related to V2X have been outlined. The second section summarizes the research on centralized and distributed based data offloading studies in C-V2X. Selected vehicle based data offloading studies in C-V2X literature review is in the third subsection.

2.1. Test & Simulation Environment

The MAC scheduler processes data requests from the UEs and vehicles and forwards them in a specific order. Therefore, the MAC scheduling strategy has an important role in transmitting the data requests. The MAC scheduling method used in the test environment has a significant impact on the performance results. In literature there are different purpose scheduling strategies such as Proportional Fair (PF), Round Robin (RR), First In First Out (FIFO), Earliest Deadline First (EDF), Modified Largest Weighted Delay First (M-LWDF), Maximum Throughput (MT) etc. In [18], LTE MAC scheduling methods were presented comprehensively according to the criteria of fairness, throughput, packet lose rate (PLR) and cumulative distribution function (CDF). MAC scheduling techniques are reviewed in detail in [19][20]. Zain et al. [21] compared most studied three MAC scheduling policies in LTE-Advanced network and they concluded that MAX C/I outperforms all the other two scheduling policies.

In [22], the authors focus on the V2X application requirements and its challenges, the necessity of testing, and also investigate and summarize testing methods for V2X in the communication process, describing them in detail from an architectural perspective. Additionally, they propose an end-to-end testing system capable of undertaking the testing task of the protocol stack. The authors in [23] describe the development of an integrated simulation environment for simulating V2X technology. This environment combines three software packages: VISSIM for traffic modeling, MATLAB for traffic management applications, and NS3 for communication network simulation. The integration of these simulators allows for the exchange of data among them, facilitating comprehensive analysis and testing of V2X systems. The performance of the proposed integration is evaluated by creating fixed-size data requests and placing vehicles randomly on the road.

2.2. Centralized/Distributed Data Offloading

Related work classifies workload offloading methods under two categories: computational/task workload offloading and data traffic workload offloading [24]. Computational/task workload offloading methods can be performed by utilizing cloud or edge computing resources [25]. Data traffic workload offloading processes can be achieved in two different ways: centralized/cloud-based traffic offloading and distributed traffic offloading with edge nodes. Centralized/cloud-based traffic offloading and distributed traffic offloading with edge nodes can also be implemented with selected vehicle-based offloading, which acts as a relay node [26]. Taxonomy of workload offloading in V2X as illustrated in Figure 2.1.

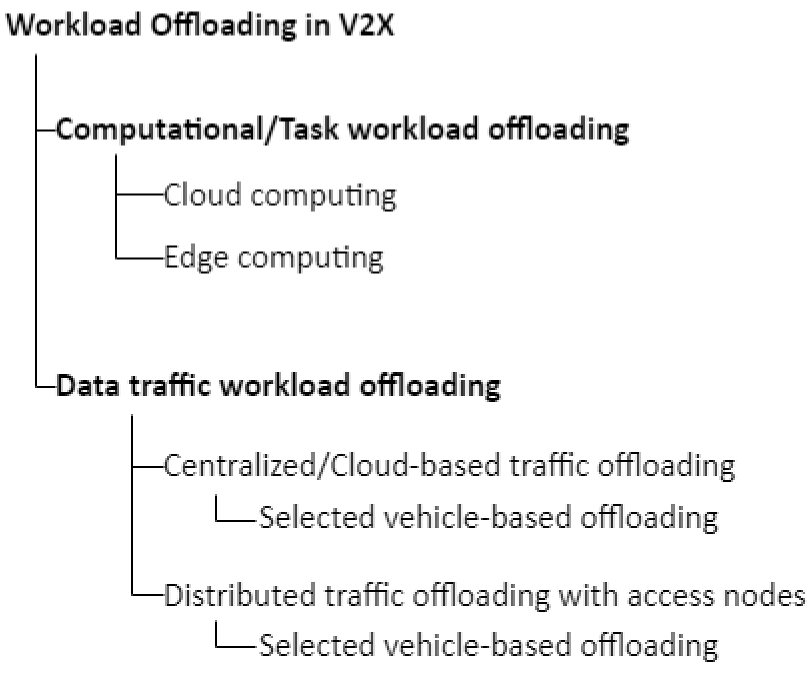


Figure 2.1 Taxonomy of Workload Offloading in V2X.

Cloud-based and edge-based computational offloading approaches aim for different goals. While cloud-based computational offloading methods aim to enhance the capacity of vehicles, computational offloading in edge nodes leverages the unused resources of vehicles. In [27], a task offloading scheme based on vehicle-to-vehicle (V2V) communication is designed, utilizing the resources of the vehicles stopped for traffic lights in an urban environment. The Max–Min fairness scheme is used to optimize the task execution time via Particle Swarm Optimization (PSO). In the optimization problem [27], first, the assignment of task proportions to service vehicles is determined using the PSO algorithm. Once the task proportions are defined, this parameter is incorporated into the optimization problem and solved using the Max–Min fairness algorithm. For computation workload offloading in a vehicular cloud, the authors in [28] propose a Modified Genetic Algorithm (MGA)-based solution for task scheduling to reduce the response time of the computing task in a cloud system. Zhang et al. [29] proposed a centralized task offloading method considering the changes of vehicle speed and location to minimize task delay.

Aujla et al. propose an SDN-based approach for data offloading in 5G as a centralized solution [30]. The proposed method builds on the Stackelberg-game [31] where the SDN controller uses an Offload Manager and a Priority Manager. The Offload Manager computes the network load and alerts the Priority Manager if the computed load exceeds a certain threshold. The Priority Manager examines the priority of the requesting vehicle and runs a Stackelberg game to determine whether or not to migrate if the requesting vehicle is of low priority.

The authors in [32] propose a greedy approach that aims for minimum total latency between a vehicle and the edge node where vehicles periodically check packet lifetime and request connection setup to the edge node which is responsible for resource allocation and connection establishment for the requesting vehicles.

In [33], the authors propose a new distributed approach for CAVs that uses deep learning-based prediction of the uplink resource allocation process in 5G. The proposed scheme allows the base station to allocate the necessary resources by predicting vehicle maneuvers without scheduling the demands. The authors in [34] propose a data offloading solution between the vehicles and Road Side Units (RSUs). Vehicles need to transmit data such as traffic conditions, accident data, or emergency health data to the RSUs as quickly as possible. Depending on the priority of the data held in the vehicle, and considering the Quality of Service (QoS) requirements, the RSU makes a schedule to offload data of the vehicles that are in its transmission range. In [35], two game-theoretical-based offloading approaches are proposed: auction game-based offloading (AGO) and congestion game-based offloading (CGO). The proposed methods use a Markov chain for potential offloading decision-making.

2.3. Selected Vehicle Based Data Offloading

In this subsection, we provide a summary of existing studies related to offloading strategies in selecting vehicle-based offloading, which selected vehicles act as a relay node.

It is possible to increase network capacity by utilizing the resources of selected vehicles according to specific criteria [36] - [39]. In [37], vehicles act as cloud cars, where they cache popular content, and when neighboring vehicles request the cached data, those requests are directly fulfilled through V2V communication. gNodeB's determine which content to cache, and a portion of the requests is stored on all vehicles for a certain period of time. The solution has been formulated as an optimization problem and attempts to find a solution by minimizing the number of accesses to gNodeB's.

Stanica et al. [38], introduce three heuristic offloading strategies for floating car data such that every vehicle transmits the generated sensor data to a selected neighboring vehicle. The selected vehicle aggregated the data collected from all vehicles and forward it to the gNodeB (BS). The primary determinant for selecting the vehicle, in all three algorithms, is the count of neighbors within one-hop distance. Performance of the algorithm is compared against centralized heuristic models in [40], and distributed solutions provide better performance results. Pierpaolo at al. [39], propose a cluster-based offloading approach. A cluster head (CH) is chosen to relay the collected messages to the access node. The CH selection relies on two factors: 1) the proximity of neighboring vehicles. 2) whether the message has been previously transmitted by another vehicle. Using these criteria, the CH is elected within the one-hop neighborhood. The CH gathers vehicle data through a one-hop V2V communication link and then forwards the aggregated data to the access node via V2I communication link. A Traffic Differentiated Clustering Routing (TDCR) method using non-linear programming for Software Defined

Networking (SDN) is proposed by [41]. The proposed clustering method is centralized and operates within a one-hop distance, aiming to transmit data through the CH to the access nodes. In article [42], the authors propose the Movement- and Fairness-Aware Heuristic (MFAH) algorithm for the transmission of sensor data from vehicles to the gNodeB using vehicle cluster relays (VCRs). This algorithm suggests two channel allocation schemes, Exclusive Channel Allocation (ECA) and Compatible Channel Allocation (CCA), that take into account sensor fairness and transmission rates as key parameters. ECA focuses on resource allocation between the CH and the infrastructure (vehicle-to-infrastructure), while CCA is focuses on resource allocation between the CH and relay vehicles (V2V).

In [43], a centralized controller is employed, and some vehicles are selected as seed vehicles for downloading data from the gNodeB (BS) and subsequently distributing it among other vehicles through opportunistic communications. The data demands of the seed vehicles and their neighbors are forwarded to the controller via the BS. The controller employs these requests to compute a content utility value for each vehicle, taking into account the interests of neighboring vehicles. The content utility value for each vehicle is determined based on the data interest rates of the vehicle's neighbors. Subsequently, the vehicle with the highest content utility value is chosen as the seed vehicle. To assess the efficacy of the algorithm, the content utility rate is used as the primary performance metric. The hybrid relay node selection scheme proposed by [44] aims at disseminating messages over vehicles by selecting relay nodes. This method proposes a sender-oriented V2V-based solution in a highway area, selecting relay nodes based on inter-node distance to consider link-quality and end-to-end delay parameters.

In [45], the authors proposed a multi-hop relay node selection method for vehicles in non-covered areas to transmit their data to the server, aiming at minimum delay and cost. Cost parameter represents the fee paid by vehicles to route the data, whereas delay indicates the distance to the server where the data will be transmitted. In [46], a relay node selection algorithm, considering channel capacity, link stability, and end-to-end delay parameters, is proposed to ensure the transmission of safety messages from the vehicle involved in an accident to the destination node. The selection of static relay nodes, considering the parameters of maximum offloading ratio and minimum delivery rate, is proposed in [47]. In this method, a greedy algorithm is proposed for the decision of vehicles to either continue holding the data or offload it to a static relay node. Wang et al. [48] propose offloading cellular data traffic by sharing demanded content among nodes, named Traffic Offloading by Social Network Service-Based Opportunistic Sharing in Mobile Social Networks (TOSS). A subset of nodes is created from users requesting the same content, and the request is received through the cellular network. Then, nodes requesting the same content share among themselves by opportunistic sharing (Device-to-device, Wifi etc.).

3. PERFORMANCE EVALUATION OF V2X COMMUNICATIONS AND SERVICES IN CELLULAR NETWORK WITH A REALISTIC SIMULATION ENVIRONMENT

5G technologies will enable the necessary connectivity between people, devices, machines and any object. In addition to existing services, new and smart services will be provided with effective and intelligent solutions to be provided by 5G technologies at every level of the hierarchy, through sensors, edge computing, the Internet and the cloud. In addition to improving data transfer rate, the evolution that comes with 5G will require new and improved types of performance due to the new application use cases and the need for critical communications. Ultra low latency feature will provide real-time interaction between objects and services which is essential for the success of autonomous driving. Similarly, the connected objects will live for months to years with the feature of ultra low power consumption.

Table 3.1 V2X Service requirement defined by 3GPP [5]

Vehicles Platooning	Payload (Bytes)	Tx rate (Message/ Sec)	Max Latency (ms)	Reliability (%)	Data rate (Mbps)
Cooperative driving for vehicle platooning information Exchange - Lower degree automation - Higher degree automation	 300-400 50-1200	 30	 25 10	 90 99.99	 - 80
Reporting needed for platooning	50-1200	2	500		
Advanced Driving					
Cooperative collision avoidance	2000	100	10	99.99	10
Emergency trajectory alignment	2000		3	99.999	30
Cooperative lane change - Lower degree automation - Higher degree automation	 300-400 1200		 25 10	 90 99.99	
Extended Sensors					
Sensor information sharing - Lower degree automation	 1600	 10	 100	 99	 -

- Higher degree automation	-	-	3	99.999	50
Video sharing - Lower degree automation - Higher degree automation			 50 10	 90 99.99	 10 90
Remote Driving					
Information exchange			5	99.999	25

Among the services defined by 3GPP [3] as shown in Table 3.1 and the other standardization organizations, connected vehicles are the most important step taken by using 5G technologies to enable autonomous vehicles to operate at desired performance and autonomy. Vehicle-to-everything (V2X) communications designed in 5G for low latency, reliability and service availability for the Autonomous Vehicles (AV) provides the key communication methods that meet the basic requirements of autonomous driving. Vehicles will receive the information necessary for autonomous driving from the cellular network via V2X communication, while also collecting the sensory information with on-board sensors (e.g. camera, radar, lidar). By applying data fusion, autonomous vehicles will be able to understand the environment and predict the conditions for its autonomous movement on the road.

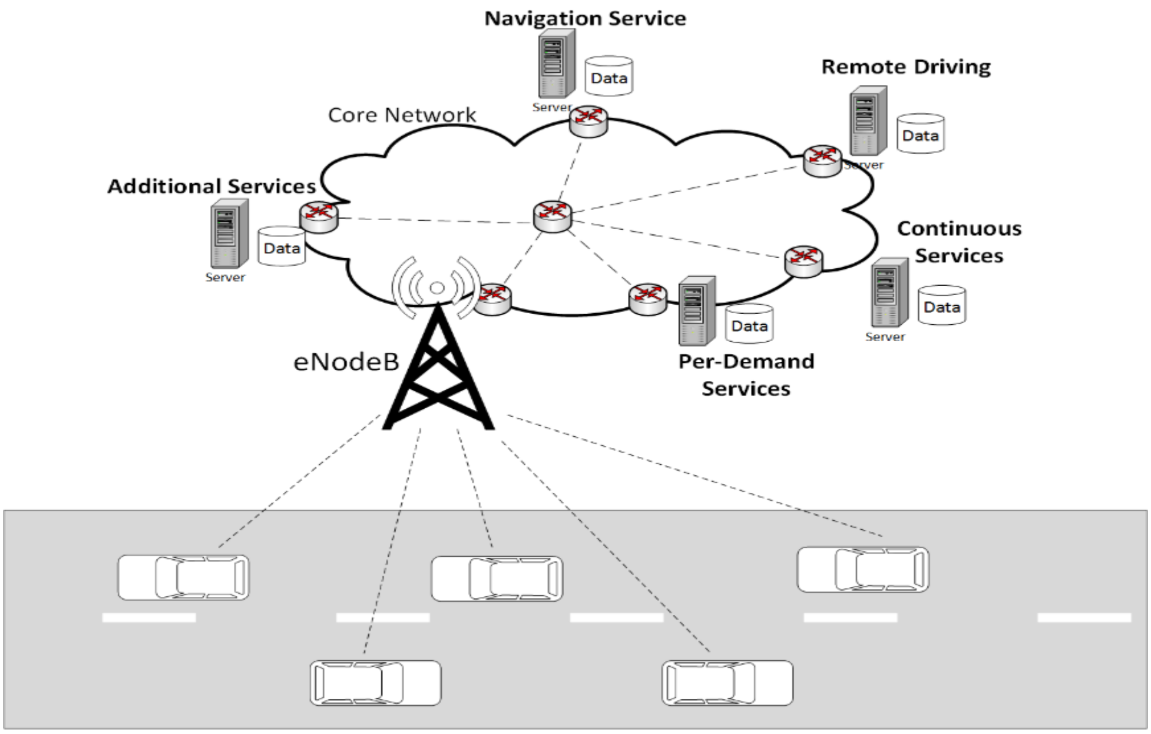


Figure 3.1 V2X Services Demand from the Cellular Network [5]

3GPP recently defined the services be provided to vehicles via V2X communication (remote driving, platooning etc.) as shown in Figure 3.1 and the requirements for these services in the relevant standards [4]. V2X services included to the 5G cellular network and previously defined requirements for LTE network is changed in 5G networks. As shown in Table 3.2, frame structure type and bandwidth size are different in 5G than LTE. In this chapter, we are working towards meeting these requirements with cellular infrastructure. The V2X services provided to the vehicles have different data size, reliability and delay requirements [5]. However, it is challenging to meet these requirements when the topology and the density of the vehicles vary fast due to dynamic mobility of the vehicles [49]. Performance measurement is a crucial task to improve and optimize the efficient use of network resources and the performance of services provided to vehicles, based on the movement patterns and the density of the vehicles.

Table 3.2 LTE vs 5G Physical channels and modulation defined by 3GPP

Specifications	**LTE**	**5G NR**
Full Form	Long Term Evolution	3GPP 5G New Radio
Radio Frame Duration	10 *ms*	10 *ms*
Number of sub-frames in a frame	10	10
Number of slots in a frame	Fixed, 20	Variable, depends on subcarrier spacing
Number of RBs (Resource Blocks)	100 (maximum for 20 MHz)	100 or more
Subcarrier Spacing	Fixed, 15 KHz	Flexible: 2^n*15 KHz (Where, n = -2,0,1,....,5) 15, 30, 60, 120, 240, (480 KHz)
Carrier Bandwidth	1.4/3/5/10/15/20 MHz (For 20 MHz, using carrier aggregation, BW up to 100 MHz can be used)	Variable (From 100 to 200 MHz for less than 6 GHz band, From 100 MHz to 1 GHz for greater than 6 GHz band)

In this chapter, a realistic modeling and simulation environment is built for the performance measurement of V2X communications and 5G networks in order to understand, evaluate and optimize the performance of these services depending on various parameters (e.g. network parameters, vehicle density, vehicle speed etc) or new solutions and approaches to be proposed in various layers of the protocol stack. 5G standards, interfaces, the communication protocol stack and the vehicle movement patterns are realistically implemented in the model. The services provided by the network to vehicles (such as navigation services for autonomous vehicles) are also included. We observe and analyze the performance of the network and the quality of services provided to vehicles considering the varying parameter values in the network.

The rest of chapter is organized as follows. In Section 3.1, preliminary information about V2X are given. The methodology and the developed simulation environment are described in Section 3.2. In Section 3.4, the performance results are given. Finally, Section 3.5 summary of the chapter.

3.1. Preliminary Information About V2X

This section provides an introductory overview of V2X, setting the stage for a deeper understanding of the key concepts and technologies explored throughout the thesis.

3.1.1. Vehicle-to-Everything (V2X) Communication Modes

V2X communication modes are designed to fulfill different communication needs in different scenarios. For example, V2V communication may be preferred for critical communications like emergency alerts, while V2N communication may be more suitable for obtaining general information such as current traffic conditions.

3.1.1.1. Vehicle-to-Vehicle (V2V) Communication

In this communication mode, vehicles communicate directly with each other. V2V communication is utilized for vehicles to perceive other vehicles in their vicinity, gathering information such as their position, speed, direction of movement, and other relevant data. This information can serve various purposes, including issuing hazard warnings to drivers, improving traffic flow, reducing accident risks, and supporting automated driving systems. V2V communication plays a significant role in the automotive industry for enhancing safety and developing driver assistance systems.

3.1.1.2. Vehicle-to-Infrastructure (V2I) Communication

V2I (Vehicle-to-Infrastructure) refers to the communication between vehicles and infrastructure elements such as traffic lights, roadside sensors, and road signs. This mode of communication allows vehicles to exchange various types of information with the surrounding infrastructure. V2I communication enables vehicles to receive information from infrastructure sensors or traffic management systems and adjust their driving behavior accordingly. This communication method is utilized to enhance driving safety, optimize traffic flow, and provide better services to drivers. Additionally, it plays a crucial role in the development and optimization of autonomous driving systems.

3.1.1.3. Vehicle-to-Pedestrian (V2P) Communication

V2P (Vehicle-to-Pedestrian) refers to the communication between vehicles and pedestrians. This communication is designed to allow vehicles to detect, recognize, and potentially alert drivers of pedestrians in their vicinity. V2P communication typically occurs through sensors and cameras installed on vehicles. Vehicles can detect pedestrians, determine their position, speed, and direction of movement. This information can be utilized to send warnings to the driver in case of an approaching danger or to prevent collisions.

3.1.1.4. Vehicle-to-Network (V2N) Communication

In this communication mode, vehicles communicate over cellular networks. This communication mode enables vehicles to send and receive information directly or indirectly to and from infrastructure elements such as base stations, roadside units, or central network servers. V2N communication allows vehicles to connect to the network and access various services or exchange data with other devices on the network. For example, vehicles can receive updates on traffic conditions, weather forecasts, or road status information over the network, or autonomous driving systems can access cloud-based services. This type of communication enhances vehicles' connectivity and intelligence, improving the driving experience and safety.

3.1.2. Communication Protocols and Technologies

Vehicular network technologies encompass specialized communication protocols and technologies designed to facilitate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. In this subsection, we will explore some of the key communication protocols and technologies commonly used in vehicular networks.

3.1.2.1. Dedicated Short-Range Communication (DSRC)

DSRC (Dedicated Short-Range Communication) [6] is an IEEE 802.11p-based WAVE technology specifically designed for use wireless communication between vehicles and infrastructure, particularly designed for vehicular networks. It utilizes WLAN technology to establish short-range communication generally up to 300 m, enabling vehicles to exchange information. Developed by the United States Federal Communications Commission (FCC) over the past two decades, DSRC has become the initial V2X communication standard [7].

In Europe, DSRC is known as the ETSI ITS-G5 [8] standard, tailored to meet the requirements of the European market. Both regions have dedicated the 5.9GHz spectrum band to intelligent transport systems, ensuring that DSRC communication remains unaffected by other devices or communications.

3.1.2.2. Cellular V2X (C-V2X) Communication

C-V2X (Cellular Vehicle-to-Everything) [9] is another vehicular communication protocol developed for V2X that enables vehicles to communicate with each other, with infrastructure, and with other objects. This technology allows for communication between vehicles and from vehicles to infrastructure over cellular communication networks. It can operate over LTE and 5G networks, offering wide coverage, high speeds, and low latency.

C-V2X, as defined by the 3rd Generation Partnership Projects (3GPP) [3], utilizes cellular radio instead of WLAN, essentially employing the same cellular radio technology found in cellphones. What distinguishes C-V2X from DSRC is its ability to facilitate both direct (PC5/sidelink) and indirect (Uu/network) communication methods. In direct C-V2X, vehicles communicate directly with other vehicles (V2V) and roadside units (V2I) similar to how DSRC operates. Conversely, in indirect C-V2X, vehicles communicate with other entities indirectly via the cellular network (V2N), a capability not present in

DSRC. Indirect C-V2X proves advantageous as the cellular network can aggregate data from numerous vehicles, enabling more effective traffic management on a larger scale. Originally designed to operate on the LTE standard in Release 14, 3GPP subsequently introduced compatibility for 5G and 5G NR in Releases 15, 16 and 17 [5][10].

3.1.3. Key Concepts Used in Thesis

In this subsection, we will define the key concepts that are of fundamental importance in the thesis study.

3.1.3.1. Offloading

Offloading is the process of transferring the workload requested by vehicles from one edge node to another. In scenarios of heavy data traffic, the high workload density from an edge node can be reduced by transferring specific vehicle requests to another edge node with lower workload.

3.1.3.2. Reliability/Efficiency

Reliability can be defined as the ability to prevent or minimize data loss in communication, while efficiency denotes the capability to utilize available resources most effectively. These terms are crucial in terms of network performance and communication quality. Reliability is the ability to ensure that data is transmitted reliably between vehicles and infrastructure, reaching the demanded vehicle. Reliability measurements are typically conducted using methods such as field tests and simulations. Reliability can be scaled based on various criteria such as:

- *Transmission Success Rate*: The percentage of transmitted data that successfully reaches the intended receiver. This indicates how much of the transmitted data reaches its intended destination. In our study, we used the successful demand rate performance metric to measure this criterion.
- *Delay*: The time difference between data transmission and reception. A low delay indicates more reliable communication. In our study, we used the turnaround time and waiting time performance metrics to measure these criteria.
- *Error Rate*: The percentage of false packets in the received data. A low error

rate indicates more reliable communication.

Efficiency refers to the optimal utilization of resources in communication and the effective execution of the communication process. It wants achieving the desired communication objectives while minimizing resource consumption and maximizing performance. This involves optimizing factors such as bandwidth usage, transmission speed, energy consumption, and system capacity to ensure that communication is manage in the most effective and resource-efficient manner possible.

3.1.3.3. Fairness

Fairness refers to the equitable distribution of communication resources and services, ensuring that all users in the communication network have equal access and receive services equally. Fairness is an important factor in the management and allocation of resources in the communication network and can affect network performance, user satisfaction, and communication quality. For example, fairness in a V2X network ensures that vehicles and infrastructure have fair access to communication resources and that communication requests are equally addressed, thereby enhancing the experience of all users and improving network efficiency.

3.1.3.4. Realistic Simulation

Realistic simulation refers to the process of simulating communication scenarios and environments that closely mimic real-world conditions. This involves creating simulation models that accurately represent the behavior of vehicles, infrastructure, and other elements within the communication network. Realistic simulations aim to capture various factors such as vehicle movements, environmental conditions, network congestion, and signal propagation characteristics to provide a reliable representation of how V2X systems would perform in actual deployment scenarios.

Realistic simulation enables researchers to evaluate the effectiveness, reliability, and performance of V2X communication technologies in a controlled and repeatable environment before deployment in the real world.

3.2. Methodology and The Framework

Network performance measurement is a major and essentially important task for the efficient use of the resources on the network and to ensure the quality of services provided to users. For 5G networks and V2X communications, it is costly, impractical, time consuming, might be dangerous (unsafe), and sometimes impossible to make performance measurement tests in real world for the proposed solutions on improving the efficient use of the resources etc. On the other hand, modelling and simulation provide more comprehensive demonstration of all possible solutions and cases in large scale and in safe. The effects of the environmental conditions and the varying parameter values, and the impact of the proposed solutions on the performance can be tested and analyzed as well. However, it is very important to build a realistic simulation environment to obtain reliable performance results. Unrealistic experiments will perform unreliable results. Reality must be satisfied not only in the network infrastructure, but also in the modeling of communication protocols, the data traffic patterns and the mobility patterns of the communication devices (vehicles in our case) on a real topological map.

One of our goal is building a realistic simulation environment;

- with realistic network services
- with realistic vehicle movements and traffic patterns
- with realistic data communication/interfacing/signaling at the cellular network
- to get reliable results for observing and analyzing the performance and extracting valuable insights.

Another goal is proposing solutions to improve the performance for a specific problem and use cases under investigation.

3.3. Modules, Simulation & Test Environment

3.3.1. Used Modules in Simulation

The developed simulation environment uses the reliable simulation tools and the reliable modules of the communication protocols which are well known and acknowledged in the literature. Vehicles, vehicle communication modules, 5G access network modules, 5G network components and the related protocols at each component/module are included and integrated in the simulation environment to simulate a complete V2X communication in 5G networks. A simplified illustration is given in Figure 3.2.

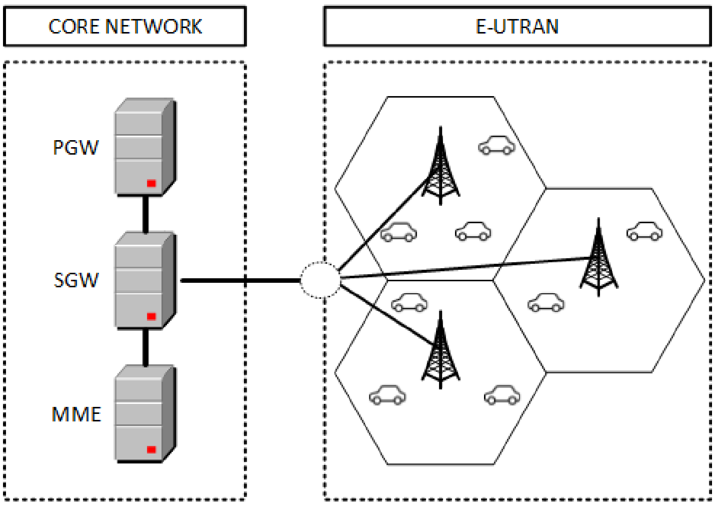


Figure 3.2 LTE Architecture

In our on-going research study, a comprehensive and large-scale model is designed for 5G V2X Communications. In this chapter, we want to underline the capabilities of the early releases of V2X communication support in cellular networks. Therefore, a basic and simplified network architecture and test environment based on the LTE Advanced used for benchmarking purposes. Part of the core network components is given below.

PGW: It is the simplified version of the Packet Data Network (PDN) Gateway (P-GW). PGW is one of the key elements of Evolved Packet Core (EPC) which is the core network architecture of the LTE/LTE Advanced and beyond. This module contains UDP protocol, tunneling protocol for user plane (GTP-U) and traffic flow control modules.

SGW: Serving Gateway (SGW) canalize user traffic in LTE networks, provides movement management and manages data transmission processes, thus ensuring users have an uninterrupted and secure mobile internet experience.

MME: Mobility Management Entity (MME) plays a crucial role in LTE networks by tracking registered user equipment (UEs), managing network access requests, authenticating and authorizing users, selecting SGW and PGW for data sessions, ensuring users are registered with only one MME at a time, and querying the Home Subscriber Server (HSS) for subscriber information.

Binder: This module is the LTE Binder which currently stores a table with the corresponding node ID for each IP address. It is used by the sender to find the identity of the destination node.

MAC Scheduler: This module (Figure 3.3) processes data requests from the UEs and vehicles and allocates the Resource Blocks (RB) to the users for the data traffic.

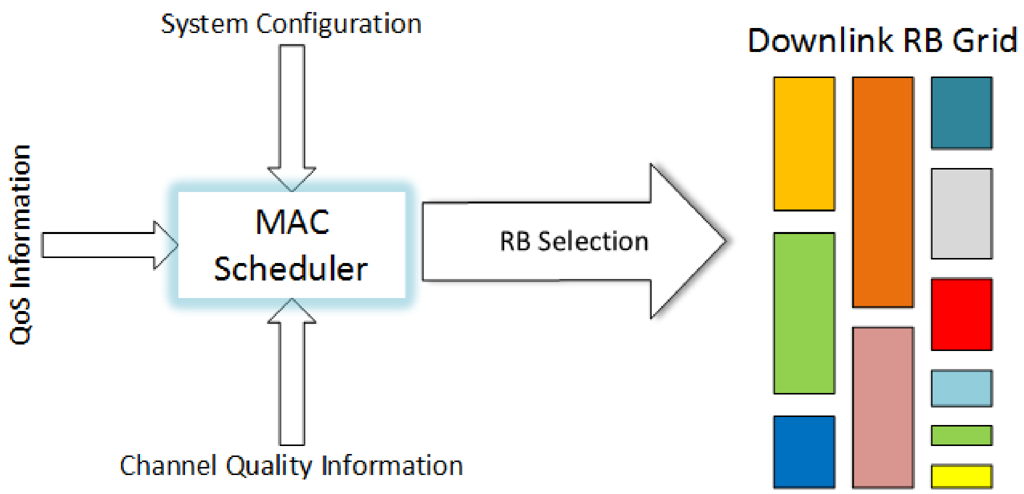


Figure 3.3 MAC Scheduler

3.3.2. Used Simulators

3.3.2.1. OMNeT++

Object-Oriented Modeling and Simulation Environment (OMNeT++) [50] is an open-source event-based network simulator. Written in C++, OMNeT++ features a modular architecture, allowing users to create their own models or extend existing ones. It is used to model, analyze, and simulate the performance and behavior of complex systems, particularly for simulating network protocols and communication systems

3.3.2.2. SUMO

Simulation of Urban Mobility (SUMO) [16] is an open-source road traffic simulator. The adjustment of map scenarios by incorporating new vehicles and their attributes is facilitated through XML files. It is used to simulate traffic flow, vehicle movements, traffic lights, intersections, and other traffic elements. It is particularly utilized for modeling and analyzing urban transportation systems and traffic. SUMO provides users with a platform to test different transportation scenarios and traffic management strategies. Vehicle mobility can be customized individually, allowing for specific configurations to be assigned to each vehicle.

3.3.2.3. Veins

Vehicles in Network Simulation (Veins) [17] is a simulation framework designed for simulating vehicle networks. It is particularly used to model and simulate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Veins is built upon the OMNeT++ simulator and supports wireless communication protocols such as IEEE 802.11p (DSRC).

Features of Veins include:

- Simulation of vehicle movements, traffic flow, and road topologies.
- Simulation of wireless communication channels and protocols.
- Simulation of vehicle interactions and collisions.
- Modeling and testing various V2X applications.

Veins is an important tool for researchers to understand and improve real-world V2X applications' behavior. As shown in the architecture of Veins is illustrated in Figure 3.4, Veins and SUMO can collaborate to perform the simulation of complex traffic scenarios and can be used to analyze the performance of V2X technologies. Additionally, it is used to examine interactions between traffic and communication infrastructure and develop new traffic management strategies.

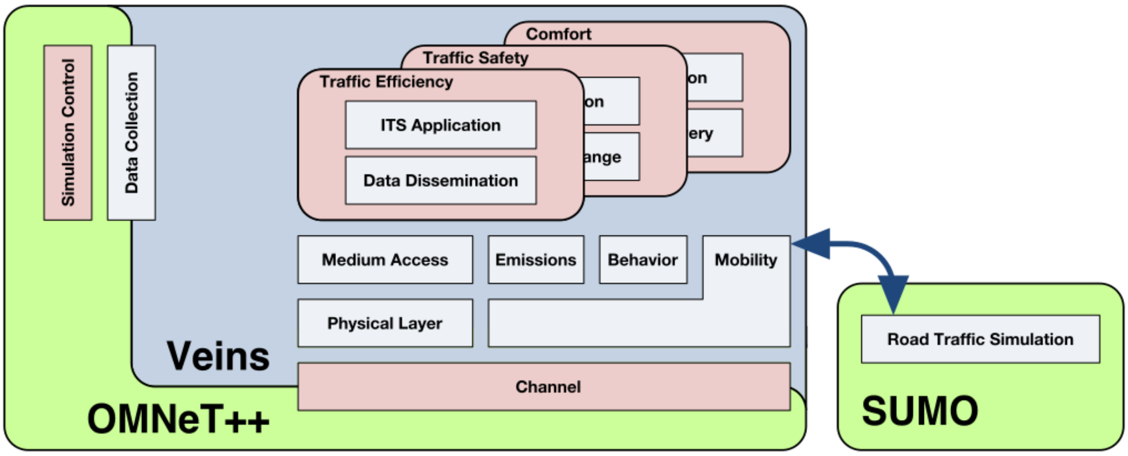


Figure 3.4 Architecture of the Veins Simulator [17]

3.3.3. Simulation & Test Environment

In the simulation environment, we developed services which will be used by the vehicles for their autonomous driving. While the vehicles access some of these services upon request/on-demand, part of the services are provided periodically/continuously e.g. navigation service for remote driving. Service requirements are based on the specifications in [12]. Realistic vehicle mobility patterns are integrated to the simulation environment with the use of SUMO [16].

In the test environment, a single service at the core network is accessed by the vehicles continuously to download the data for navigation. For comparable results and benchmarking, a single access node (eNodeB) is used to scale the network. Main aim is observing the effects of varying vehicle density on the performance of the network and the provided services in terms of Quality of Service. The model under test is shown in Figure 3.5.

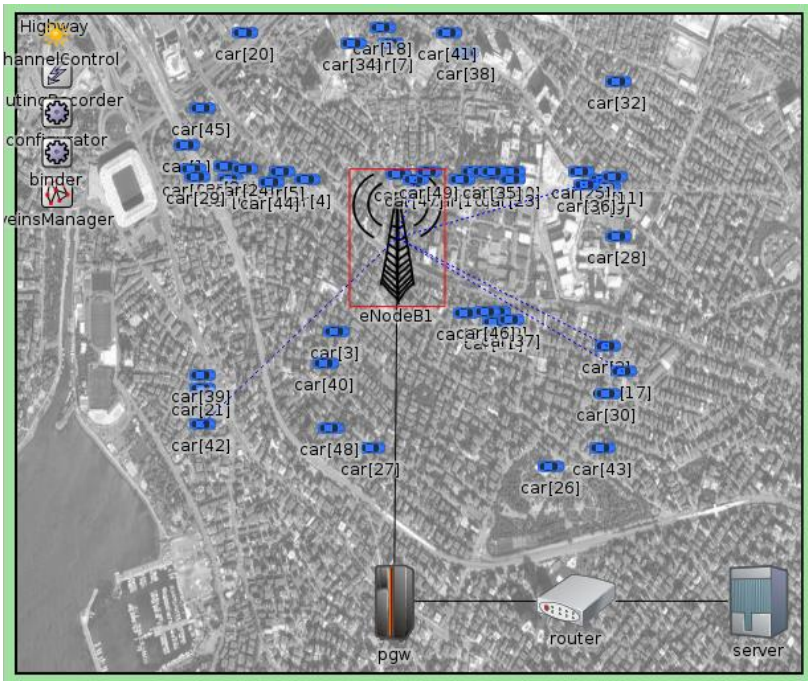


Figure 3.5 Simulation topology

3.4. Performance Metrics and Simulation Results

3.4.1. Used Performance Metrics

- ***Average Number of Service Demands*** indicates how many times, on average, each vehicle requested a service from eNodeB throughout the simulation (see Equation 3.1).

$$\frac{\sum_{i=0}^{|V|} V_i^{Demand}}{|V|} \quad (3.1)$$

- ***Number of Acknowledged Service Demands*** is the total number of service demands requested by vehicles throughout the simulation that successfully reach the eNodeB. Number of acknowledged service demands value is equal to the sum of the number of successful and unsuccessful service demands as shown in Equation 3.2.
- ***Number of Successful/Unsuccessful Service Demands*** refers to the number of service demand requested by vehicles indicating how many of them are fulfilled or not fulfilled by the eNodeB.

$$\sum_{i=0}^{|V|} V_i^{Demand} = \sum_{i=0}^{|V|} V_i^{Demand,successful} + \sum_{i=0}^{|V|} V_i^{Demand,unsuccessful} \quad (3.2)$$

- ***Number of Unsuccessful Packages***, the service demand requested by the vehicles includes more than one package. This metric expresses how many of these packets are not successfully received.
- ***Delay on Service (Turnaround time)*** refers to the duration between the arrival and completion times of a service demand.

3.4.2. Results

We have evaluated the system performance of the defined objectives using the realistic V2X and cellular network simulation environment built and defined in Section 3.2 that consists and integrates OMNeT++ [50], Veins [17] and SUMO [16]. Vehicle traffic is generated with realistic methods using SUMO and incorporated into urban area topology in the simulation environment. Vehicles are initially positioned on the road infrastructure with 2-lanes in each direction and follow mobility pattern defined with vehicle speed generated from Normal Distribution with mean 50 km/h and standard deviation 10 km/h. Vehicles demand the navigation data continuously from the service located in the cellular network. Path loss model with shadowing is also considered. The cellular network allocates the channels (and RBs) to the vehicles in reverse link to download the required data for navigation and remote/autonomous deriving. In the RB allocations, MAX C/I [51] is used as MAC scheduler. Other simulation parameters are listed in Table 3.3. The performance is measured in terms of the quality of service metrics; delay, reliability, and the number of packet drops and is shown in Figure 3.6 – Figure 3.11.

Table 3.3 Simulation Parameters

Parameter	Value
Simulation Area	Urban
Area Size	600x600 m
Number of Vehicles	50, 100, 150, 200, 250, 300, 350, 400
Average Vehicle Speed	50 km/h
Simulation Time	120 s
Carrier Frequency	2 GHz
Radio Frame Duration	10 ms
Number of sub-frames in a frame	10
Number of slots in a frame	20
Number of RBs	6
Subcarrier Spacing	15 KHz
Schedulers	MAX C/I
Vehicle transmit power	26 dBm
eNodeB transmit power	40 dBm
eNodeB/vehicle antenna gain	16 dBi/0 dBi
eNodeB/vehicle noise figure	5 dB/7 dB
Thermal noise power	-104.5 dBm/Hz
Data Size (per demand)	10 Kbyte
Packet Size	1000 Byte

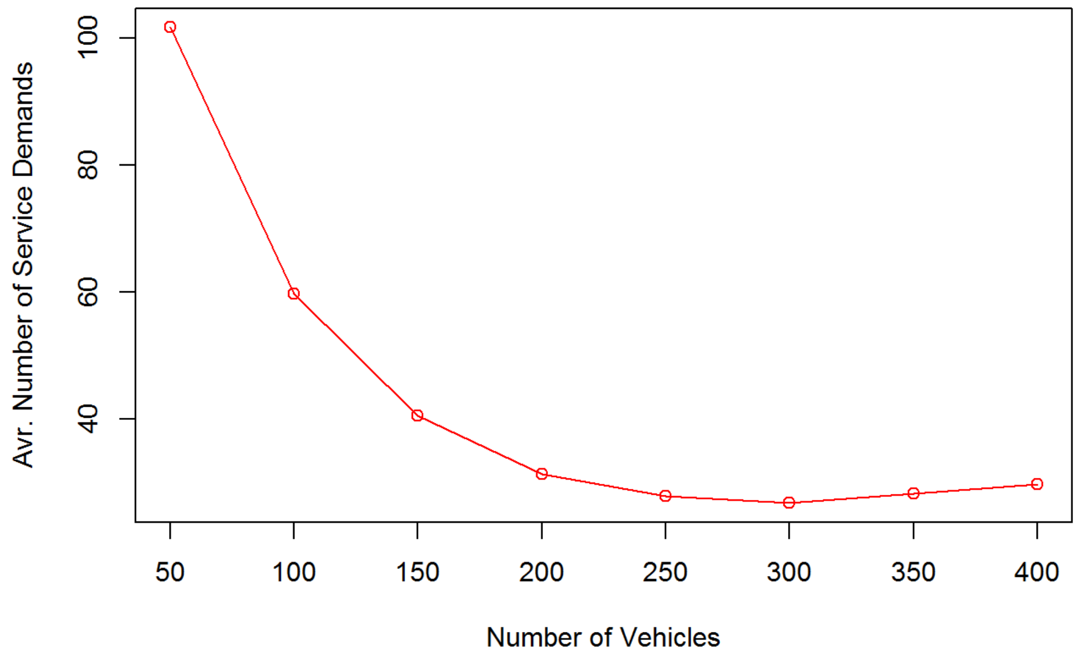


Figure 3.6 Average Number of Service Demands per Vehicle

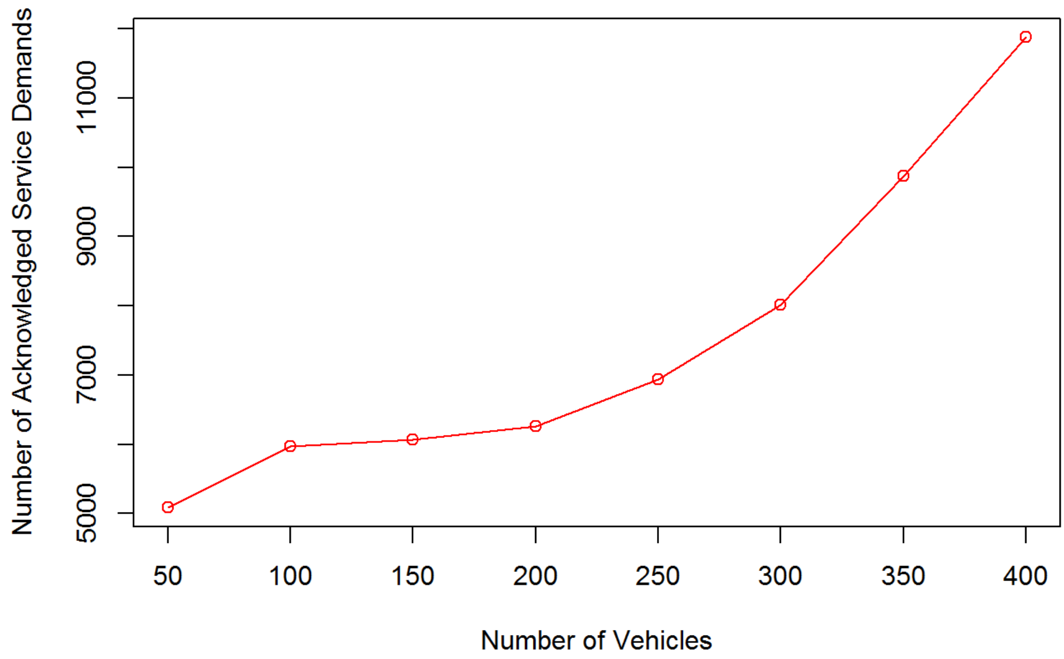


Figure 3.7 Number of Acknowledged Service Demands

Figure 3.6 shows the average service demand per vehicle to access and demand the data service for remote driving. It is seen that as the number of vehicles increases, the demand per vehicle decreases. When the density is low, the network (MAC scheduler) allocates more RBs per demand to use the resource more efficiently and to satisfy the quality of service requirements. As the requested service data is downloaded more quickly, vehicles re-demand the service data for up-to-date information. However, when the vehicle density increases, resources (RBs) becomes limited to satisfy all incoming data requests, and less number of RBs are allocate per demand. This causes the turnaround time increase (will be explained in Figure 3.11) and causes the per-vehicle demand decrease, because less number of demands are completed in the same time interval. It is also seen that when the network density becomes very dense (350 vehicles and more), average demand per vehicle slightly increases. The reason is related to the distance of vehicles to the eNodeB. The scheduling algorithms allocates the RBs based on the channel quality and the QoS in the data traffic. When density is very high (350 vehicles and more), the scheduling algorithms allocates the RBs to the closer vehicles (which also large in number compared to the other density values) and those closer vehicles which completes the requested service data, re-demands immediately.

Figure 3.7 is complementary to the Figure 3.6. Figure 3.7 shows the total demanded requests in the network side. eNodeB receives more service demands as the number of vehicles increases. This is naturally as expected result for a continuous service demand in the whole network.

Figure 3.8 shows the number of unsuccessful service demands on network side. It is also related to the Figure 3.7. As the number of vehicles increases, the number of requests increases as mentioned previously together with Figure 3.7. However, all service demands are not processed successfully. Due to the increase in the vehicle density and increased number of total demands, the network becomes incapable to process and allocate the resources for the demanded services.

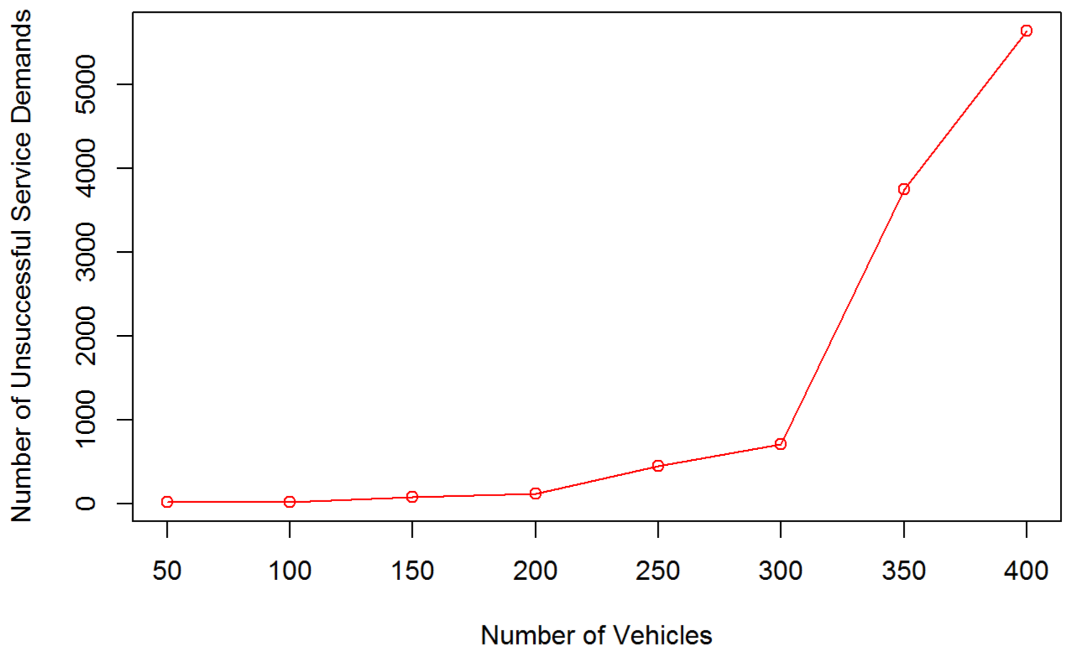


Figure 3.8 Number of Unsuccessful Service Demands

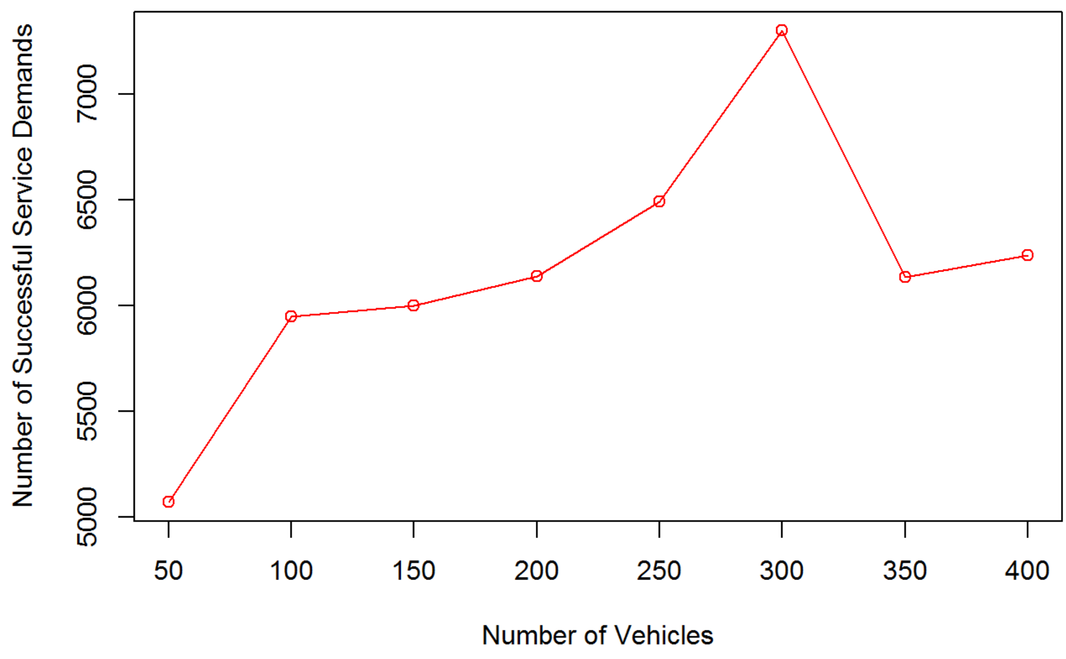


Figure 3.9 Number of Successful Service Demands

Figure 3.9 is complementary to both Figure 3.7 and Figure 3.8. Figure 3.9 shows the number of successful service demands processed and acknowledged at the network side. As the number of vehicle density increases more demands are placed in the network as shown in Figure 3.7. Among these, a large number of them are satisfied by the network and Figure 3.9 present this information. On the other hand, there are some unsuccessful demands which are not satisfied by the network and is shown in Figure 3.8. In Figure 3.9 it is shown that as the density and correspondingly the demands increase, more demands are satisfied by the network. However, when the vehicle density reaches 300 vehicles, successfully services decreases to the limited RBs available. When the vehicle density 350 and 400 compared, it is seen that more demands are satisfied at the density 400 vehicle. The reason is totally related to the reason mentioned in Figure 3.6.

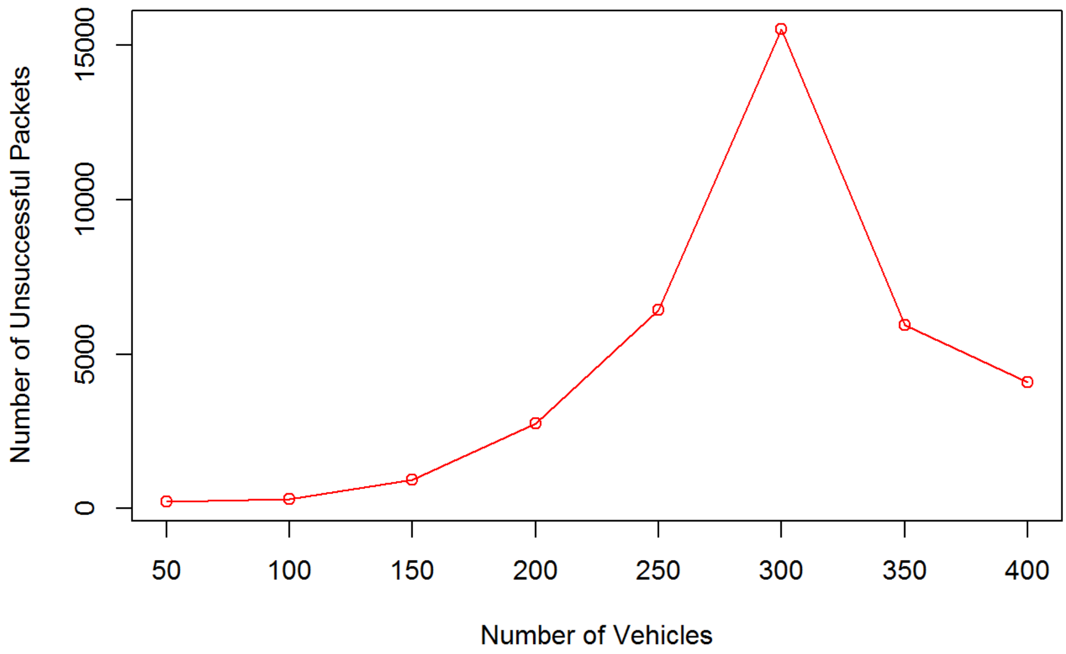


Figure 3.10 Number of Unsuccessful Packages

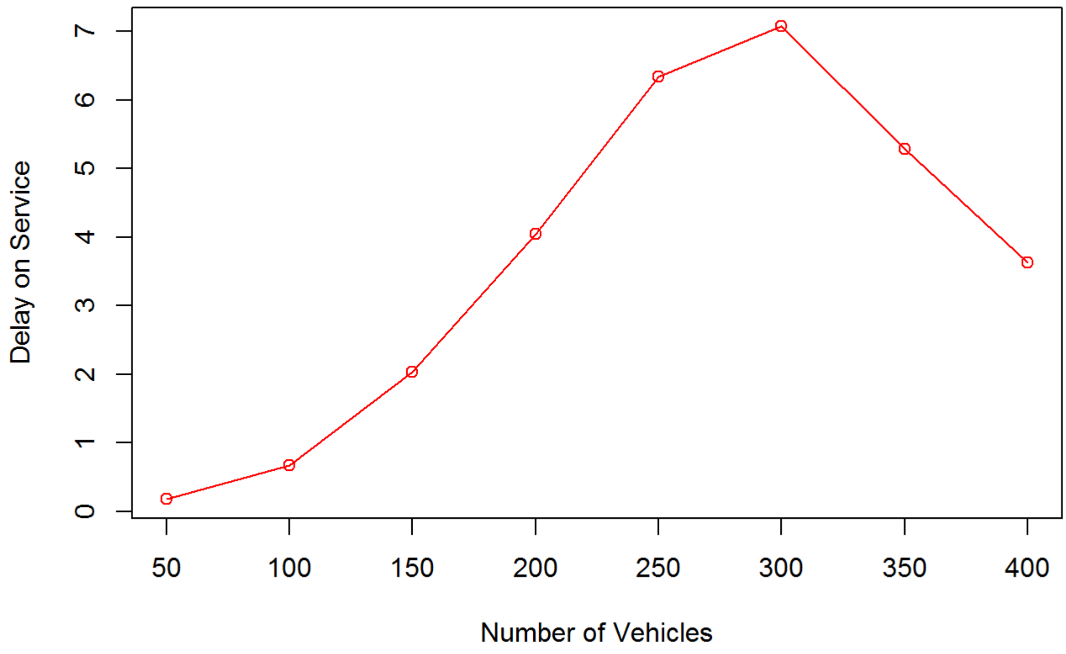


Figure 3.11 Delay on Service - Turnaround time

Figure 3.10 shows the number of data packets which were not sent to the vehicles due to the unavailability of the RBs to be allocated. As the vehicle density increases, more demands are requested. RBs become unavailable to allocate for data transmission in the reverse link. Vehicles fail to receive data for the requested service. Although the service demands are processed and the data transfer is initiated in the network, all data packets were not transmitted successfully due the resource unavailability. Figure 3.10 is also very related to the delay measurement in Figure 3.11.

Figure 3.11 shows the delay on the service. When the vehicles demand the service data, demand is placed to be processed in the network. According to the availability of the resources, service demands and current QoS and channel characteristics, the MAC scheduler assigns the RBs for the processed and acknowledged service demands. However, the scheduler/the network fails to complete all demands in short time due to the increased load in the network. Therefore, the service completion duration increases causing an increased turnaround time. The turnaround delay decreases slightly at vehicle density 350 and more, with the same reason mentioned in Figure 3.6. Because the demands of the closer vehicles are satisfied and completed earlier than others, these vehicles demand more service data. The completion of their service demands reduces the turnaround time when the network density is more than 350 vehicles.

These results mainly show that the network becomes incapable as the vehicle density and the service demands increase. Although some of the services are acknowledged, the service data interrupted due to the unavailability of the RBs. On the other hand, some vehicles which are closer the eNodeB get better service. All these show that there is a need for a better MAC scheduler algorithm which provides fairness, as well as efficiency. The scheduler should consider both the new requests and the remaining data of the acknowledged request for better QoS. The results present the insights for a small scale network with one eNodeB and also for large scale network with more eNodeBs. Demands can be acknowledged based on the vehicle movements and the availability of the resources. The schedulers can assign the RBs to improve the performance by reducing the turnaround time and increasing the number of acknowledged service demands. Data offloading approaches will also be very useful to provide these enhancements without incurring resources additions in the network.

3.5. Summary

In this chapter, the performance of cellular networks services with V2X communications is analyzed using the realistic simulation environment developed for this purpose. The results provide the basics and means in the design of the solution approaches for V2X communication in 5G networks. In V2X communications defined in the LTE Advanced standards, it is seen that the delay and the reliability requirements are not satisfied when the vehicle density and the demands for data increases. Results present insights about the required improvements in the network resource and the allocation mechanisms. It is seen that LTE Advanced poorly satisfies the demands for remote driving services. It is also seen that the MAC scheduler is one key mechanism that have to be improved for V2X communications.

4. FAIR AND EFFICIENT RESOURCE ALLOCATION VIA VEHICLE-EDGE COOPERATION IN 5G-ENABLED V2X NETWORKS

Next generation vehicles are equipped with advanced hardware and software capabilities that aim for driver assistance and autonomous driving. Therefore, network connectivity is an integral asset for connected and autonomous vehicles to mitigate safety risks and incorporate situational awareness[52].

The Society of Automotive Engineers (SAE) has defined six levels of autonomy depending on the vehicles' equipment and autonomous driving capabilities [53]. Advancing from Level 0 to Level 5, the quantity and capabilities of hardware and software in vehicles increase, which ultimately leads to an increase in the amount of data processed by these hardware and software components. Advancing from Level 2 to Level 5 also requires vehicles to communicate with each other and the infrastructure to meet safe driving requirements.

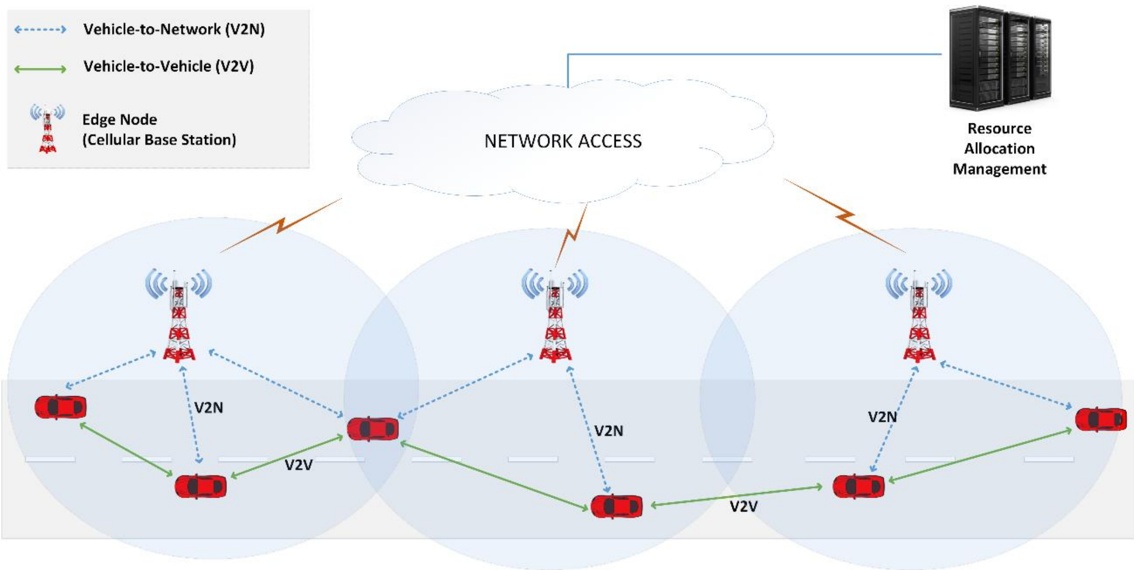


Figure 4.1 A high level illustration of C-V2X communication in 5G network.

The communication method defined for driving safety is V2X (Vehicle to Everything) communication, and the standards of cellular mobile networks are determined by 3GPP [3] and are called Cellular Vehicle to Everything (C-V2X). A minimalist example of C-V2X communication is presented in Figure 4.1. The increase in the number of Connected Autonomous Vehicles (CAVs) [54] also increases the communication load on the mobile network due to the increase in the number of users (mobile and vehicle) connected via the mobile network. Autonomous driving applications further increase this burden due to the need for high-bandwidth data communication [55]. Furthermore, latency and reliability are at the highest priority level of the requirements of autonomous driving. These requirements are highly stringent, and cannot be met by the existing solutions on the current infrastructure [56] [57]. Studies in the literature also point out that the existing LTE/5G mobile network infrastructure fails to meet the 3GPP requirements of such use cases [58].

Movement patterns of CAVs throughout the day lead to specific areas to experience increased vehicle density around certain gNodeBs. This concentration of vehicular presence poses a challenge, as the associated high volume of data demanded by CAVs may exceed the resource capacity limits of the edge nodes. Consequently, spatio-temporal variations in CAV mobility and high-volume data demands pose a challenge for mobile network infrastructure [59]. Addressing the local congestions around specific edge nodes due to vehicle movements requires strategies that deal with consider both the dynamic nature of vehicular traffic and the limitations of edge node resource capacities. As edge computing has emerged as a promising paradigm [60], the deployment of data offloading strategies across edge nodes, with a focus on resource allocation, emerges as a solution to reduce the overload on the networks [61] - [63]. As leveraging edge computing advances the vehicular clouds concept [64] [65], we advocate that intelligent distribution of data traffic demands of vehicles across multiple edge nodes can significantly reduce the load on individual edge nodes. This approach not only ensures a more efficient use of the network's resource capacity but also minimizes latency, a key factor in the responsiveness and reliability of autonomous driving applications.

In this chapter, the causes of these problems are examined, and it is observed that the existing resource allocation methods are not designed to meet these requirements in autonomous vehicles and do not provide fairness. It is essential to use the existing LTE/5G mobile network capacity more efficiently and fairly, taking into account these demands and the requirements defined by 3GPP for CAVs that create variable and large amounts of data transmission demands. In order to meet the requirements [12], resource planning and allocation must be performed in an optimized manner. The optimization method should also consider and respond to workload variations that might occur in the network. A traffic jam or heavily dense region will introduce an increase in user data traffic in that region which may cause an increase in communication delay and even data loss, therefore, this situation must be anticipated and resource assignments must be made in a way to reduce delays and losses. Although there are resource allocation and channel planning solutions in the literature to prevent timeout and delay, these do not prevent possible problems due to user density changes [66] - [69]. In places where vehicle traffic is heavy and network resource capacity is not sufficient, solutions are needed to reduce data transmission intensity by enabling the use of unused resources in the environment. These solutions must meet not only the data transfer requirements but also the low latency and high-reliability requirements of autonomous and safe driving.

In the case of intensive data requests from vehicles, the fair and balanced allocation of resources by the edge nodes is a complex task [70]. Integer Linear Programming (ILP) presents a versatile and adaptive approach to dynamic changes in network architecture. Its applicability thrives on the capability to adjust ILP rules dynamically, ensuring adaptability to evolving conditions. The clarity of ILP formulations makes it an accessible tool, as the rules are easily understandable and interpretable [71]. Moreover, ILP's flexibility extends to accommodating changes in formulations over time, allowing for adjustments to address emerging scenarios [72]. This inherent adaptability positions ILP as a robust and effective method, particularly in dynamic environments where network conditions and requirements fluctuate. ILP serves as a powerful tool for achieving optimal solutions by considering integer constraints, ensuring accuracy and precision in scenarios where simpler approaches might fall short. In instances where a meticulous and exhaustive optimization is paramount, ILP proves its worth by providing a robust and comprehensive methodology for problem-solving. The ILP model aims to address this complexity by optimizing the distribution of intense data requests to edge nodes in a fair manner, subject to specific constraints, thereby providing the opportunity to achieve the best outcome.

This work; (1) sheds light on the challenges of current approaches in addressing the high bandwidth and data transfer requirements essential for autonomous driving, attracting attention to the delays and data losses observed in meeting these crucial needs;

(2) to prevent these problems, offers a solution that uses network resources more effectively and balanced, prevents delays and data losses by load balancing, and also ensures fairness. Furthermore, considering the challenges of C-V2X communication, the proposed solution involves the use of ILP. ILP serves as a mathematical optimization technique for data offloading and resource allocation in C-V2X scenarios. With the integration of ILP, the method aims to contribute to creating a balanced and fair communication infrastructure for C-V2X applications, aiming to optimize data transfer and use of network resources.

The rest of the chapter is organized as follows. Section 4.1 presents the background information followed by the proposed solution. Section 4.2 presents performance metrics, simulation scenario and numerical results. Finally, Section 4.3 summary the chapter.

4.1. Background, Methodology and The Proposed Approach

This section begins with a brief introduction of the frame structure defined by 3GPP to draw the motivation for efficient use of network resources and further performance improvements. This is followed by a detailed presentation of the proposed offloading methodology for C-V2X settings.

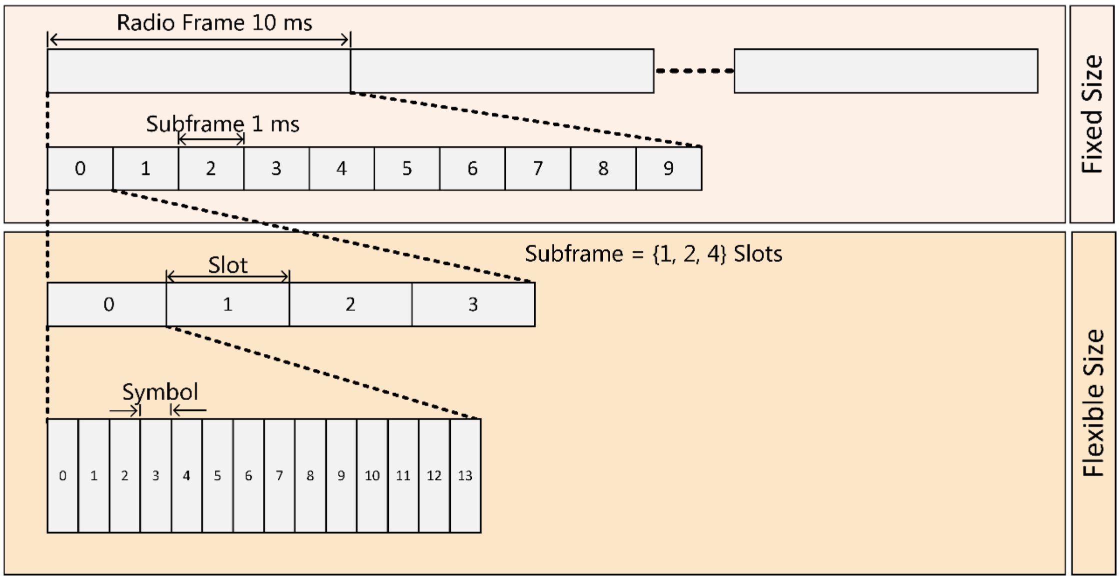


Figure 4.2 5G Frame Structure in 3GPP Rel. 17 [10].

Table 4.1 Notation table

Notation	**Equation**	**Definition**
T_{slot}	4.3, 4.8	time frame (*ms*)
N_{symb}^{slot}	4.4	number of OFDM symbols per slot
$N_{slot}^{subframe,\mu}$	4.2, 4.3	number of slots per subframe
$N_{slot}^{frame,\mu}$	4.3, 4.4	number of slots per frame
$\triangle f$	4.1, 4.5	subcarrier spacing [*kHz*]
μ	4.1, 4.2	subcarrier spacing configuration
M_{RB}	4.4, 4.8	data size of the resource block
B_{RB}	4.5, 4.6	resource block bandwidth
N_{RB}	4.6, 4.8	number of resource blocks
$N_{Channel}$	4.8	number of channels
Q_m	4.4	frame modulation order
N_{SC}^{RB}	4.5	number of subcarriers per resource block
B	4.6, 4.7	channel bandwidth
B_{guard}	4.6	guard interval
C	4.7	channel RB capacity
C_{AN}	4.8, 4.9	edge node data capacity
N_{AN}	4.9	number of edge nodes
C_{System}	4.9, 4.10	total data capacity of the system
$SINR$	4.7	signal to interference plus & noise ratio
α	4.10	ratio of the total RB requests

4.1.1. Background and Communication Settings

According to the frame structure standardized in 3GPP Release-17 [10], a time frame has a duration of 10 *ms* which consists of 10 subframes each having 1 *ms* duration similar to LTE. All notations used in equations are listed in Table 4.1. Each subframe can have 2^{μ} slots where μ denotes the subcarrier spacing configuration that can be identified individually by each base station. Each slot typically consists of 14 OFDM symbols. The frame structure is illustrated in Figure 4.2.

Table 4.2 Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

T_{slot} is a 10 *ms* time frame which is divided into ten equal subframes. Based on the value of μ, number of slots per subframe $\left(N_{slot}^{subframe,\mu}\right)$ is 2^{μ}, and the total number of slots per frame $\left(N_{slot}^{frame,\mu}\right)$ is $10x2^{\mu}$. Table 4.2 presents the values of these parameters under varying values of μ. According to the formula below, the number of resource blocks and the size of the resource block are formulated considering the changing of the μ value. Equations 4.1-4.6 present the formulation of the number of resource blocks and the size of a resource block with respect to the value of μ [10].

$$\triangle f = 2\mu * 15 \tag{4.1}$$

$$N_{slot}^{subframe,\mu} = 2^{\mu},\ \mu \in \{-2,0,1,2,3,4,5\} \quad (4.2)$$

$$N_{slot}^{frame,\mu} = T_{slot} * N_{slot}^{subframe,\mu} \quad (4.3)$$

$$M_{RB} = N_{slot}^{frame,\mu} * N_{symb}^{slot} * Q_m \quad (4.4)$$

$$B_{RB} = \triangle f * N_{SC}^{RB} \quad (4.5)$$

$$N_{RB} = \frac{\left(B - 2 * B_{guard}\right)}{B_{RB}} \quad (4.6)$$

In Equation 4.1, $\triangle$ f is the subcarrier spacing value that stands for the signal space between two subcarriers. In Equation 4.4, M_{RB} is the data size of the resource block and calculated using number of slots per frame $\left(N_{slot}^{frame,\mu}\right)$, number of OFDM symbol per slot $\left(N_{symb}^{slot}\right)$ and OFDM frame modulation (Q_m) symbol size. In Equation 4.5, N_{SC}^{RB} is the number of subcarriers per resource block, set at 12 thus, 15-kHz subcarrier spacing translates into 180 kHz [74]. A resource block bandwidth (B_{RB}) is obtained by using the values of N_{SC}^{RB} and subcarrier spacing value ($\triangle f$) as formulated in Equation 4.5. Guard interval value (B_{guard}) is a short gap that is maintained between transmitted data packets. The number of resource blocks (N_{RB}) is calculated by using the channel bandwidth (B), guard interval of the channel (B_{guard}), and the bandwidth of the one resource block as formulated in Equation 4.6.

Table 4.3 Frame Modulation order (*Qm*)

Modulation	**Symbol Size**
QPSK	2 bits
16-QAM	4 bits
64-QAM	8 bits
256-QAM	16 bits (only 5G)

The channel capacity is calculated by the Shannon capacity formulation [75] as in Equation 4.7. In the formulation, C represents the capacity of the channel in bps, B stands for the bandwidth of the channel and SINR is the theoretical upper bounds of the channel capacity for the signal-to-interference plus noise ratio.

$$\mathrm{C} = \mathrm{B}\log_2(1 + SINR) \tag{4.7}$$

The data capacity of the edge node ($\mathrm{C_{AN}}$) is calculated using the OFDM frame modulation (see Table 4.3) [10] via Equation 4.8.

$$C_{AN} = N_{RB} * M_{RB} * \frac{1}{T_{slot}} * N_{Channel} \tag{4.8}$$

$$C_{System} = \sum_{i=1}^{N_{AN}} C_{AN,i} \tag{4.9}$$

$$\alpha = \frac{DemandedRB}{C_{System}} \tag{4.10}$$

$\mathrm{N_{AN}}$ is the number of edge nodes and $\mathrm{C_{System}}$ is the total data capacity of the edge nodes of the system. As in (4.10), α represents the ratio of the total RB requests to the channel capacity, and the condition of $\alpha \geq 1$ represents an overloaded state for the network.

4.1.2. Proposed Method

We propose a new offloading method for C-V2X networks that ensures both efficient use of resources and fairness in data transmission by load balancing throughout the network. The proposed approach evaluates the vehicular data traffic demands and makes decisions according to the network status and available resources. Taking into account data traffic demands of the vehicles, their connectivity status and the current status of the network resources are analyzed to ensure the use case requirements (defined by 3GPP) and fairness while optimizing the resource allocation with offloading.

As illustrated in Figure 4.3, vehicles forward their data demands to the network edge node they access. Instant data requests at the edge nodes are forwarded to the Resource Allocation Management Unit (RMU) [76] [77]. The RMU assesses the incoming data requests to determine balanced and fair offloading decisions for workload distribution and optimized resource allocation. The output of the decision made by RMU is a map of edge node-vehicle mapping alongside a time interval for vehicular data offloading. This decision is made in light of the current status of the network, vehicular data demands, and the resource availability in the edge nodes. The only exception for opting out load balancing is the situation when the closest edge node can undertake a vehicular data demand. In all other cases, load balancing is performed, which ensures efficient use of the edge node resources. Such behavior is common, especially during rush hours in central districts or downtowns of cities, and data demands of the vehicles must be met without data loss and delay in data transmission. Such a solution is achieved by (1) demand management for the vehicles and resource management for the access points in the region where the vehicles are located, (2) taking into account the connectivity to the edge nodes that are accessible by the vehicles, and (3) taking into account the availability of the resources over time.

The proposed scheme is inspired by the edge enabler architecture defined in 3GPP TS 23.558 v17.4.0 [78]. Thus, a vehicle is considered as a UE equipped with an application client and an edge enabler client that communicates with an edge configuration server as well as edge enabler servers (EES) that reside in the edge data network alongside edge application servers (EAS). According to the specification, EAS communicates with the application client on UEs. An EES is responsible for discovering the EASs, which are analogous to the source and target edge nodes in our design. As the resource management unit determines the offloading decisions and data offloading to the edge nodes, the RMU assumes the responsibility of an EES in the edge enabling architecture in the 3GPP specification.

The RMU allocates network resources such as channel capacity by determining the corresponding network edge node and data transmission times to ensure load balancing. Vehicular data demands are satisfied over time, considering the network specifications, either through the network edge nodes they currently have access to or through neighboring network edge nodes that are within transmission range.

This seemingly simple approach is not easy to implement and requires consideration of many constraints identified in the proposed resource allocation solution. The number of resource blocks of the channel varies depending on the 5G modulation mentioned in Section 4.1.1. Considering the channel capacity, the size of data that the edge node can send and receive should not exceed its capacity. Likewise, since the channel capacity of the vehicles is limited, the total amount of data they can receive must be within the resource block size limit. The data requested by the vehicle is transmitted by the edge node in packets in each timeslot until completed, depending on the assigned RB size. For this complex and time-based approach, we propose a linear programming-based model that takes into account the capacity limits of the channel resource block size.

$$\varphi_{ijd}(t) = \begin{cases} 1, & d_i(t) > 0 \wedge A_{ij}(t) = 1 \wedge i \neq C_j(t) \\ \epsilon, & otherwise \end{cases} \tag{4.11}$$

$$\max \sum_{t=1}^{T} \sum_{j=1}^{|N|} \sum_{i=1}^{|V|} \sum_{d=1}^{|D_i(t)|} x_{ijd}(t) \varphi_{ijd}(t) \tag{4.12}$$

Each edge node *j* maintains a list of closest vehicles over the timeslots such that $C_j(t)$ denotes the closest vehicle to edge node *j* within its communication range at timeslot *t*. As mentioned earlier, data demand from vehicle *i* can be offloaded to either the closest node or a farther node. The parameter, $\varphi_{ijd}(t)$ keeps track of whether the $d - th$ non-zero demand of vehicle *i* ($d_i(t)$) at timeslot *t* is assigned to the closest node or a farther edge node. In the farther edge node case, $\varphi_{ijd}(t)$ takes the value of one whereas in the case of closest node, this parameter leads to a significantly small value (ϵ). The objective is to maximize the size of offloaded data over all time slots as formulated in Equation (4.12), and the output is obtained by solving this linear programming model.

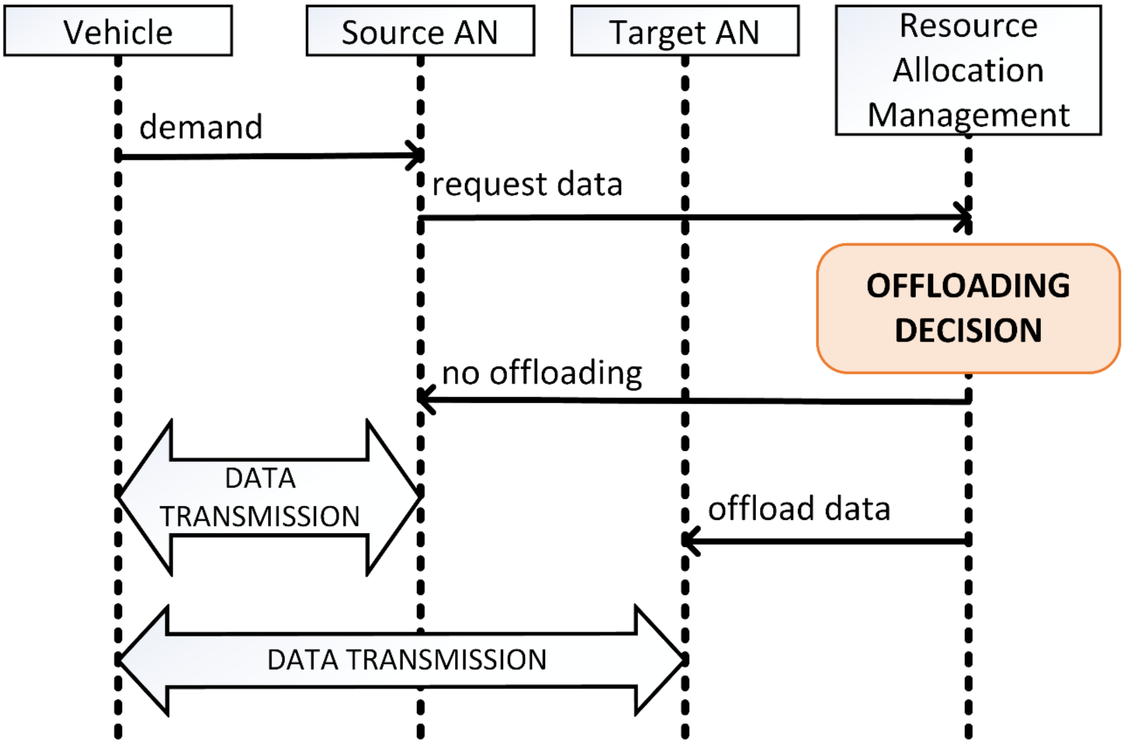


Figure 4.3 Sequence Diagram for Data Offloading Decision.

The constraints we defined in the linear programming method are outlined below.

$$A_{ij}(t) = \begin{cases} 1, & D_{v_i}^{n_j} \leq R_{n_j} \\ 0, & otherwise \end{cases} \quad (4.13)$$

In the equation, $D_{v_i}^{n_j}$ denotes the distance between vehicle *i* and edge node *j* whereas R_{n_j} is the transmission range of edge node *j*. Thus, $A_{ij}(t)$ denotes the availability of the edge node *j* to vehicle *i* at timeslot *t*, and it takes the value of one if vehicle *i* is within the transmission range of node *j* during the timeslot *t*.

$$\sum_{j=1, A_{ij}(t)=1}^{|N|} \sum_{d=1}^{D_i(t)} x_{ijd}(t) \leq RB, \quad \forall i \in \{1,2,, \ldots, |V|\} \quad (4.14)$$

The first constraint is formulated in Equation 4.14, and it ensures that the data volume requested from the available edge nodes by vehicle *i* cannot exceed the length of a channel resource block.

$$\sum_{d=1}^{D_i(t)} x_{ijd}(t) \leq D_i^{size}, \qquad i \in \{1,2,,\dots,|V|\},$$

$$\text{j} \in \{1,2,,\dots,|N|\}, \text{t} \in \{1,2,,\dots,\text{T}\} \tag{4.15}$$

$$\wedge A_{ij}(t) = 1.$$

The second constraint in Equation 4.15 ensures that, during the entire period *T*, the total volume of data assigned to the edge nodes cannot exceed the size of the data ($\mathrm{D_i^{size}}$) demanded by the vehicle *i*.

$$\sum_{i=1}^{|V|} \sum_{d=1}^{D_i(t)} x_{ijd}(t) \leq R\text{B}, \quad j \in \{1,2,\dots,|N|\} \wedge A_{ij}(t) = 1 \tag{4.16}$$

The third constraint in Equation 4.16 ensures that the total data demand of vehicle *i* offloaded to an edge node *j* a timeslot *t* cannot exceed the size of a RB.

4.2. Performance Metrics & Results

In this section, the performance of the proposed solution is evaluated and comprehensively compared to the renowned and state-of-the-art approaches in the literature. We begin with introducing the state-of-the-art solutions that form baselines for our performance evaluation. Then, we proceed with introducing the performance metrics and simulation settings. These are followed by the presentation of our performance evaluation results along with thorough discussions.

4.2.1. State-of-the-art Solutions and Baselines

State-of-the-art algorithms in [79] - [81] form the baselines for our performance evaluations. These algorithms are summarized below:

- **Maximum Carrier-to-Interference (MAX C/I)** is a scheduling algorithm that aims to maximize overall network throughput by considering the current channel conditions. MAX C/I scheduler sorts the requests in descending order considering the SINR of the demands and then performs the assignment based on this order. Therefore, this scheduling approach prioritizes the vehicles closer to the edge node because the signal quality is expected to be better for vehicles closer to the edge node than for vehicles further away from the edge node [51]. Although the overall throughput is maximized by this approach, it may cause fairness and starvation issues for vehicles that are at distant locations with respect to the edge node [82].

- **Round Robin (RR)** aims to distribute channel capacity equally among all users, taking each user into account in a round-robin fashion, thus allocating resources fairly. Since the aim is to ensure fairness and equal channel access rather than effective bandwidth utilization, degradation in the bandwidth utilization can be expected [83].
- **Proportional Fairness (PF)** aims to distribute system resources fairly, while also taking into account the historical channel usage of users to improve system efficiency [84] [85]. This method considers how much system resources have been used for the demands in previous time frames to decide how to allocate resources for each demand in the current time slot [86].
- **First Come-First Served (FCFS)** is a scheduling algorithm that determines the order of resource allocation based on the first-come-first-serve fashion. Demands are served in the order they arrive at the edge node and therefore there is no prioritization between users/requests (other than the time of arrival). FCFS has a disadvantage for latency-sensitive demands, as other demands must wait for the previous demand to complete [87]. Furthermore, FCFS cannot guarantee high throughput and resource efficiency. The only benefit of FCFS is its easy-to-implement nature.

4.2.2. Performance Metrics

The performance of the proposed offloading solution is evaluated by using the commonly used metrics in the literature as explained below:

- **Turnaround Time** is the amount of time between the arrival and completion times of a demand.

- **Wait Time** indicates the duration of time between the time to start processing a demand and its arrival.

- **Successful/Unsuccessful Demand Rate** is used to indicate whether a demand is successfully serviced. A demand is marked as successful only if all data (RBs) associated with that demand are provisioned by the network as unsuccessful. The Successful Demand Rate is the ratio of demands that are successfully completed to all demands.

- **Jain's Fairness Index** indicates how fairly the demands requested by vehicles are assigned to the edge nodes. The Jain's fairness index is defined as formulated in Equation 4.17.

$$\mathcal{J}(u_1, u_2, \ldots, u_n) = \frac{(\sum_{i=1}^{n} u_i)^2}{n.\sum_{i=1}^{n} u_i^2} = \frac{1}{1 + \widehat{c_v}^2} \qquad (4.17)$$

  where $\mathcal{J}$ is the fairness index value for *n* demands, u_i is the size of assigned demand *i*, $\widehat{c_v}$ is the sample coefficient of variation. Jain's fairness index takes its value from the range $(0,1]$. The value of $\mathcal{J}$ is one when all network resources are distributed equally among all demands. On the other hand, a lower value of $\mathcal{J}$ represents a situation where a minority of demands dominate network resources while other demands remain with no resources [88].

- **Starvation Rate** indicates the ratio of starved vehicles to all vehicles. A vehicle is marked as starved when its demand cannot be met within a certain amount of time. It is worth noting that a vehicle's demand is considered to be starved even if it is included in the resource allocation schedule.

- **Offloading Ratio** defines the amount of data transferred from heavily loaded edge nodes to lightly loaded edge nodes. Higher values of offloading ratio indicate better load balancing across the edge nodes.

4.2.3. Simulation Settings

Approaches in the literature generally consider a smooth traffic flow in the applied scenario and perform evaluations by taking into account uniformly distributed vehicle traffic. However, as stated earlier, vehicle density may vary. High vehicle density situations may occur at different times of the day and may also occur at the same time in the same location on days of the week (for example, heavy traffic in the morning, traffic congestion at bridge entrances on the main road, etc.). Algorithms/approaches designed for expected conditions may lead to a performance degradation in the quality of services provided in that region if the local vehicle density reaches unusual levels. Therefore, the following two scenarios are considered to evaluate the performance of the proposed approaches and analyze the effects of the differences 1) vehicle density follows a usually experienced pattern in all regions/road segments 2) certain road segments or intersections experience heavier vehicular traffic than usual. The former creates uniformly distributed vehicle traffic, consistent with scenarios in the literature whereas the latter leads to spatio-temporal variation in the vehicular densities.

Table 4.4 Simulation and C-V2X Communication Parameters

Parameters	**Value**
Time Slot	1000
Number of vehicle	5, 10, 15, 20, 25, 30, 35, 40, 45, 50
Number of demands	125, 250, 375, 500, 625, 750, 875, 1000, 1125, 1200
Number of demands per vehicle	25
Number of Edge Node	4
Road length	2500 m
Transmission Range	500 m
Request frequency	40 ms
Demand size	30-42 RB
Channel Bandwidth	1.4 MHz
Physical Resource Block Size	6 RBs

The scenarios simulated in this work are explained below:

- **Scenario-1 (Benchmark)** is identical to the scenarios in the literature (as mentioned above). Thus, the algorithms are expected to align with the state-of-the-art performance measurements with no necessary improvements. On the other hand, network performance may vary depending on the vehicle density and variations in the demand profiles. This scenario is simulated to form a benchmark to the real-world scenarios.

- **Scenario-2** differs from the 1st Scenario based on spatio-temporal variations of the vehicular density on the road infrastructure / vehicular network, which is a realistic imitation of real-world settings. Depending on time and space, there can be heavy vehicle traffic at some road segments. This phenomenon leads to an imbalance of network resource usage such that the vehicles in heavy traffic may not achieve the throughput they need while the vehicles in sparse traffic might have been allocated abundant resources. The resource imbalance also translates into low fairness among vehicles alongside performance degradation due to dropped demands.

Both scenarios are generated based on the parameters in Table 4.4. According to the 5G frame specification [10], the time to interval value is set at 1 ms. For C-V2X communications, the transmission range is defined as 500 m, and the physical resource block size is determined based on the channel bandwidth, with a size of 6. The simulation environment is created with vehicles submitting periodic data requests with varying demand sizes between 30 and 42 RBs [89] - [91]. Vehicles are placed on the road infrastructure according to pre-defined distribution patterns. While the same number of vehicles are used in both scenarios, vehicular density is varied across sub-regions. Thus, the impact of highly dense presence of vehicles in certain regions on the network performance can be observed. For vehicle mobility, we use the Simulation of Urban Mobility (SUMO) [16] simulator. We simulate a highway area with a 2-lane bidirectional road infrastructure in both directions. Vehicle speeds follow a normal distribution with values ranging between 20-36 m/s where both the road infrastructure and vehicles are introduced to SUMO. Vehicles move with a realistic movement pattern that closely mimics real-world conditions on the road infrastructure. This is implemented by introducing realistic mobility characteristics, including speed, acceleration, maintaining a safe following distance into SUMO. We collect the updated vehicle positions for each time slot in SUMO, and use those positions to introduce vehicle mobility into the proposed model. Resource allocation and meeting the data requirements follow the 5G specifications implemented on the gNodeB's deployed along the road infrastructure.

Both scenarios are identical in terms of the number of vehicles and their data demands so that the impact of varying spatio-temporal vehicular density can be observed in the simulations. In the objective function of proposed method, by choosing a negligibly small and positive ϵ value, demand assignment to the edge node is ensured whenever offloading is not possible. We conduct various tests to determine the ϵ value and observe a significant decrease in the offloading rate for values above 0.5; approximately, a 10% offloading rate was measured. However, as no significant difference in the offloading rate was observed for the values in the range of (0, 0.5], we set ϵ at 0.1. The GUROBI solver is used to solve the linear programming model for the data assignment problem in the proposed method.

4.2.4. Performance Evaluation under Scenario-1

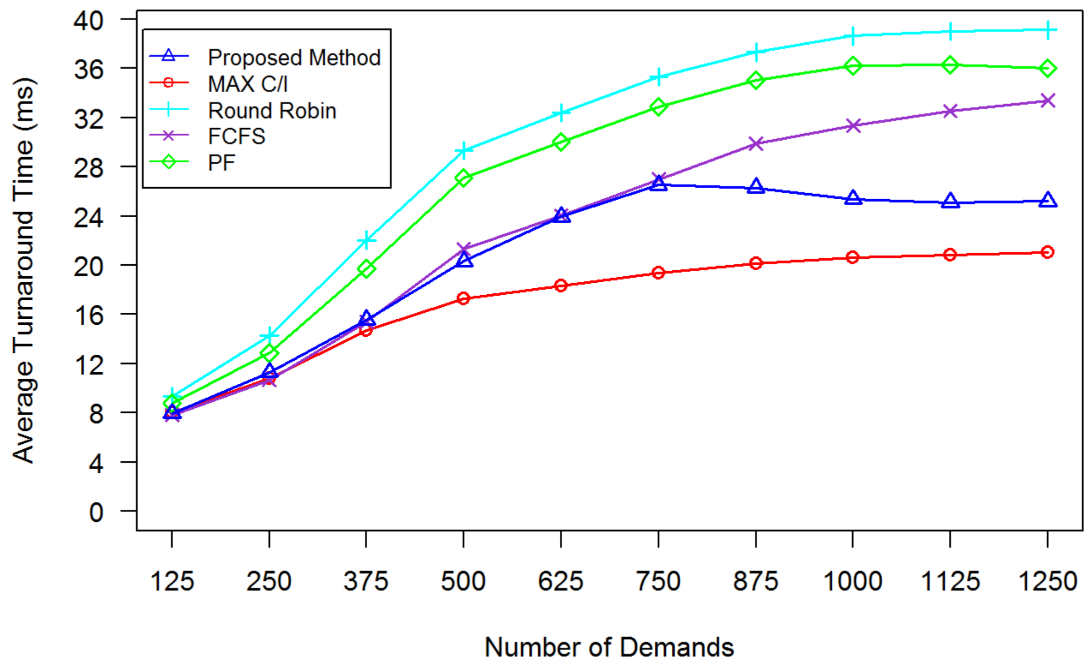


Figure 4.4 Average Turnaround Time versus Number of Demands (Scenario-1).

Figure 4.4 and Figure 4.5 present the average turnaround time per demand and average waiting time per demand under varying number of demands, respectively. In Figure 4.4 and Figure 4.5, MAX C/I exhibits the best performance in terms of turnaround time and wait time, with improvements of 46% and 57% for 1250 demands, respectively, while the Round Robin method gives the worst outcomes. This performance improvement is because of the fact that MAX C/I is designed to optimize these metrics whereas Round Robin, on the contrary, is designed to ensure fairness. Furthermore, our proposed method outperforms all other methods but MAX C/I in terms of waiting and turnaround times. Moreover, under increasing vehicular densities, the gap between our proposed method and the baselines PF and FCFS increases leading to a more favorable outcome under our proposed scheme. The reason why the proposed method cannot outperform MAX C/I in Scenario-1 is that the rationale for the proposed method is to ensure throughput and fairness whereas MAX C/I is designed by considering the overall throughput objective.

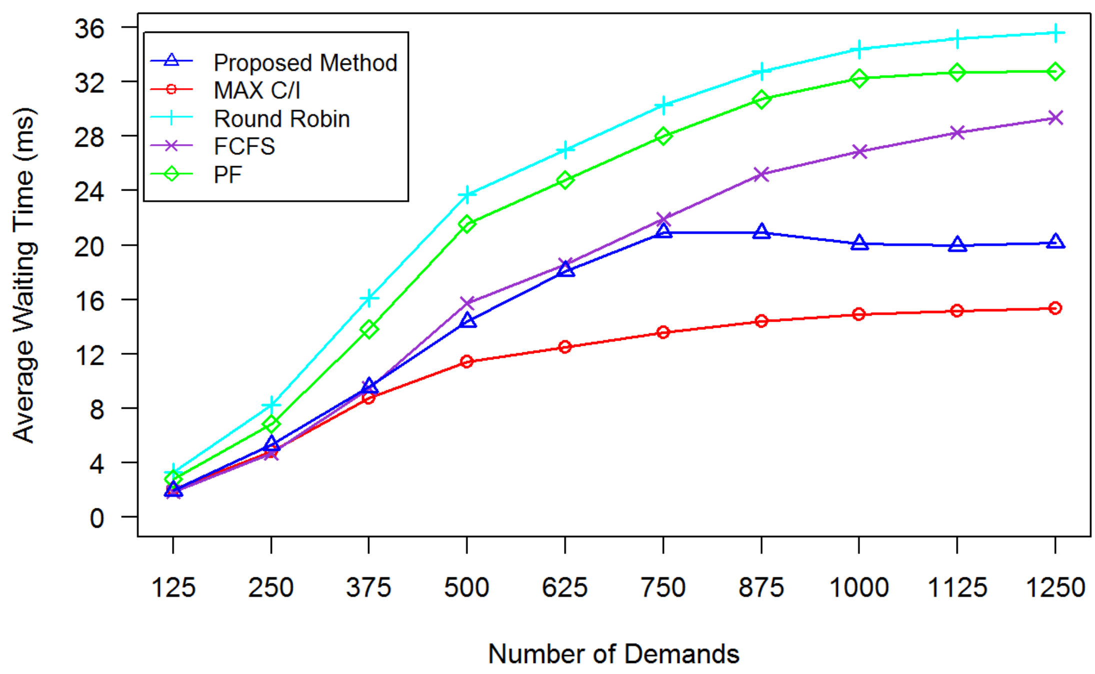


Figure 4.5 Average Waiting Time versus Number of Demands (Scenario-1).

Comparisons in terms of fairness (i.e., Jain's fairness index) fairness are presented in Figure 4.6. Due to its load balancing and capacity optimization via data offloading, the proposed method appears to be superior to its counterparts up to 750 demands. Furthermore, it maintains the same performance improvement over MAX C/I and FCFS for 875 demands and beyond whereas it under-performs in comparison to Round Robin and PF beyond 875 demands due to the design principles of these approaches. The penalty for this good situation, as previously illustrated in Figure 4.4 and Figure 4.5, is observed in the Round Robin and PF methods shown in Figure 4.6 for demand levels exceeding 750. These methods yield the worst results in terms of turnaround time and waiting time performance. Under the proposed method, while no significant changes are experienced in turnaround and wait times beyond 750 demands, Round Robin and PF methods are significantly affected by the increase in the number of demands and tend to prolong wait and turnaround times. This phenomenon shows the compromising nature of our proposed approach for fairness and throughput.

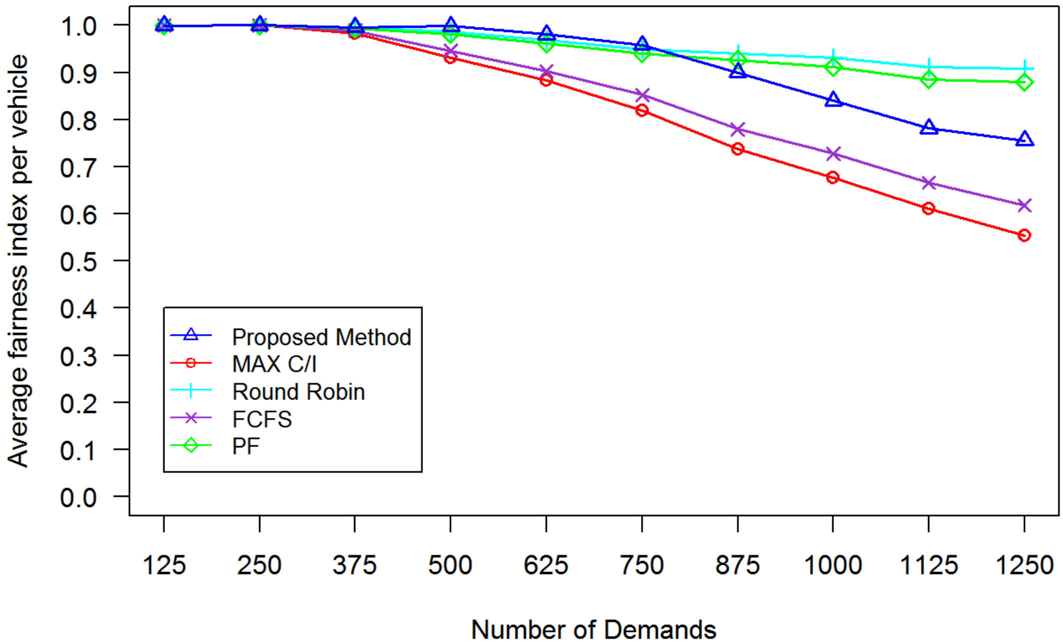
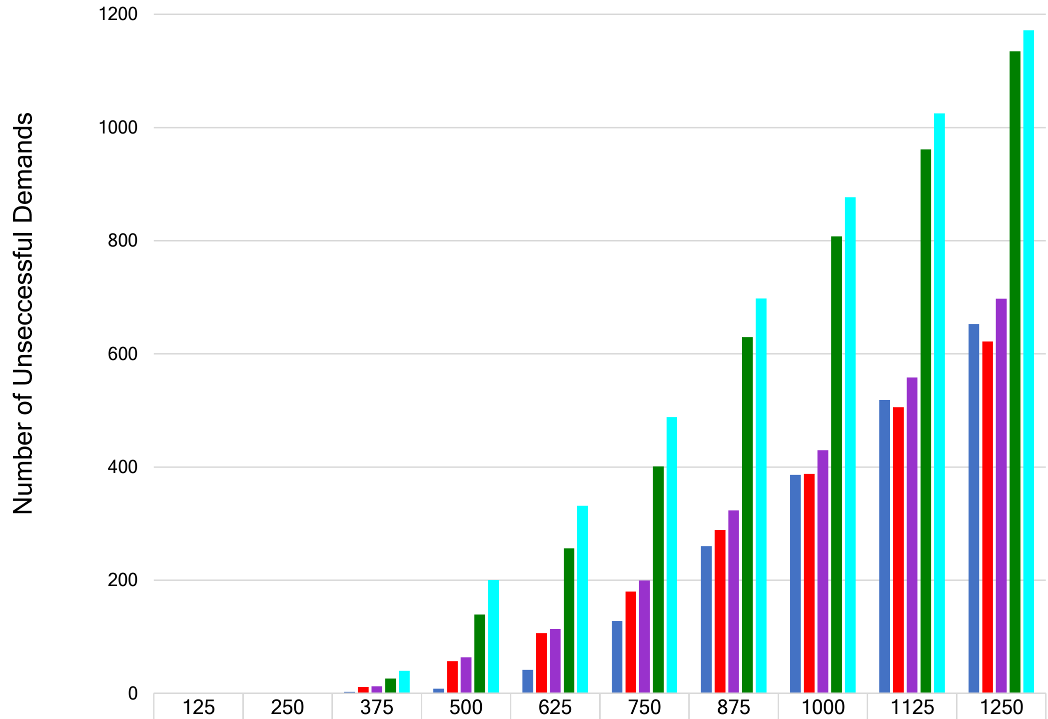


Figure 4.6 Jain's Fairness Index Value for Each Vehicle's Requests (Scenario-1).



	125	250	375	500	625	750	875	1000	1125	1250
Proposed Method	0	0	2,63	8,45	41,55	127,7	260,3	386,25	518,4	652,85
MAX C/I	0	0	11,13	56,95	106,6	180,15	288,75	388	505,6	621,95
FCFS	0	0	12,53	63,75	113,9	199,7	323,55	429,65	558,5	697,65
PF	0	0	26,07	139,5	256,5	401,2	629,7	807,5	961,55	1134,65
RoundRobin	0	0	39,77	200,6	331,75	488,1	697,75	876,9	1025,05	1171,95

Figure 4.7 Number of Unsuccessful Demands versus Number of Demands (Scenario-1).

Figure 4.7 and Figure 4.8 present the number of unsuccessful demands and successful demands rate under varying number of demands, respectively. The proposed method outperforms all of its counterparts until the number of demands reach 1,000, and beyond 1,000 demands (inclusive), performances of the proposed method and MAX C/I coincide. The reason for outperforming its counterparts is that the proposed method builds on the objective to optimize channel resource allocation. The dashed black line in Figure 4.8 represents the maximum achievable ratio based on the network resources i.e., RBs. The decrease in the successful demand rate beyond 750 demands is due to the insufficient resources in the network. As observed in the figure, the proposed method demonstrates the closest performance to the maximum achievable rate.

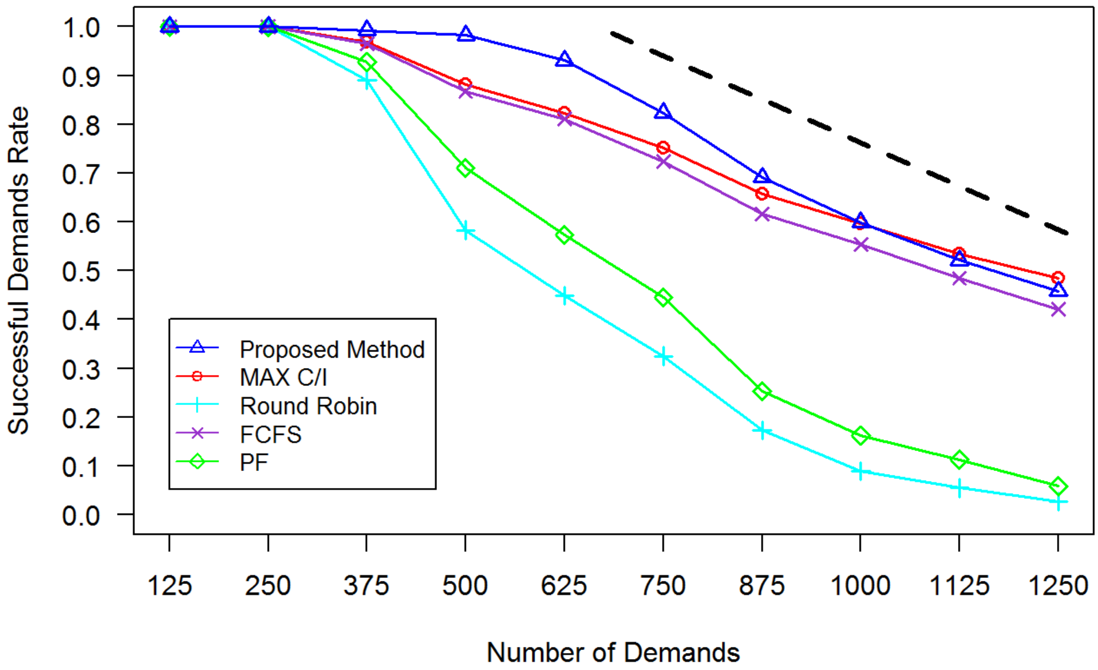
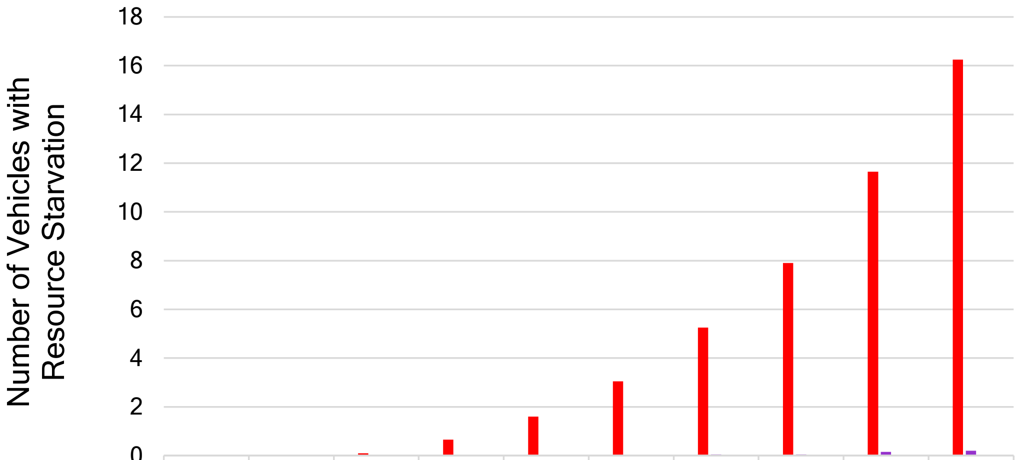


Figure 4.8 Successful Demands Rate versus Number of Demands (Scenario-1).

Table 4.5 presents additional information on the behavior of MAX C/I and the proposed method in terms of the ratio of the responded demands. Even though some demands are not successfully satisfied (not all resources e.g. RBs for the demand are allocated), some of these unsuccessful demands are partially fulfilled such that a fraction of demanded resources (i.e., RBs) are allocated. Table 4.5 presents the overall demands that are partially or completely satisfied. The numerical results suggest that the proposed method is capable of responding to more demands either partially or fully when compared to MAX C/I. It is worth noting that due to insufficient number of RBs, it is possible to have some of the packets of a demand remain undelivered, and in such cases, the demand is marked as unsuccessful.

An important phenomenon is as follows. MAX C/I responds to fewer demands however, the delivery of all packets of those responded demands results in higher successful demand ratio as depicted in Figure 4.8. This behavior can be explained based on the channel assignment policy of MAX C/I since it considers signal quality and the number of RBs required by each demand. Thus, nodes can transmit all packets within the allocated time. On the other hand, such an approach may cause starvation in some nodes which might have weaker signal quality. Figure 4.9 supports this analysis as it can be seen that the demands of some vehicles have not been allocated any RBs leading to resource starvation for those vehicles under the MAX C/I algorithm.



	5	10	15	20	25	30	35	40	45	50
Proposed Method	0	0	0	0	0	0	0	0	0	0
MAX C/I	0	0	0,1	0,65	1,6	3,05	5,25	7,9	11,65	16,25
FCFS	0	0	0	0	0	0	0,05	0,05	0,15	0,2
PF	0	0	0	0	0	0	0	0	0	0
RoundRobin	0	0	0	0	0	0	0	0	0	0

Proposed Method MAX C/I FCFS PF RoundRobin

Number of Vehicles

Figure 4.9 Number of vehicles that experience resource starvation under varying number of vehicles in the network (Scenario-1).

Figure 4.9 presents the starvation results for the compared methods under varying number of vehicles in the network under Scenario-1. It is evident that only the methods that do not consider fairness (MAX C/I and FCFS) lead to resource starvation for some of the vehicles in the network. The greedy approach to maximize the overall throughput in MAX C/I causes serious starvation approximately 32% results as the number of vehicles in the system increase. Although vehicles that experience resource starvation remain under FCFS, the number is significantly lower in comparison to MAX C/I. On the other hand, MAX C/I starts experiencing starvation even though in a small network of a few vehicles. As the network size increases linearly (i.e., linear increase in the number of vehicles in the network), the number of starving vehicles increases exponentially under the MAX C/I method. For the case of 50 vehicles, it can be observed that approximately 32% of the vehicles receive no response concerning RB allocation to meet their demands. FCFS also leads to starvation problems for scenarios with 35 vehicles or more, but these values are negligible. Round Robin, PF, and our proposed method are the only methods that do not cause any starvation for the vehicles in the network. The starvation under the MAX C/I algorithm is due to its preference to allocate resources to closer vehicles to the edge node for the sake of low turnaround and wait times. Furthermore, it is worth to note that MAX C/I demonstrates the poorest fairness performance among all evaluated methods as shown in Figure **4.6**, whereas our proposed method is shown to be beneficial in terms of turnaround time, wait time, and fairness with no resource starvation for the vehicles in the network.

Table 4.5 Percentage of responded demands by MAX C/I and our proposed method under varying number of demands under Scenario-1

Number of Demands	**Responded Demands (MAX C/I) [%]**	**Responded Demands (Proposed Method) [%]**
125	100	100
250	100	100
375	98.47	99.85
500	93.87	99.78
625	89.16	97.35
750	82.89	94.77
875	74.32	86.19
1000	68.69	76.66
1125	61.83	69.76
1250	56.25	64.64

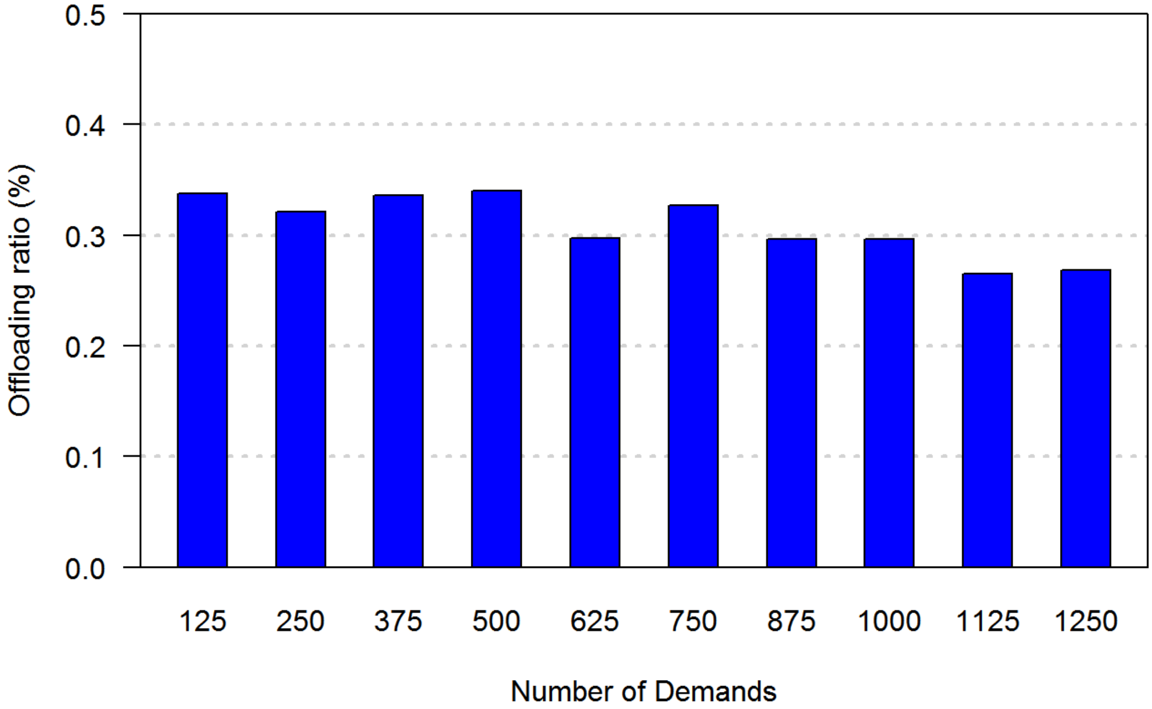


Figure 4.10 Data offloading ratio with varying number of demands under the proposed method. By enabling offloading up to 30% of the demands, the proposed method can improve the turnaround and wait times with no starvation (Scenario-1).

Our proposed method meets more demands not only because it aims to allocate resources more effectively and ensure fairness, but also because it distributes the load using the resources of the neighboring edge node if they are available. Figure 4.10 depicts the data offloading ratio achieved by our proposed method. The results indicate that approximately 30% of the demanded data are offloaded to the edge nodes. Consequently, with the offloading approach, the network is able to use its capacity more effectively and efficiently, leading to the fulfillment of a higher number of vehicle demands. Not to mention the proposed method improves the turnaround and wait time performance with no starvation.

As a result, it is seen that the proposed method outperforms its counterparts in terms of the aforementioned performance metrics, and ensures resource efficiency by leveraging the offloading mechanism. It is worth to note that the actual benefit of the proposed method is more evident under Scenario-2 (see next subsection) where vehicular traffic density is varies spatio-temporally in the network.

4.2.5. Performance Evaluation under Scenario-2

Scenario 2 presents more realistic situations to demonstrate the behavior and performance of the algorithms with variations in the traffic demand and densities of the vehicles in certain regions.

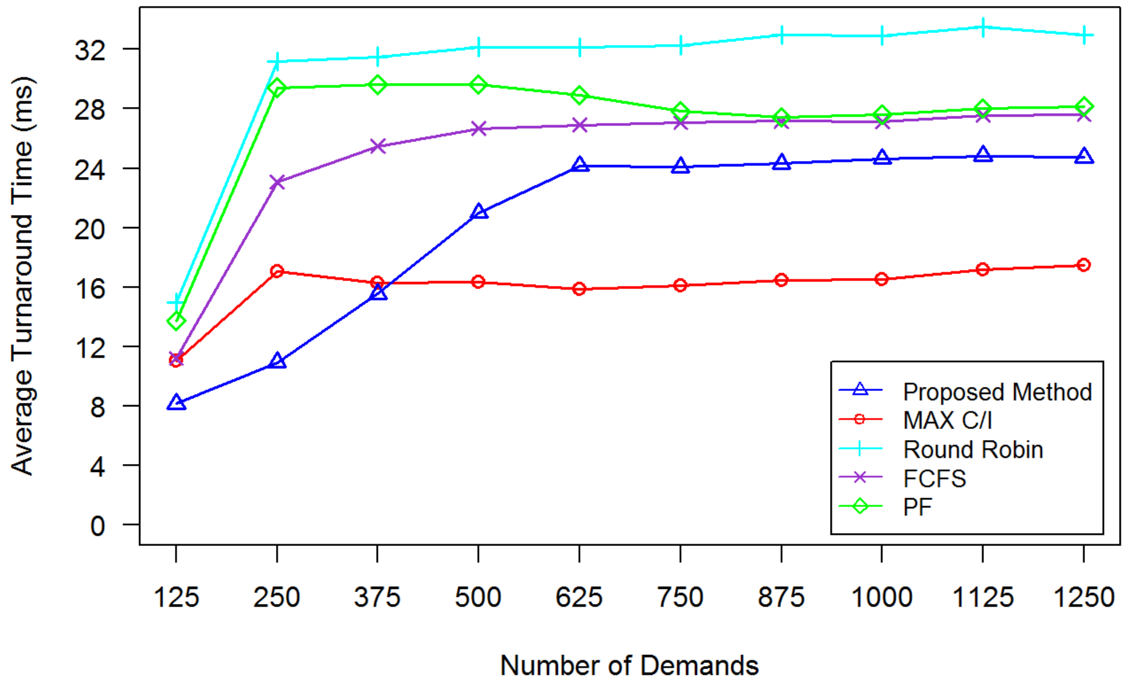


Figure 4.11 Average Turnaround Time versus Number of Demands (Scenario-2).

Figure 4.11 and Figure 4.12 depict the average turnaround time and waiting time performance, respectively. Waiting time and turnaround time have negligibly small values when the number of demands is less than 125 since all edge nodes possess sufficient channel capacity to accommodate the demands requested by the vehicles.

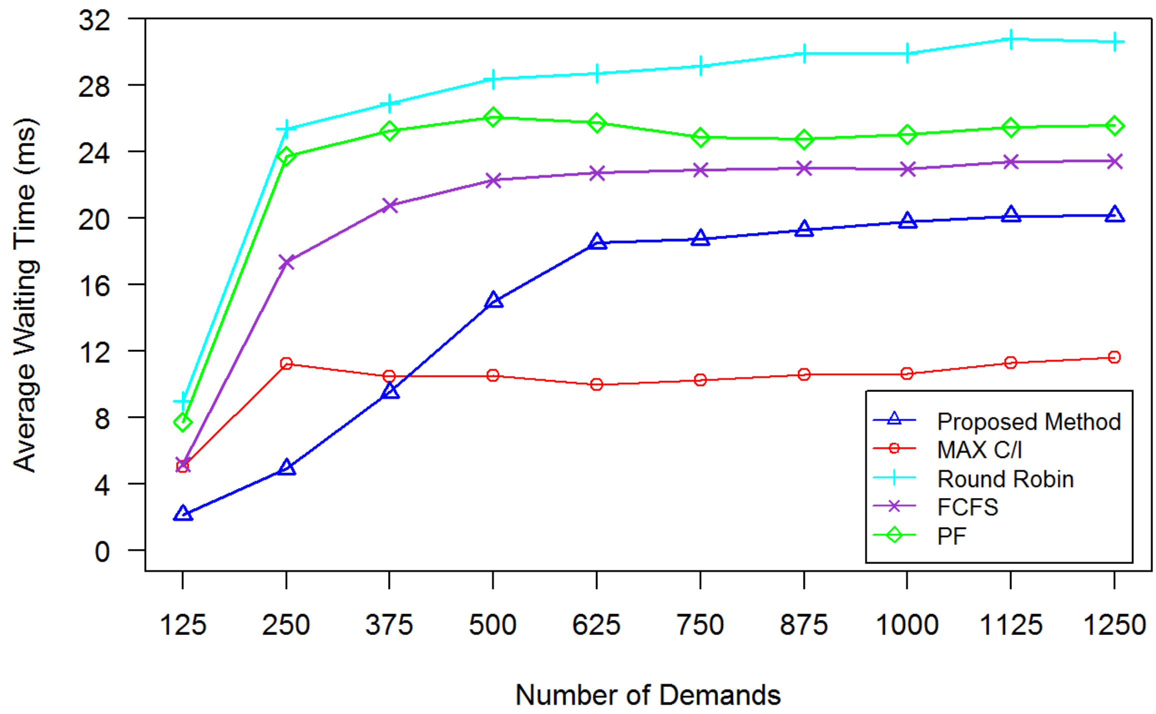
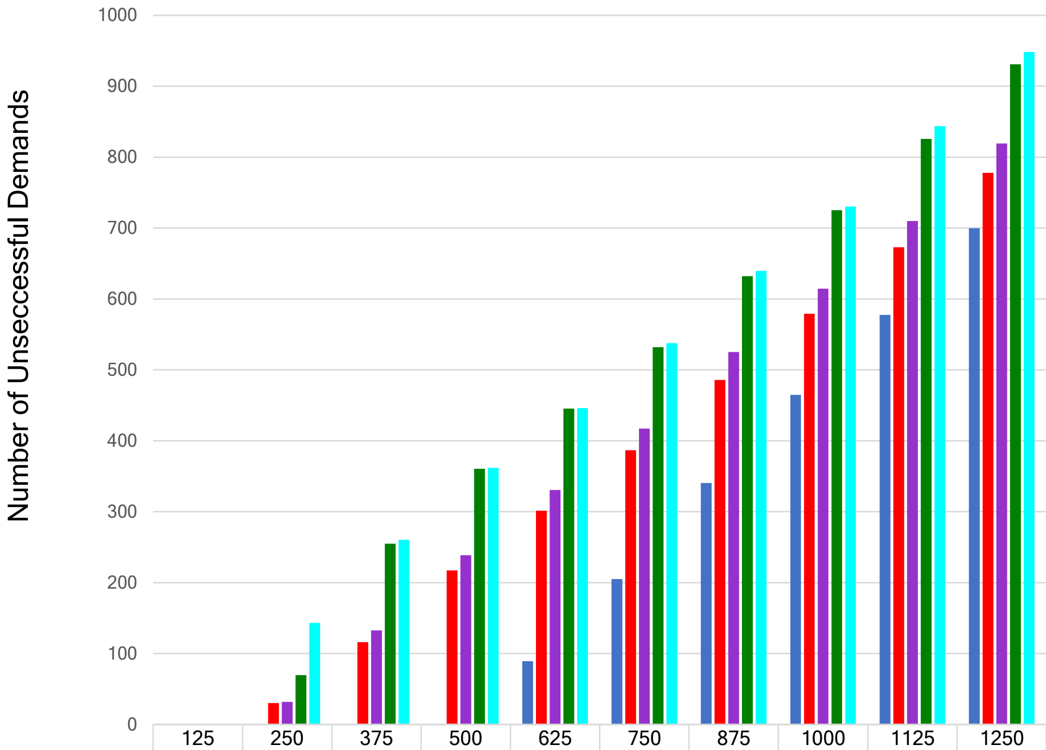


Figure 4.12 Average Waiting Time versus Number of Demands (Scenario-2).

Turnaround and wait times increase with the increasing number of demands. Under 250 demands and beyond, since some of the edge nodes reach their capacity limit, all methods experience higher wait and turnaround times. The proposed method, achieves minimum turnaround and wait times compared to Round Robin, FCFS and PF thanks to its offloading-based provisioning approach. In Figure 4.11 and Figure 4.12, MAX C/I outperforms the other methods in terms of the average waiting and turnaround times as the number of demands go beyond 375. The reason of this phenomenon can be explained by interpreting the results concerning the ratio of the successfully responded demands under these schemes. As observed in Figure 4.14, only the proposed method can respond to all demands successfully under 500 demands and beyond. Thus, the reason of lower wait and turnaround times under MAX C/I is due to the presence of demands that are not successfully responded and its tendency to allocate channels to the vehicles with the best channel conditions, i.e., those located in closer positions to the edge node. A similar phenomenon is observed under Round Robin, PF and FCFS when the demand count goes beyond 250 as these schemes are unable to respond to all demands beyond this point. It is worth noting that these three baselines under-perform in comparison to the proposed method and MAX C/I in terms of turnaround and wait times under this load. Since a limited number of demands are successfully responded by all methods except the proposed method, the turnaround time and waiting time for other methods reach an average value for 250 demands and do not vary significantly as the number of demands increase beyond 250. This situation is observed in our proposed method only after the number of demands exceeds 625. Our proposed method is able to offload the arriving demands to neighboring edge nodes and, therefore can respond to all demands up to 625. Beyond this point, the average turnaround time and waiting time remain stable.



	125	250	375	500	625	750	875	1000	1125	1250
Proposed Method	0	0	0	0	89,3	205	340,4	464,7	577,35	699,75
MAX C/I	0	30,05	115,95	217,15	301,35	386,65	485,95	579,25	672,75	778
FCFS	0	31,85	132,7	238,4	330,65	417,05	525,15	614,45	709,9	819,14
PF	0	69,35	254,85	360,5	445,35	532,1	632,2	725,1	825,7	931,11
RoundRobin	0	143,05	260,35	361,8	445,95	537,75	639,7	730,45	843,8	948,43

Proposed Method MAX C/I FCFS PF RoundRobin

Number of Demands

Figure 4.13 Number of Unsuccessful Demands versus Number of Demands (Scenario-2).

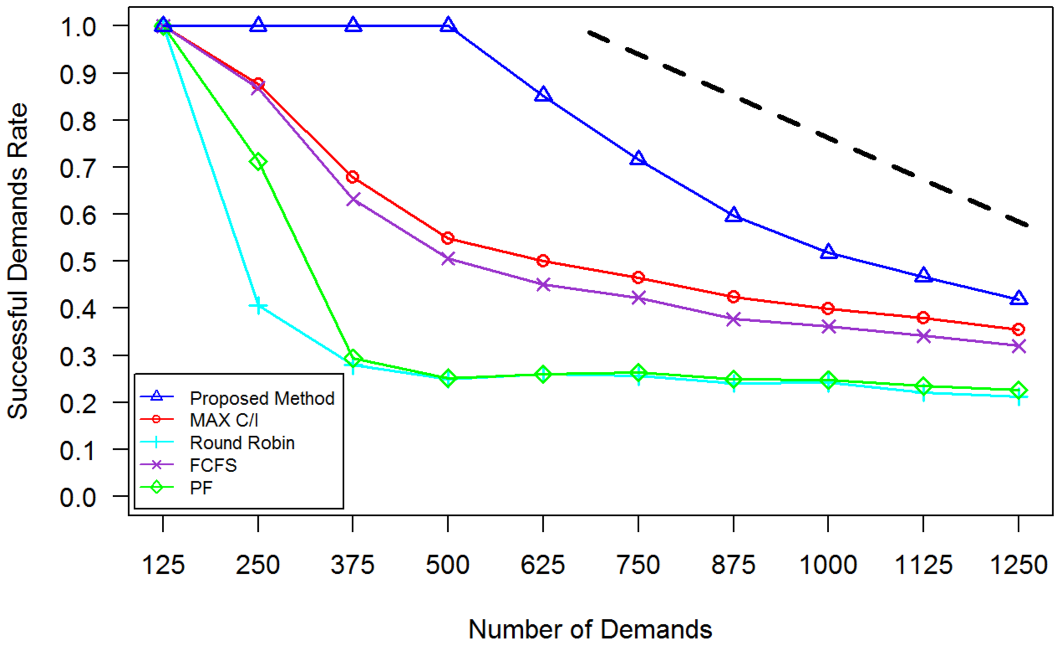


Figure 4.14 Successful Demands Rate versus Number of Demands (Scenario-2).

Table 4.6 Percentage of responded demands by MAX C/I and our proposed method under varying number of demands under Scenario-2

Number of Demands	Responded Demands (MAX C/I) [%]	Responded Demands (Proposed Method) [%]
125	100	100
250	97.22	100
375	74.64	100
500	60.11	100
625	54.16	97.08
750	50.23	90.46
875	45.55	83.44
1000	42.66	77.96
1125	40.18	73.76
1250	38.05	68.41

In support of our analyses regarding the turnaround and wait times, Figure 4.13 and Figure 4.14 present performance results related to the successful and unsuccessful demands. Unsuccessful demands for all methods (except our proposed method) start at 250 demands while unsuccessful demands for our proposed method start under 625 demands in Figure 4.14, and all methods except our proposed method respond to demands successfully only for 250 demands while our proposed method respond all demands up to 625.

As seen in Figure 4.13 and Figure 4.14, when the number of demands is 250 or above, the existing channel capacity is completely utilized by all other methods and these methods cannot respond to more demands. In contrast, our proposed method effectively utilizes the capacity of the system for up to 625 demands by offloading the load and sharing it with neighboring edge nodes. Overall, our proposed method demonstrates the best results with a minimum number of unsuccessful demands and a maximum rate of successful demands with an improvement around 38%. Table 4.6 supports these results as it presents the demands that are completely or partially responded by MAX C/I and our proposed method. It is seen that the proposed method responds successfully to almost all demands when the system capacity is sufficient. Under 625 demands and beyond, the responded demands ratio decreases slightly whereas the proposed approach successfully responds all demands when the number of demands is 500, however, MAX C/I responds only 60% including the completed and incomplete responds

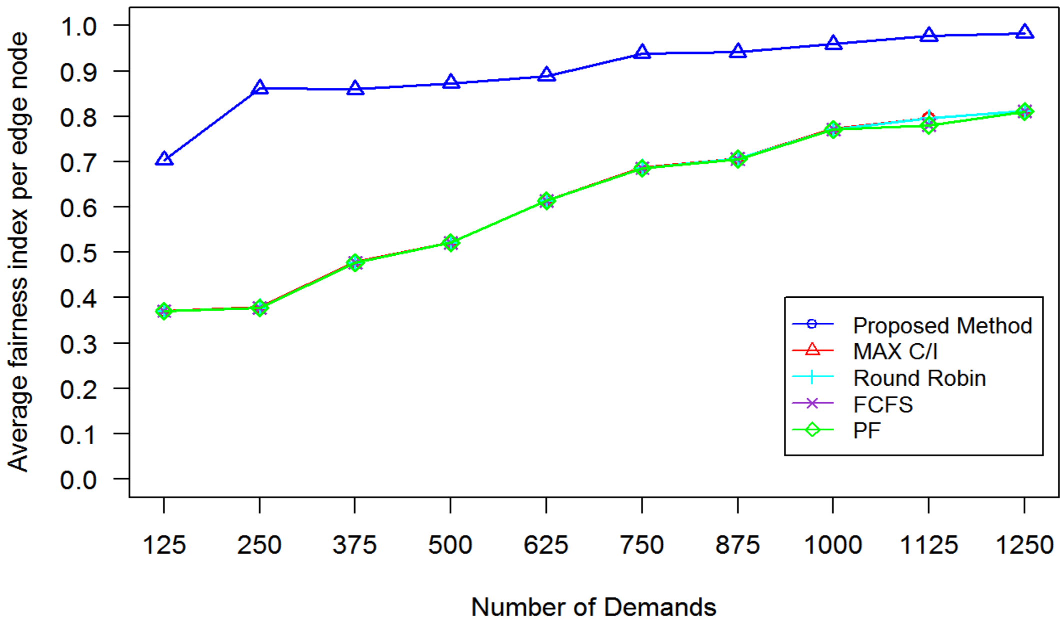


Figure 4.15 Jain's Fairness Index Value for Edge Nodes (Scenario-2).

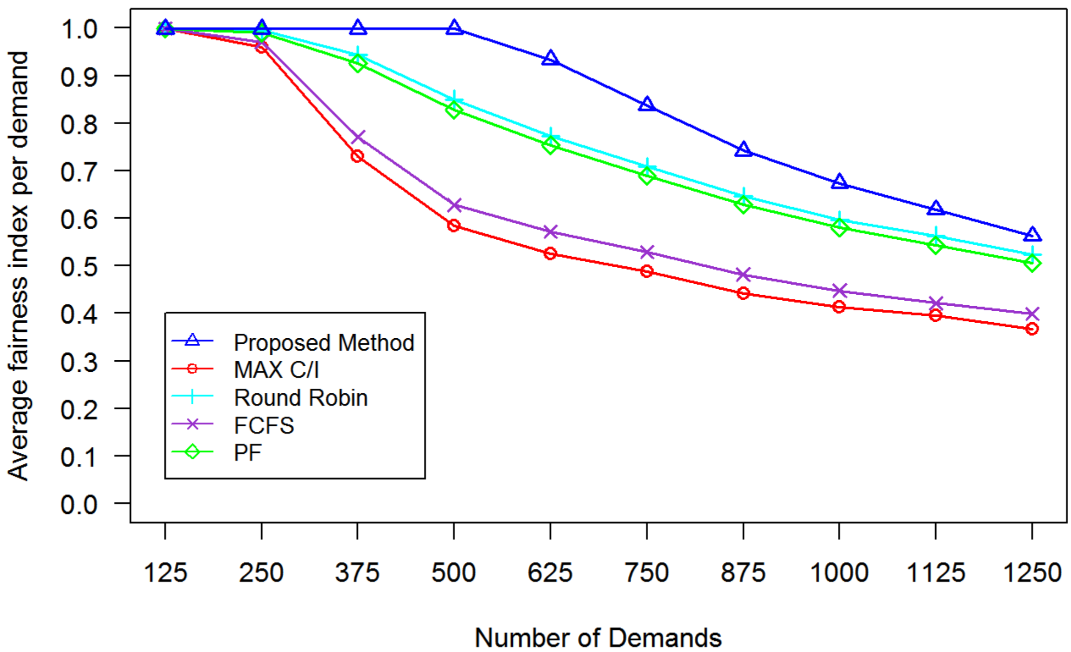


Figure 4.16 Jain's Fairness Index Value for All Demands Throughout The Simulation (Scenario-2).

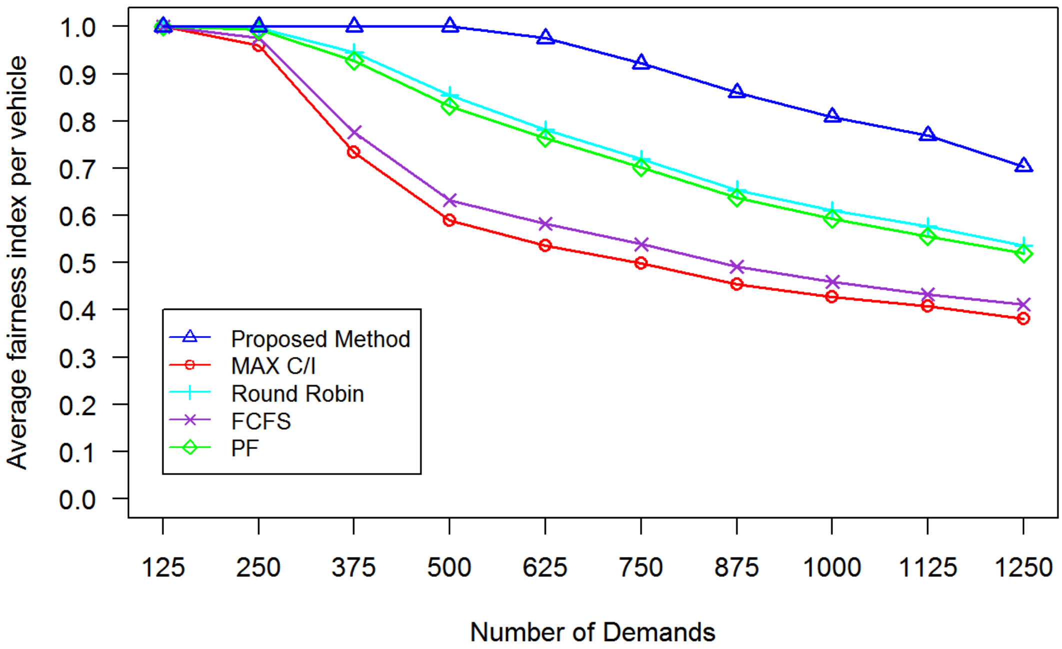
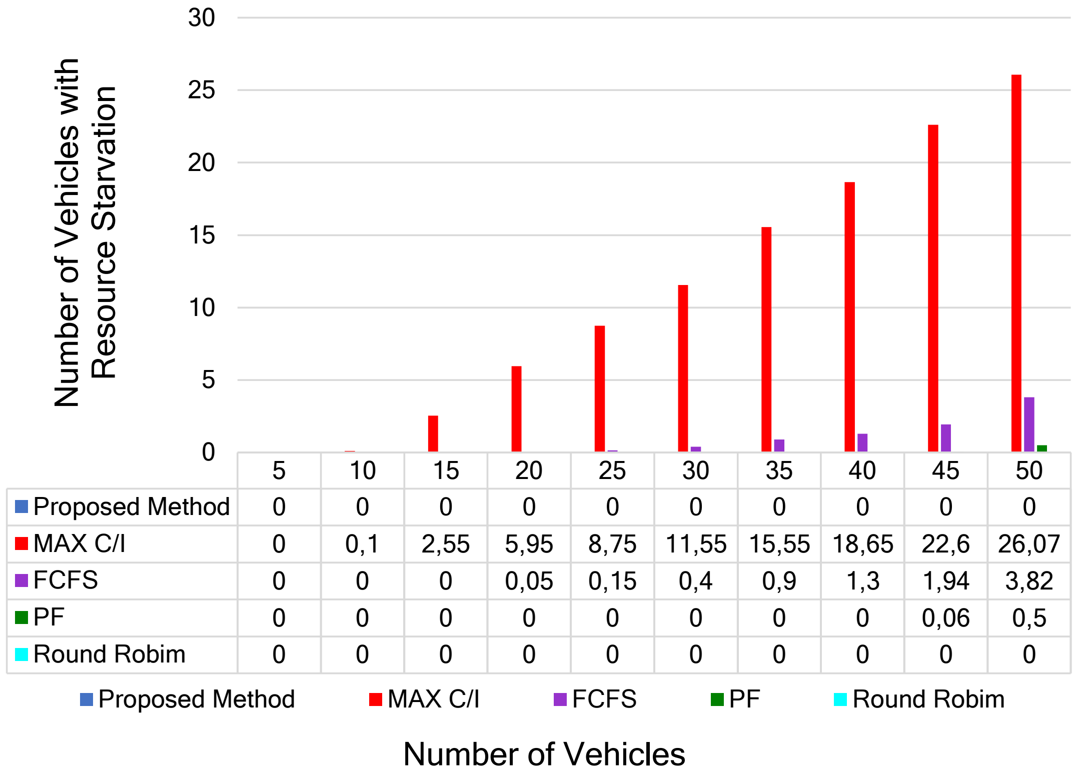


Figure 4.17 Jain's Fairness Index Value for Each Vehicle's Requests (Scenario-2).

Jain's fairness index is calculated and presented separately according to the number of demands requested by each vehicle, the total demand made, and the resource assignment of the edge nodes. Figure 4.15 depicts how the capacity utilization of all edge nodes is fairly distributed throughout the simulation. The proposed method achieves the highest fairness index value at least 20.47% higher, and the average channel capacity utilization under the proposed method is at least 48.68%. Fairness of all other methods is outperformed by the proposed method, and it is observed that the performance of MAX C/I and FCFS coincides whereas the performances of Round robin and PF coincide in terms of Jain's fairness. This is because MAX C/I and FCFS have a priority-based assignment, whereas Round Robin and PF assign equal priority to all demands.

Figure 4.16 presents the fairness index values calculated for all demands during the simulation and Figure 4.6 presents the fairness index values calculated for data demands requested by each vehicle. According to both figures, the proposed method outperforms its counterparts, while MAX C/I is outperformed by other methods. Particularly, up to 500 demands, the proposed method achieves the highest fairness values for all demands, as well as for the vehicles due to data offloading.

As mentioned earlier, some of the methods may lead to starvation for the vehicles in the network. Figure 4.18 illustrates an increasing trend of starvation under MAX C/I with the increasing number of vehicles. A closer glance at the figure would reveal that the demands of at least half of the vehicles remain unresponded when the number of vehicles reach 50. Although it is not as noteworthy as that under MAX C/I, FCFS and PF methods lead to starvation for a minority of vehicles as the network gets denser. The only methods that end up with zero starvation are Round Robin and the proposed method. Since Round Robin allocates capacity equally to all vehicles, there is no starvation observed. However, as shown in Figure 4.13, the Round Robin method yields the worst results for the number of unsuccessful demands. In contrast, our proposed method not only avoids starvation but also provides the best results for the number of unsuccessful demands.



	5	10	15	20	25	30	35	40	45	50
Proposed Method	0	0	0	0	0	0	0	0	0	0
MAX C/I	0	0,1	2,55	5,95	8,75	11,55	15,55	18,65	22,6	26,07
FCFS	0	0	0	0,05	0,15	0,4	0,9	1,3	1,94	3,82
PF	0	0	0	0	0	0	0	0	0,06	0,5
Round Robim	0	0	0	0	0	0	0	0	0	0

Figure 4.18 Number of vehicles that experience resource starvation under varying number of vehicles in the network (Scenario-2).

It is worth noting that starvation of vehicles becomes more severe if the demand profile is not uniformly distributed across the network when starvation results under Scenario-1 (Figure 4.9) and Scenario-2 (Figure 4.18 are compared. For instance, MAX C/I demonstrates the poorest performance in terms of starvation such that even with 20 vehicles in the network, it leaves almost 30% of the vehicles starved. Starvation under FCFS, on the other hand, begins when the number of vehicles reaches 20, and demonstrates a constant increase in the ratio of starved vehicles as the network gets denser. As the PF method considers fairness as a factor in resource allocation, it does not lead to any starvation until the number of vehicles reaches 45. Even with 45 and 50 vehicles, the percentage of starved vehicles remain at 1-2% on average.

The reason of our proposed method's favorable performance when compared to its counterparts is its leverage of the edge-assisted offloading support. Figure 4.19 presents the data offloading ratio under varying demand loads. The offloading ratio is around 50% for the demands up to 625. This high offloading ratio supports the edge nodes to distribute their load to neighboring nodes, therefore more demands are successfully responded to as shown in Figure 4.14 where 100% demands were responded to up to 625 demands (or 0 unsuccessful responses as shown in Figure 4.13 for demands up to 625). This presents that the proposed method utilizes the available capacity very efficiently. It is seen that the offloading ratio decreases at and beyond 625 requests. Such a decrease can be explained by the unavailability of resources under heavy demands. The dashed line indicates the maximum achievable offloading ratio based on the available resources in the overall network. The proposed approach distributes the load to the available neighboring nodes, but as the number of demands in the entire network increases, the resource usage of the neighbor nodes also increases, therefore as the available capacity to distribute the load decreases, the offloading ratio decreases. The proposed method distributes the load via effective use of the available capacity so as to serve more vehicles and demands with edge-assistance even under heavy demands. The benefit of edge assistance for demand offloading is three-fold: 1) Higher response ratio for the incoming demands (Figure 4.14), 2) Minimum unsuccessful responses to the demands (Figure 4.13) and 3) No starvation (Figure 4.18).

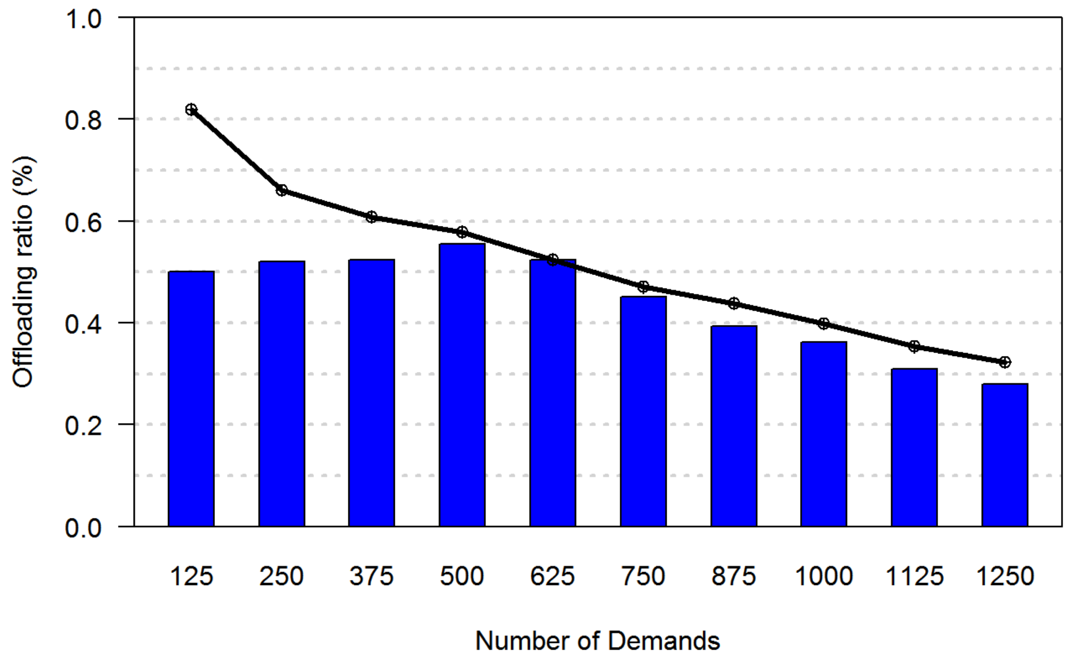


Figure 4.19 Data offloading ratio with varying number of demands under the proposed method. By enabling offloading an average of 44% of the demands, the proposed method can improve the turnaround and wait times with no starvation (Scenario-2).

4.3. Summary

To meet the requirements of the services and applications defined by 3GPP in 5G/LTE networks, effective and fair use of network resources is needed, particularly in the presence of time-critical applications. To overcome these challenges, this work has proposed a novel edge-assisted efficient, and fair resource allocation scheme for 5G V2X networks. The proposed scheme distributes the demands across neighboring edge nodes when the capacity of the closest edge node is exceeded by the data demands of the vehicles. To formulate this approach, we have formulated an optimization model along with an edge-assisted offloading approach. The performance of the proposed approach has been evaluated under a conventional simulation setup where demands are distributed uniformly across the network and a realistic scenario where demands exhibit spatio-temporal variations across the network. Comparisons with the state-of-the-art resource allocation approaches have been pursued in terms of wait time, turnaround time, fairness, starvation ratio, and successful/unsuccessful response rates of the vehicles in the network.

The basic principle of our proposed method is to ensure that edge nodes allocate resources fairly and effectively in case network resources become insufficient as a result of increasing user density and data traffic density. While implementing this fair and effective approach, performance metrics such as delay, response time, and turnaround time are also improved. This proposed approach requires knowing the amount of data demanded by users and processing it in a centralized algorithm such as RMU in the core network. In such multi-criteria performance improvements, these computations require the use of additional computing resources in the core network and will also introduce a computational delay. Instead of making a choice in this trade-off, improving network performance has been our main approach. Decentralizing the centralized computation in the proposed approach may contribute to reducing the computational latency. Additionally, predictive solutions can reduce computational complexity if parametric values such as vehicle density, movement patterns, and data transmission needs are learned from historical data. This study proposes a solution approach to improve network performance metrics. Moreover, feasible performance of the proposed approach compared to other approaches occurs when limited resources are insufficient due to increasing data transmission demand. Other algorithms also result in feasible performance when network resources meet the data transmission demands as mentioned in the performance analysis section.

Our ongoing research includes detection of the malicious nodes in such environments and the development of intelligent detection methodologies to eliminate those nodes to free up the edge resources. Furthermore, we are also tacking differentiated demand profiles with respect to the service requirements of the vehicles in the network. Adverse situations such as frequent disconnections of vehicles in the network and fragmentation of the vehicular network are expected to degrade the quality of service and efficient use of network resources. Particularly, in the case of multi-hop communications end-to-end communications would be impeded in the occurrence of fragmentations. Reliability of communication is formulated as a function of the mean time to fail and mean time to restore the communication; hence, low reliability would translate into increased latency due to retransmission attempts and reduced throughput in data transmission. Such a study could address the exact opposite of the situation discussed in our study. Countermeasures to prevent from those phenomena would involve further investigation on the impact of fragmentation and reliability-aware routing and resource assignment in data transmission, which is also included in our research agenda.

5. DATA TRAFFIC OFFLOADING WITH SELECTING RELAY NODE IN C-V2X NETWORKS

As vehicles become smarter, the volume of data that vehicles need for these new features is also increasing accordingly [54]. With the rapid increase in the number of these smart vehicles, the overall required data demand has skyrocketed [92]. Thanks to the new standards set by 3GPP Release 17 [10], it has become possible for vehicles to receive the data they need through the cellular network called as C-V2X, thanks to the 5G/LTE network infrastructure.

Reliable, timely, and successfully completed delivery of data that vehicles require is of critical importance for smart vehicles. In situations where vehicles are not within the range of a gNodeB or cannot access data due to high workload on the accessible gNodeB, accessing data may not be possible. In such cases, vehicle-to-vehicle (V2V) communication with neighboring vehicles within the coverage area with access to the cellular network/gNodeB enables data access. In cases where the requested data cannot be met by the gNodeB, another vehicle that acts as a relay node with access to the gNodeB ensures the data reaches the vehicle that requests data service.

The communication between the relay node and the gNodeB is carried out over the cellular network. In cellular networks, relay node selection can be applied for different purposes on uplink (UL) and downlink (DL) communication channels. On the downlink, cellular network must be used for broadcast services to all vehicles whereas in the case of unicast communication where the data needs to be transmitted to a particular vehicle that is out of the gNodeB range, leveraging a relay node within the cellular network is inevitable. In so doing, the workload on the cellular network is reduced by the selected relay node. Another scenario is when there exists heavy demand for vehicular data that exceeds the resource capacity of the gNodeB. In this case, the requests from vehicles can be transmitted by a gNodeB with light workload through a relay node. This ensures a more balanced utilization of the cellular network capacity, leading to effective provisioning of data requests from vehicles. Similarly, for uplink data transmissions, if a vehicle is out-of-range of a gNodeB, the request is transmitted to the gNodeB through a relay node within the coverage area. Thus, by leveraging relay nodes, vehicles with no cellular connectivity can gain access through relay nodes, expanding the reach of a cellular network. The data that vehicles need to transmit to the gNodeB (sensor data, emergency messages, etc.) is collected by the relay node through V2V communication and then transmitted only through the relay node's communication with the gNodeB. In this way, not all vehicles need to establish a connection to the gNodeB, and also similar data is filtered by the relay node to reduce the amount of data transmitted to the gNodeB. Thus, the resource usage required for each vehicle to send its data is reduced by the relay node.

In this chapter, we propose a relay node selection solution to enable access to demanded data when vehicles have limited access or are unable to access due to heavy data traffic. The objective of the proposed method is to enable access to data for vehicles that cannot access it. This is achieved through a relay node selected by a low workload gNodeB, ensuring access to the data.

The main contribution of the proposed method is to facilitate the fulfillment of vehicle data demands that high workload gNodeBs cannot meet, by leveraging relay nodes connected to low workload gNodeBs. By transferring workload from a high workload gNodeB to a low workload one, a more balanced load distribution has been achieved. Furthermore, the efficient utilization of unused resources through relay node selection has resulted in a more efficient network RB capacity and a more effective utilization of network resources. When our proposed relay node selection method is applied to state-of-the-art algorithms (Section 5.2.1), it enabled the utilization of approximately 39% (Table 5.5) more channel resources. With a more effective use of channel RB capacity, approximately 44% more vehicle data requests were fulfilled by gNodeBs on average.

The rest of the chapter is organized as follows. Section 5.1 presents our proposed solution. Section 5.2 presents performance metrics, simulation scenario and results. Finally, Section 5.3 summary of this chapter.

5.1. The Proposed Relay Node Selection Approach

The proposed approach builds on the 3GPP Release 17 [10] specifications. According to the frame structure of 5G standardized in 3GPP Release-17 (see Figure 5.1**5.1**), time duration for one radio frame is 10 *ms* which consists of 10 subframes each having 1 *ms* duration. μ is the frame modulation defined based on gNodeB, and value of μ can be between 0 and 4. Each subframe can have 2^{μ} slots and each slot named as

Resource Block (RB). Each RB typically consists of 14 OFDM symbols.

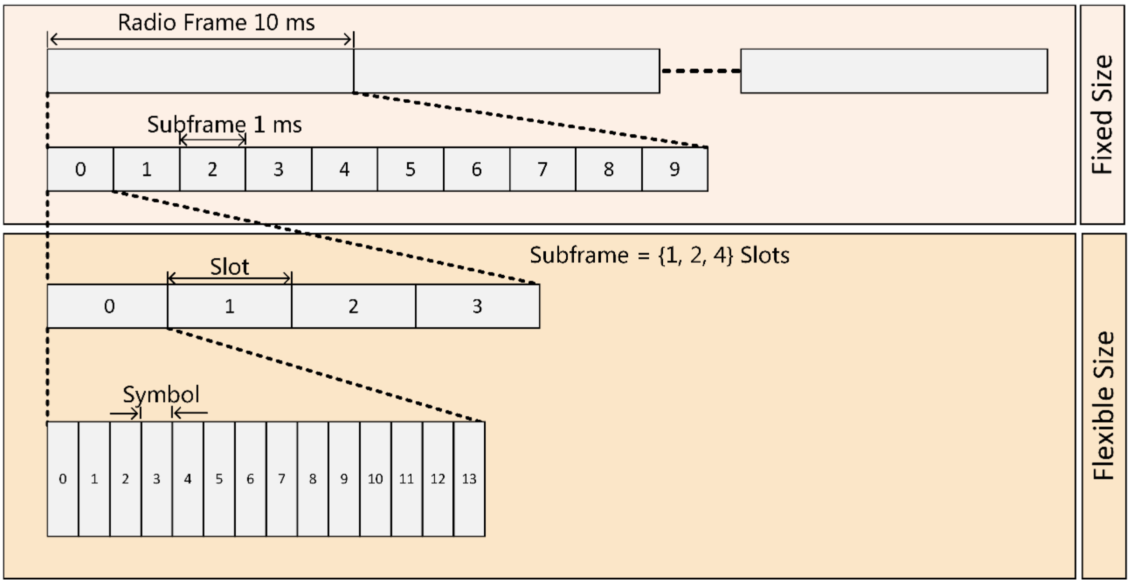


Figure 5.1 5G Frame Structure in 3GPP Rel. 17 [10]

Depending on the frame modulation at the gNodeB, the number and size of RBs vary. The data demands of vehicles are assigned to each RB according to the MAC scheduling protocol employed at the gNodeB. If the size of data requests from vehicles exceeds the RB capacity of the gNodeB, the gNodeB may not be able to respond to all requests in a timely manner. Therefore, scheduling and resource allocation mechanisms on gNodeB play a critical role.

We propose a new relay node selection-based offloading method for C-V2X networks, aiming at both efficient use of resources and meeting a higher number of data requests by transferring the load to alternate gNodeB's via relay nodes. Due to a high volume of vehicle requests at the gNodeB, there is a significant load on the system. The excessive load on the gNodeB prevents its service capabilities, so we perform data offloading to alleviate the load at the heavily loaded gNodeB's. By distributing this excessive load through a relay node consisting of pre-selected vehicles, the aim is to enable the gNodeB to efficiently serve more vehicles. Thus, by efficiently utilizing the resource capacity of a gNodeB with lighter workload, more vehicle data requests can be fulfilled. Throughout this data offloading process, service quality of cellular network is also maintained.

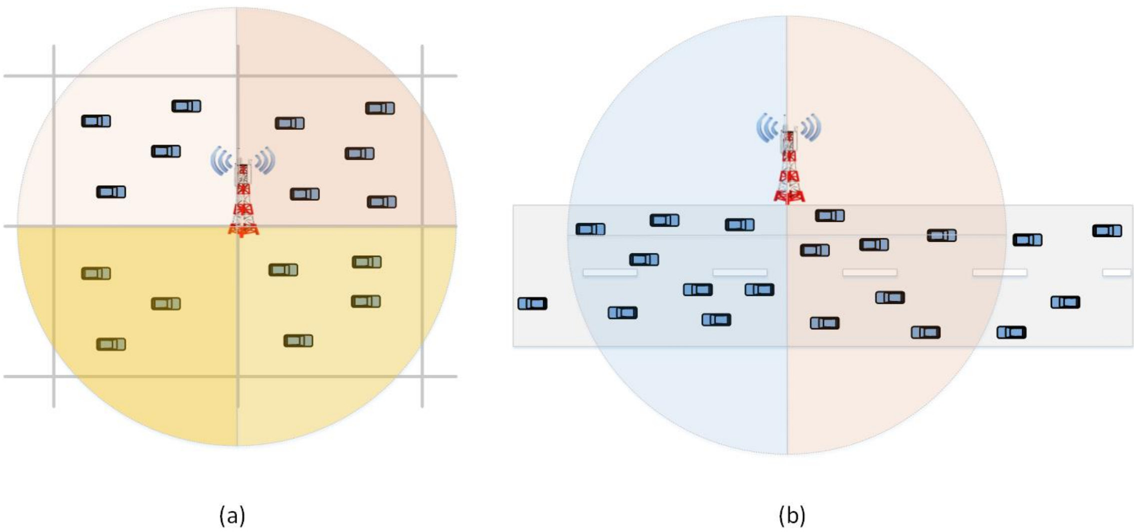


Figure 5.2 Illustration of the proposed model a) urban area b) highway area.

The gNodeB with light workload selects relay nodes out of the vehicles within its transmission range. The surrounding of the gNodeB is divided into sub-cells, and relay node selection is performed separately for each sub-cell. Depending on the area where the gNodeB is located, the communication area is divided into sub-cells for each direction. For urban area as shown in Figure 5.2a, the surrounding of the gNodeB is partitioned into four sub-cells, and for the highway area as shown in Figure 5.2b, into two sub-cells.

In order to make faster decisions and reduce complexity, only one relay node can be selected for each sub-cell [93] [94] [95]. Thus, in this case, for urban area, each gNodeB can select a maximum of four relay nodes, and for highway, two relay nodes can be selected. The relay node to be selected for each sub-cell is determined by considering their distances to the gNodeB within that cell, and a candidate relay node list is created. A node is selected out of the candidate list.

The implementation of the proposed method is carried out through the following steps;

Table 5.1 Algorithm 1: Update Vehicle List

```
for i ← 0 to |V| do
    for j ← 0 to |B| do
        if vehicle i is in transmission range of gNodeB j then
            add V_i to gNodeB neighboring list L_j^BS
        end if
    end for
    for k ← 0 to |V| do
        if vehicle k is in transmission range of vehicle i then
            add V_k to vehicle neighboring list L_i^V
        end if
    end for
end for
```

The Update Vehicle List algorithm (Algorithm 1) is employed to identify the lists of 1-hop neighbor vehicles within the transmission range. These lists include the neighboring vehicles for gNodeB *j* (L_j^{BS}) which is kept and updated by the gNodeB *j* and the neighboring vehicles of vehicle *i* (L_i^V) which is kept and updated by the vehicle *i*. Thus, the gNodeB *j* selects a relay node e.g. *i* using the neighboring list (L_j^{BS}) with the use of Algorithm 2, and the selected relay node *i* use its own neighbor list *i* (L_i^V) to determine which vehicle's request to transfer to the gNodeB.

Table 5.2 Algorithm 2: Candidate Relay Node Selection

```
if C_j > 0 then
    for n ← 0 to |S| do
        for i ← 0 to L_j^BS do
            if vehicle i is in the sub-cell S_n area then
                if C_i > 0 then
                    add V_i to the sub-cell n candidate relay node list R_n,j
                end if
            end if
        end for
    end for
end if
```

The second step is the determination of the candidate relay node list to identify which vehicles can serve as relay nodes (Algorithm 2). The gNodeB and relay node should have available resource capacity (C) for the allocation of the vehicle's data demands. If the available resource capacity of the gNodeB (C_j) is greater than 0, relay node selection is performed; otherwise, it is not carried out. Therefore, the available resource capacity of the gNodeB is checked first. Subsequently, depending on the number of sub-cells ($|S|$) determined according to the gNodeB, a separate candidate relay node list is established for each sub-cell ($\mathrm{R_n}$). Then, the available resource capacities of the vehicles within the coverage area of the gNodeB ($\mathrm{L_j^{BS}}$) are checked. If the resource capacity of vehicle i is not fully utilized, it is selected as a candidate relay node for the current sub-cell (n) and added to the candidate relay node list ($\mathrm{R_{n,j}}$) of gNodeB j.

Table 5.3 Algorithm 3: Relay Node Selection

```
max_distance ← 0
for n ← 0 to |S| do
    if |R_{n,j}| > 0 then
        for i ← 0 to |R_{n,j}| do
            if V_i ∈ L_j^BS then
                vehicle_distance ← distance(i, j)
                if vehicle_distance > max_distance then
                    max_distance ← vehicle_distance
                    relay_node ← i
                end if
            end if
        end for
        if relay_node ∈ R_j then
            select vehicle as a relay node
            return relay_node
        end if
    end if
end for
```

The third step is to select one relay node among the candidate nodes for each sub-cell (Algorithm 3). The previously determined list of candidate relay nodes ($R_{n,j}$) is used for the relay node selection in each sub-cell. First, the candidate relay node list for current sub-cell n is checked, and if the list is not empty, the relay node selection process continues. Then, it is verified whether the vehicle in the list is still within the communication range of the gNodeB. If the vehicle is out of the communication range, it cannot be selected as a relay node, otherwise selection process continues. The distance between the vehicle within the communication area and its gNodeB is calculated. If the distance value is greater than the *max_distance* value, then the *max_distance* value and *relay_node* index value are updated. Thus, the *relay_node* index value is determined as the farthest from the gNodeB in the candidate vehicle list. If the *relay_node* value is not assigned, relay node selection is not performed in the current sub-cell; otherwise, the vehicle with the assigned index value is determined as the relay node for the current sub-cell.

5.2. Simulations and Performance Results

In this section, performance of the proposed solution is evaluated comprehensively and compared to renown and state-of-the-art approaches in literature. We begin with introducing the state-of-the-art solutions that form baselines to our performance evaluation. Then, we proceed with introducing the performance metrics and simulation settings. These are followed by the presentation of our performance evaluation results along with thorough discussions.

5.2.1. State-of-the-art Solutions and Baselines

Our proposed method is evaluated by applying it to the state-of-the-art algorithms presented in [79] [80] [81] for our performance evaluations. These algorithms are summarized below:

- **Maximum Carrier-to-Interference (MAX C/I)** scheduling algorithm is designed to maximize the overall network throughput by considering the current channel conditions. MAX C/I scheduler prioritizes requests by sorting them in descending order based on the Signal-to-Noise plus Interference Ratio (SINR) of the demands and then assigns resources accordingly. Consequently, this scheduling approach gives higher priority to vehicles closer to the gNodeB, as their signal quality is expected to be better compared to vehicles farther away from the gNodeB [51]. Although the overall throughput is maximized by this approach, it may cause fairness and starvation issues for vehicles that are at distant locations with respect to the edge node [82].
- **Round Robin (RR)** is a scheduling algorithm that tries to allocate channel

capacity impartially among all users, employing a round-robin approach that considers each user in sequence. This methodology is implemented to ensure fair distribution of resources and equal access to the channel for all users. Unlike other scheduling algorithms that prioritize effective bandwidth utilization, Round Robin focuses on fairness and impartial channel access. Consequently, while it promotes equitable resource allocation, it may lead to a reduction in overall bandwidth utilization efficiency [83].

- **Proportional Fairness (PF)** is a scheduling algorithm designed to ensure equitable distribution of system resources. In addition to promoting fairness, PF considers the historical channel usage patterns of vehicles, enhancing overall system efficiency [84][85]. This approach evaluates the utilization of system resources for previous demands over specific time frames, guiding the allocation of resources for each demand in the current time slot [86].
- **First Come-First Served (FCFS)** is a scheduling algorithm that allocates resources based on the order of arrival. Demands are processed in the sequence they arrive at the gNodeB, without any prioritization between users/requests except for their time of arrival. FCFS has a drawback for latency-sensitive demands, as subsequent demands need to wait for the completion of previous ones [87]. Additionally, FCFS cannot ensure high throughput and resource efficiency. The only benefit of FCFS is its easy-to-implement nature.

5.2.2. Performance Metrics

- **Offloading Ratio** represents the parameter used for the amount of data transferred using relay nodes. A high value of the Offloading Ratio indicates that more demanded vehicle data is offloaded by the gNodeB's through relay nodes, demonstrating a more balanced distribution of the workload among gNodeB's.

$$\text{OffloadingRatio} = \frac{\sum_{j=1}^{|R|} S_j(t)}{\sum_{i=1}^{|V|} D_i(t)} \tag{5.1}$$

R is the list of the relay nodes, $S_j(t)$ is the offloaded data size by relay node *j* at time *t* and $D_i(t)$ is the data demand size of the vehicle *i* demanded at time *t*.

- **Total assigned demands size** indicates how many resource block is assigned by gNodeB's to the data requests demanded by the vehicles. Higher values close to the network capacity indicate that the demands are allocated by the gNodeB's within the capacity.

$$TotalResorceBlock = \sum_{j=1}^{|B|} A_j(t) \tag{5.2}$$

  B is the list of the gNodeB's and $A_j(t)$ is the assigned data size by gNodeB *j* at time *t*.

- **Successful Demand Rate** is used to signify the successful completion of a demand. A demand is considered successful only if all the associated data (RBs) are provided by the network; otherwise, it is marked as unsuccessful. The Successful Demand Rate represents the ratio of successfully completed demands to the total number of demands.

$$SuccessfulRate = \frac{\sum_{i=1}^{|V|} d_i(t)}{|D|} \tag{5.3}$$

D is the list of the data demands requested by vehicles, and $d_i(t)$ is the number of successfully completed data demand of vehicle *i* at time *t*.

5.2.3. Simulation Settings

Performance of the proposed approach is evaluated in a bidirectional highway area scenario with two lanes in each direction. Thus, each gNodeB selects a maximum of two relay nodes. Speed and distance between vehicles are randomly generated from a normal distribution to simulate their positions on the road. To simulate vehicle mobility, we utilized the Simulation of Urban MObility (SUMO) [16] and collected updated vehicle positions generated by SUMO at each time slot. We then used these positions in our study in the simulation scenario. A certain number of gNodeBs as edge nodes capable of meeting the data demands of vehicles are included in the simulation, complying with the 3GPP Release 17 [10] standards. We vary the number of vehicle data demands in the simulation, ranging from 625 to 1250. The transmission range is set at 500 meters, a reasonable value for C-V2X communication [96] [97]. The other parameters of the simulation are summarized in Table 5.4.

Table 5.4 Simulation Parameters

Parameters	**Value**
Time Slot	1000
Number of vehicles	25, 30, 35, 40, 45, 50
Number of demands	625, 750, 875, 1000, 1125, 1250
Number of demands per vehicle	25
Number of edge nodes	4
Road length	2500 m
Number of lanes	4
Transmission Range	500 m
Request frequency	40 ms
Demand size	30-42 RB
Channel Bandwidth	1.4 MHz

Table 5.5 Average gNodeB load ratio according to varying vehicle data request (%)

MAX C/I

	625	750	875	1000	1125	1250
No Relay	47,59	52,98	56,15	60,19	64,67	67,75
Proposed	73,18	77,53	79,46	84,22	86,65	87,25
Random	67,71	73,93	76,08	80,51	82,88	84,98
Degree	73,18	77,54	79,27	84,1	86,41	86,98

Round Robin

	625	750	875	1000	1125	1250
No Relay	47,67	53,08	56,23	60,28	64,79	67,86
Proposed	73,27	77,5	80,99	86,78	89,28	90,53
Random	67,74	74,26	77,26	82,56	84,85	87,03
Degree	73,11	77,19	79,17	84,02	86,84	87,29

FCFS

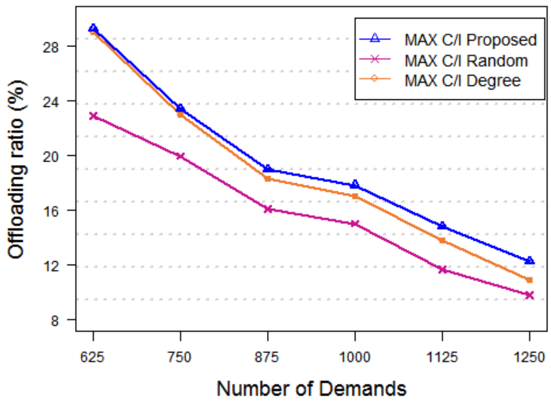
	625	750	875	1000	1125	1250
No Relay	47,72	53,13	56,26	60,31	63,88	67,91
Proposed	74,01	78,24	81,11	86,44	89,84	90,01
Random	68,55	74,82	77,4	81,89	84,58	86,6
Degree	73,85	77,75	79,51	84,32	87,05	87,46

PF						
	625	750	875	1000	1125	1250
No Relay	47,72	53,12	56,26	60,32	63,88	67,2
Proposed	73,74	78,16	81,23	87,2	89,59	90,56
Random	68,42	74,74	77,47	82,49	85,08	87,01
Degree	73,56	77,67	79,49	84,35	87,12	87,46

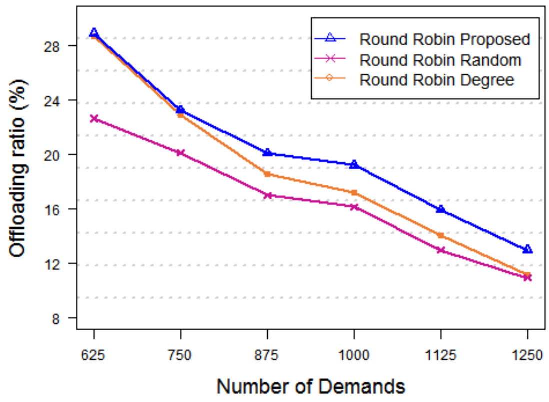
5.2.4. Performance Results

The proposed method is introduced to the following well-studied algorithms in literature: MAX C/I, Round Robin, PF, and FCFS as described in Section 5.2.1. The proposed relay node selection solution applied to these algorithms, namely Relay Node based MAX C/I, Relay Node based Round Robin, Relay Node based PF and Relay Node based FCFS have been defined as MAX C/I Proposed, Round Robin Proposed, PF Proposed, and FCFS Proposed, respectively. We add two more relay node selection methods and applied to the state-of-the-art algorithms for compare the simulation results with our proposed solution. First relay node strategy is random relay node selection. Edge node *j* selects randomly a vehicle in the candidate vehicle list for current sub-cell ($R_{n,j}$) as relay node. Second strategy is selecting highest degree which is number of neighbors. So, edge node *j* selects a vehicle in the candidate vehicle list for current sub-cell ($R_{n,j}$) with highest number of neighbors ($|L_i^V|$) as relay node vehicle.

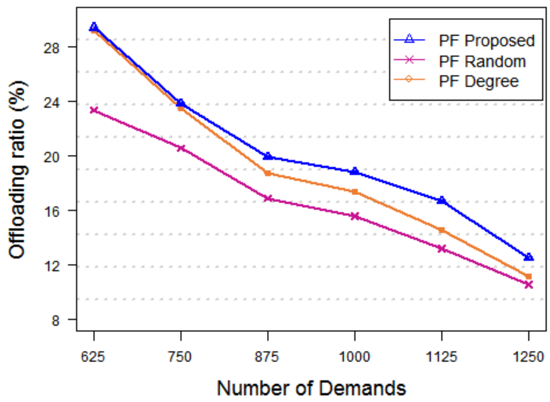
In Table 5.5, the average load ratio of all edge nodes in the network is shown when the relay node selection method is applied to state-of-the-art algorithms. As the number of vehicles demands increases, the load on the edge nodes also increases. It is observed that compared to other selection methods the edge node RB resources are more effectively utilized for all demand variations in the algorithms where our proposed method is applied. When the relay node selection method is applied to state-of-the-art algorithms, approximately there is a 39.1% increase in edge node resource utilization. The average improvement rate in our proposed method is 42.20%, while this rate is obtained as 37.55% in random and degree-based relay node selection methods.



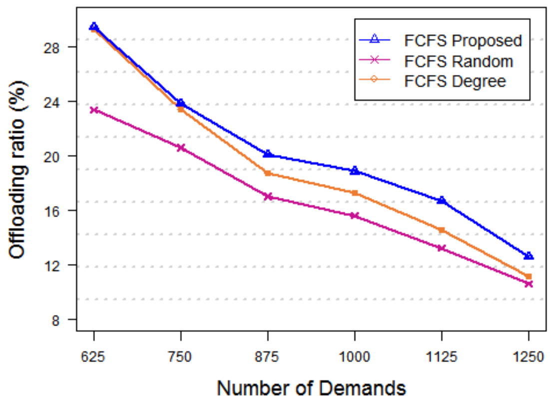
(a)



(b)



(c)



(d)

Figure 5.3 Offloading rate per number of demands

Figure 5.3 illustrates the offloading ratio of vehicle's requested data demand transferred from the gNodeB with high workload to the gNodeB with low workload through the relay node. By using network RB capacity more efficiently and effectively with data offloading, as seen in Figure 5.3, in scenarios where relay node selection method is applied, the data requested by vehicles has been offloaded from another gNodeB via selecting a relay node, with a maximum of 32% and a minimum of 12% ratio on average. As the number of demands increases, the amount of data offloaded decreases in all methods. Despite this, the proposed method compared with random and degree-based relay node selection methods, gives better results for all state-of-the-art algorithms.

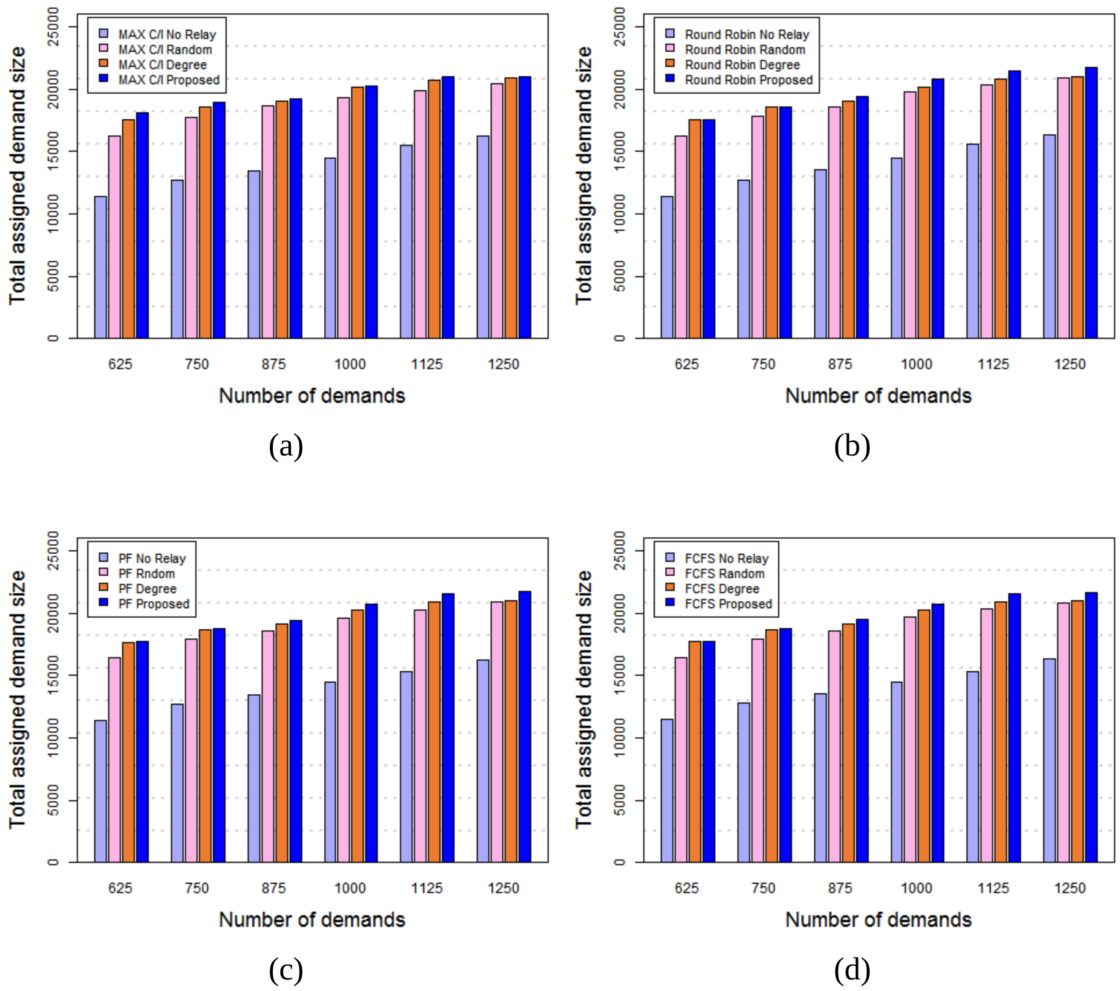


Figure 5.4 Total assigned demands size per number of demands

The comparison of the total assigned demand size among the methods employing the proposed algorithm, random selection, and degree-based selection, and those without it, is illustrated in Figure 5.4. As shown in this figure, when relay node selection is applied to state-of-the-art algorithms, the total amount of assigned data increased in all relay node methods. The proposed method has led to an average enhancement of around 43.72% in the assigned data requests by vehicles with relay node selection across all algorithms. Additionally, our proposed method has assigned an average of 2.1% more demands compared to random selection and degree-based relay node methods.

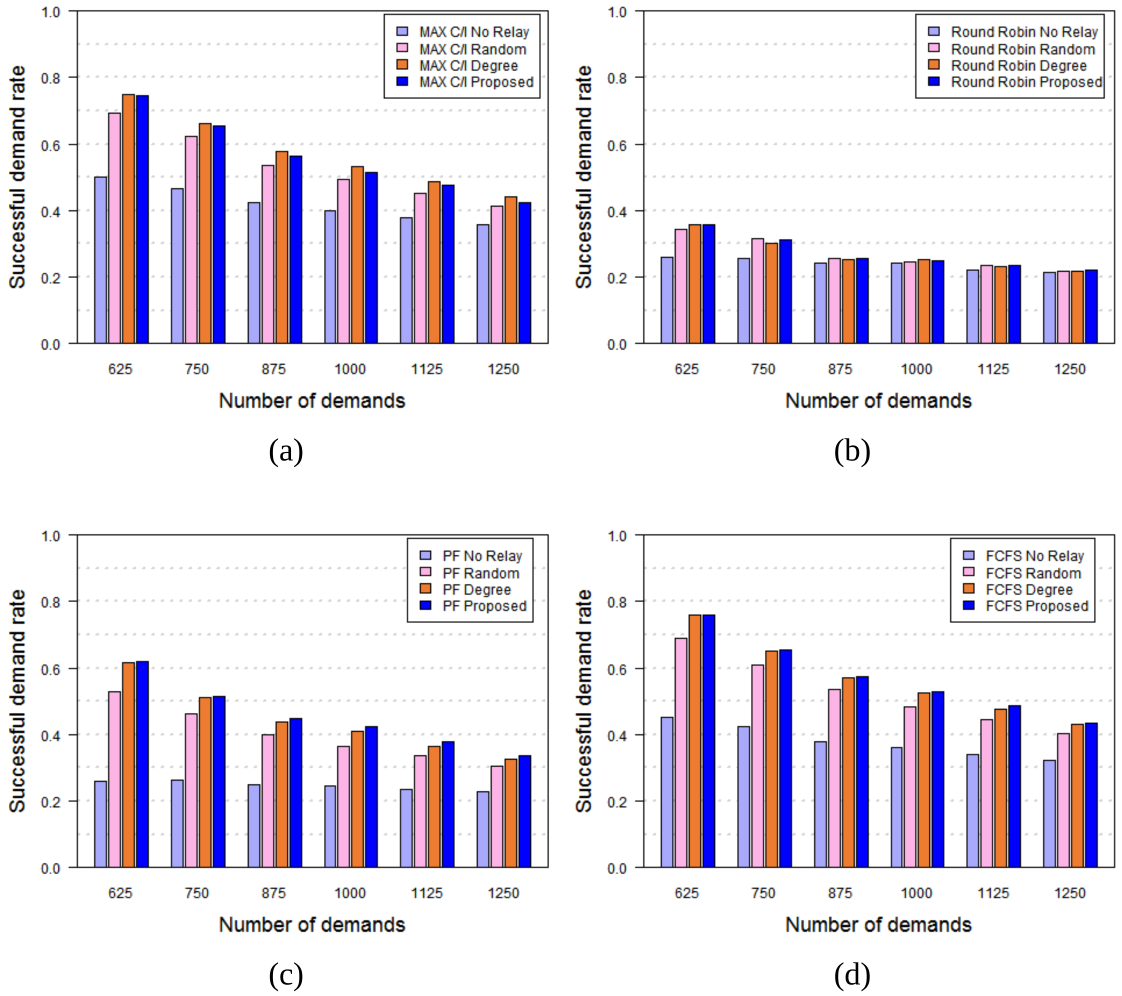


Figure 5.5 Successful demands rate per number of demands

Figure 5.5 illustrates, separately for each algorithm, the ratio of successfully completed vehicle demands transmitted by the gNodeB to all demands. As it seen, the demands requested by vehicles are successfully completed to a greater extent with all algorithms. As the number of demands increases, the available RB capacity of the gNodeB decreases, resulting in a decrease in the amount of offloaded data. Consequently, the successful demand rate improvement also decreases. While the maximum improvement is around 73.79% on average in the PF algorithm for all methods, the improvement in the Round Robin algorithm is limited, approximately around 12.05% on average. While the degree-based relay node selection method yields better results in the MAX C/I algorithm compared to other methods, our proposed method has provided the best results in the Round Robin, FCFS, and PF algorithms.

When analyzing Figure 5.4, it is evident that our proposed method results in a higher total assigned data volume compared to the degree-based method. In the MAX C/I algorithm, priority is given to vehicles with high signal quality, i.e., those closer to the edge node, in data assignment. Our proposed method selects vehicles that are closest to the high loaded edge node as relay nodes, and these relay nodes' neighbors are also similarly close to the edge node. Therefore, the requests of neighboring vehicles of the relay node are prioritized by the edge node. As a result, the relay node selected tends to offload data primarily from vehicle requests that are not prioritized by the edge node. In the degree-based relay node selection method, due to considering the number of neighbors, since the vehicles that are not within the coverage area of the selected relay node in our proposed method are within the coverage area in the degree-based method, the requests of more vehicles are evaluated in the degree-based method. As a result, although the total amount of assigned data was low, but the successfully assigned data rate value is become high.

5.3. Summary

Due to the increasing data demand of smart vehicles, which exceeds the capacity of the current 5G/LTE channel, it is essential to provide access to the data for vehicles. Protocols standardized in 5G/LTE networks by 3GPP Release 17 define strict requirements. Efficient, balanced, and fair utilization of limited channel capacity is necessary for resource management to meet the requested demands of vehicles and suitable with 3GPP requirements.

To achieve these objectives, this study proposes a relay node selection method aimed at utilizing the edge node RB capacity more efficiently and effectively. In the proposed method, the goal is to transfer the data demands from the high-load edge node to the low-load edge node via relay nodes. Unused resources of gNodeB's with low workload in regions of sparse vehicle traffic, depending on the vehicle density, have been utilized by selected relay node vehicles to transfer the requested data needed by vehicles. The effectiveness of our proposed method has been evaluated in a realistic scenario, characterized by spatial-temporal variability in data demands across the network. When integrated our proposed relay node selection method into state-of-the-art scheduling algorithms, our method has been observed to utilize the capacity more efficiently. Along with our proposed method, random relay node selection and degree-based relay node selection methods also applied to state-of-the-art algorithms. Results are obtained through performance measurements such as offloading rate, total assigned demand size, and successful demand rate.

6. CONCLUSION AND FUTURE WORK

In this chapter, general conclusions drawn from the work conducted in this thesis are presented. Additionally, possible directions for future research are proposed in detail.

6.1. Conclusion

In this thesis, we focused on analyzing the base station workload in cellular networks for V2X services and aimed to balance the load on the base station through both centralized and distributed data offloading.

In the first phase of this study, the realistic simulation environment developed specifically for this purpose is utilized to analyze the performance of cellular network services with V2X communications. It has been observed that when vehicle density and requested data volume increases, 3GPP standards defined for V2X communication are insufficient to meet delay and reliability requirements. Additionally, it has been observed that the MAC scheduler plays a critical role in the transmission of requested vehicle data in V2X communication.

In the second phase of this study, in order to meet more data demands of vehicles in C-V2X network, the centralized edge node data offloading method is proposed. The proposed method is presented as a mathematical model aimed at achieving maximum data offloading to transmit the data requests of more vehicles. The proposed approach demonstrates significant performance improvement compared to state-of-the-art techniques, particularly in terms of wait/turnaround times and fairness. It has been observed that the proposed approach enhances the successfully provisioned demands by 38% and increases the RB capacity usage of the edge node resources by 48% when compared to its state-of-the-art algorithms.

In the third phase of this study, to enhance the efficient utilization of edge node resources, a distributed relay node selection data offloading method has been proposed. More vehicle requests have been successfully transmitted by allocating them to the unused resources of the edge node. According to the results obtained from our proposed method, approximately 18.45% of the requested data has been transmitted to vehicles by the selected relay nodes, and resources were used more efficiently by utilizing the unused RB channel capacity by offloading demanded data.

6.2. Future Work

In light of the increasing data requirements driven by smart vehicles and the continuous development of communication technologies in vehicular communication, there are numerous possibilities for future exploration and advancement in the field of data offloading and relay node selection.

A potential area for future research could involve exploring different solutions through data offloading to meet the on-demand large-volume data requests of vehicles, instead of their periodic data requests. Integrating advanced machine learning techniques, such as reinforcement learning or federated learning, into data offloading and relay node selection processes could further enhance decision-making capabilities and adaptability. Moreover, addressing security and privacy concerns associated with relay node selection remains an open challenge, necessitating the development of robust authentication mechanisms and data protection protocols.

REFERENCES

[1] Hasrouny, H., Samhat, A. E., Bassil, C., & Laouiti, A. (2017). VANet security challenges and solutions: A survey. Vehicular Communications, 7, 7-20.

[2] Rasheed, A., Gillani, S., Ajmal, S., & Qayyum, A. (2017). Vehicular ad hoc network (VANET): A survey, challenges, and applications. In Vehicular Ad-Hoc Networks for Smart Cities: Second International Workshop, 2016 (pp. 39-51). Springer Singapore.

[3] 3rd Generation Partnership Project - 3GPP, https://www.3gpp.org, (Accessed 14.04.2024)

[4] 3GPP TS 22.185, "LTE; Service requirements for V2X services," 2019

[5] 3GPP TS 22.186, "5G; Service requirements for enhanced V2X scenarios," 2019.

[6] National Highway Traffic Safety Administration. (2011). Vehicle Safety Communications – Applications (VSC-A) - Final Report. DOT HS, 811, 492A.

[7] Kenney, J. B. (2011). Dedicated short-range communications (DSRC) standards in the United States. Proceedings of the IEEE, 99(7), 1162-1182.

[8] EN ETSI. "ETSI EN 302 571 (V2.1.1)" Intelligent Transport Systems (ITS). (2017-02). Radiocommunications Equipment Operating in the 5855 MHz to 5925 MHz Frequency Band; Harmonised Standard covering the Essential Requirements of Article 3.2 of Directive 2014/53/EU.

[9] Chen, S., Hu, J., Zhao, L., Zhao, R., Fang, J., Shi, Y., & Xu, H. (2023). Cellular vehicle-to-everything (C-V2X). Springer Nature.

[10] 3GPP TS 22.186 V17.0.0. (2022-04-21). 5G; Service requirements for enhanced V2X scenarios (3GPP TS 22.186 version 17.0.0 Release 17)

[11] 3GPP TS 22.885, "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on LTE support for Vehicle to Everything (V2X) services," 2015

[12] 3GPP TS 22.886, "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on enhancement of 3GPP Support for 5G V2X Services," 2019.

[13] How 5G & IoT technologies are driving the connected smart vehicle industry, https://www.businessinsider.com/iot-connected-smart-cars, (Accessed

07.02.2024)

[14] Cisco Mobile, V. N. I. " New Cisco Annual Internet Report Forecasts 5G to Support More Than 10% of Global Mobile Connections by 2023", Available at: https://newsroom.cisco.com/c/r/newsroom/en/us/a/y2020/m02/new-cisco-annual-internet-report-forecasts-5g-to-support-more-than-10-of-global-mobile-connections-by-2023.html, (Accessed 26/10/2023).

[15] Chen, N., Wang, M., Zhang, N., & Shen, X. (2020). Energy and information management of electric vehicular network: A survey. IEEE Communications Surveys & Tutorials, 22(2), 967-997.

[16] Pablo Alvarez Lopez, Michael Behrisch, Laura Bieker-Walz, Jakob Erdmann, Yun-Pang Flötteröd, Robert Hilbrich, Leonhard Lücken, Johannes Rummel, Peter Wagner, and Evamarie Wießner, (2018). Microscopic Traffic Simulation using SUMO. The 21st IEEE International Conference on Intelligent Transportation Systems.

[17] Christoph Sommer, Reinhard German and Falko Dressler, (2011). Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis. IEEE Transactions on Mobile Computing, 10(1), 3–15.

[18] Capozzi, F., Piro, G., Grieco, L. A., Boggia, G., & Camarda, P. (2012). Downlink packet scheduling in LTE cellular networks: Key design issues and a survey. IEEE communications surveys & tutorials, 15(2), 678-700.

[19] Monikandan, S. B., Sivasubramanian, A., & Babu, S. P. K. (2017). A review of MAC scheduling algorithms in LTE system. Int. J. Adv. Sci. Eng. Inf. Technol, 3, 1056-1068.

[20] Radhakrishnan, S., Neduncheliyan, S., & Thyagharajan, K. K. (2016). A review of downlink packet scheduling algorithms for real time traffic in LTE-advanced networks. Indian Journal of Science and technology.

[21] Zain, A. S. M., Malek, M. F. A., Elshaikh, M., Omar, N., & Hussain, A. S. T. (2015, April). Performance analysis of scheduling policies for VoIP traffic in LTE-Advanced Network. In 2015 International Conference on Computer, Communications, and Control Technology (I4CT) (pp. 16-20). IEEE.

[22] Wang, J., Shao, Y., Ge, Y., & Yu, R. (2019). A survey of vehicle to everything (V2X) testing. Sensors, 19(2), 334.

[23] Choudhury, A., Maszczyk, T., Math, C. B., Li, H., & Dauwels, J. (2016). An integrated simulation environment for testing V2X protocols and applications. Procedia Computer Science, 80, 2042-2052.

[24] Avcil, M. N., & Soyturk, M. (2020). Data Offloading Approaches for Vehicle-to-Everything (V2X) Communications in 5G and Beyond. In Connected and Autonomous Vehicles in Smart Cities (pp. 259–275). CRC Press.

[25] Ahmed, M., Raza, S., Mirza, M. A., Aziz, A., Khan, M. A., Khan, W. U., Li, J., & Han, Z. (2022). A survey on vehicular task offloading: Classification, issues, and challenges. Journal of King Saud University - Computer and Information Sciences, 34(7), 4135–4162.

[26] Xu, D., Li, Y., Chen, X., Li, J., Hui, P., Chen, S., & Crowcroft, J. (2018). A survey of opportunistic offloading. IEEE Communications Surveys & Tutorials, 20(3), 2198–2236.

[27] Chen, C., Chen, L., Liu, L., He, S., Yuan, X., Lan, D., & Chen, Z. (2020). Delay-optimized V2V-based computation offloading in urban vehicular edge computing and networks. IEEE Access, 8, 18863–18873.

[28] Sun, F., Hou, F., Cheng, N., Wang, M., Zhou, H., Gui, L., & Shen, X. (2018). Cooperative task scheduling for computation offloading in vehicular cloud. IEEE Transactions on Vehicular Technology, 67(11), 11049–11061.

[29] Zhang, J., Guo, H., Liu, J., & Zhang, Y. (2019). Task offloading in vehicular edge computing networks: A load-balancing solution. IEEE Transactions on Vehicular Technology, 69(2), 2092–2104.

[30] Aujla, G. S., Chaudhary, R., Kumar, N., Rodrigues, J. J. P. C., & Vinel, A. (2017). Data Offloading in 5G-Enabled Software-Defined Vehicular Networks: A Stackelberg-Game-Based Approach. IEEE Communications Magazine, 55(8), 100–108.

[31] Zhang, H., Bennis, M., DaSilva, L. A., & Han, Z. (2014). Multi-leader multi-follower stackelberg game among wi-fi, small cell and macrocell networks. 2014 IEEE Global Communications Conference, 4520–4524.

[32] Abbas, F., & Fan, P. (2018). A hybrid low-latency D2D resource allocation scheme based on cellular V2X networks. 2018 IEEE International Conference on Communications Workshops (ICC Workshops), 1–6.

[33] Kord, K., Elbery, A., Sorour, S., Hassanein, H., Sediq, A. B., Afana, A., & Abou-Zeid, H. (2022). Enhanced C-V2X Uplink Resource Allocation using Vehicle Maneuver Prediction. ICC 2022 - IEEE International Conference on Communications, 3544–3549.

[34] Saleem, Y., Mitton, N., & Loscri, V. (2021). A Vehicle-to-Infrastructure Data Offloading Scheme for Vehicular Networks with QoS Provisioning. 2021 International Wireless Communications and Mobile Computing (IWCMC), 1442–1447.

[35] Cheng, N., Lu, N., Zhang, N., Zhang, X., Shen, X. S., & Mark, J. W. (2016). Opportunistic WiFi offloading in vehicular environment: A game-theory approach. IEEE Transactions on Intelligent Transportation Systems, 17(7), 1944–1955.

[36] Jiang, X., Yu, F. R., Song, T., & Leung, V. C. M. (2022). Resource Allocation of Video Streaming Over Vehicular Networks: A Survey, Some Research Issues and Challenges. IEEE Transactions on Intelligent Transportation Systems, 23(7), 5955–5975.

[37] Vigneri, L., Spyropoulos, T., & Barakat, C. (2016). Storage on wheels: Offloading popular contents through a vehicular cloud. 2016 IEEE 17th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM), 1–9.

[38] Stanica, R., Fiore, M., & Malandrino, F. (2013). Offloading floating car data. 2013 IEEE 14th International Symposium on" A World of Wireless, Mobile and Multimedia Networks"(WoWMoM), 1–9.

[39] Salvo, P., Turcanu, I., Cuomo, F., Baiocchi, A., & Rubin, I. (2016). LTE floating car data application off-loading via VANET driven clustering formation. 2016 12th Annual Conference on Wireless On-Demand Network Systems and Services (WONS), 1–8.

[40] Ancona, S., Stanica, R., & Fiore, M. (2014, April). Performance boundaries of massive Floating Car Data offloading. In 2014 11th Annual Conference on Wireless On-demand Network Systems and Services (WONS) (pp. 89-96). IEEE.

[41] Qi, W., Landfeldt, B., Song, Q., Guo, L., & Jamalipour, A. (2020). Traffic differentiated clustering routing in DSRC and C-V2X hybrid vehicular networks.

IEEE Transactions on Vehicular Technology, 69(7), 7723–7734.

[42] Sun, S., Zhang, Z., Pan, Q., Liu, M., & Li, Z. (2023). Vehicle-cluster-based opportunistic relays for data collection in intelligent transportation systems. Computer Networks, 220, 109509.

[43] Mezghani, F., Dhaou, R., Nogueira, M., & Beylot, A.-L. (2016). Offloading cellular networks through V2V communications — How to select the seed-vehicles? 2016 IEEE International Conference on Communications (ICC), 1–6.

[44] Rehman, O., & Ould-Khaoua, M. (2019). A hybrid relay node selection scheme for message dissemination in VANETs. Future Generation Computer Systems, 93, 1–17.

[45] Deng, Z., Cai, Z., & Liang, M. (2020). A multi-hop VANETs-assisted offloading strategy in vehicular mobile edge computing. IEEE Access, 8, 53062–53071.

[46] Alnasser, A., Sun, H., & Jiang, J. (2021). QoS-balancing algorithm for optimal relay selection in heterogeneous vehicular networks. IEEE Transactions on Intelligent Transportation Systems, 23(7), 8223–8233.

[47] Qin, X., Huang, G., Zhang, B., & Li, C. (2021). Sparse Relays Assisted Opportunistic Routing for Data Offloading in Vehicular Networks. ICC 2021-IEEE International Conference on Communications, 1–6.

[48] Wang, X., Chen, M., Han, Z., Wu, D. O., & Kwon, T. T. (2014). TOSS: Traffic offloading by social network service-based opportunistic sharing in mobile social networks. IEEE INFOCOM 2014-IEEE Conference on Computer Communications, 2346–2354.

[49] Zeadally, S., Hunt, R., Chen, Y.-S., Irwin, A., & Hassan, A. (2012). Vehicular ad hoc networks (VANETS): status, results, and challenges. Telecommunication Systems, 50(4), 217–241.

[50] Varga, A. (1999). Using the OMNeT++ discrete event simulation system in education. IEEE Trans. on Education, 42(4), 11.

[51] Dahlman, E., Parkvall, S., & Skold, J. (2013). 4G: LTE/LTE-advanced for mobile broadband. Academic press.

[52] Hussain, R., & Zeadally, S. (2018). Autonomous cars: Research results, issues, and future challenges. IEEE Communications Surveys & Tutorials, 21(2), 1275–1313.

[53] Sae International. (2021-04-30). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles J3016_202104. https://www.sae.org/standards/content/j3016%5C_202104

[54] Shubham Munde. (2023). Connected Car Market Research Report: Information By Network Type (3G, 4G, 5G, and Satellite), By Technology (Embedded, Tethered, and Integrated), By Application (Mobility Management, Telematics, Infotainment, and Driver Assistance) And By Region (North America, Europe, Asia-Pacific, And Rest Of The World) – Market Forecast Till 2032. Connected Car Market, 100. https://www.marketresearchfuture.com/reports/connected-car-market-1140

[55] Wright, S. (2021). Autonomous cars generate more than 300 TB of data per year. Tech Blog, Tuxera, Finland.

[56] Coll-Perales, B., Lucas-Estañ, M. C., Shimizu, T., Gozalvez, J., Higuchi, T., Avedisov, S., Altintas, O., & Sepulcre, M. (2022). End-to-end V2X latency modeling and analysis in 5G networks. IEEE Transactions on Vehicular Technology, 72(4), 5094–5109.

[57] Boban, M., Kousaridas, A., Manolakis, K., Eichinger, J., & Xu, W. (2017). Use cases, requirements, and design considerations for 5G V2X. ArXiv Preprint ArXiv:1712.01754.

[58] Avcil, M. N., & Soyturk, M. (2019). Performance evaluation of V2X communications and services in cellular network with a realistic simulation environment. 2019 1st International Informatics and Software Engineering Conference (UBMYK), 1–6.

[59] Hakak, S., Gadekallu, T. R., Maddikunta, P. K. R., Ramu, S. P., Parimala, M., De Alwis, C., & Liyanage, M. (2023). Autonomous Vehicles in 5G and beyond: A Survey. Vehicular Communications, 39, 100551.

[60] Ferrag, M. A., Friha, O., Kantarci, B., Tihanyi, N., Cordeiro, L., Debbah, M., Hamouda, D., Al-Hawawreh, M., & Choo, K.-K. R. (2023). Edge Learning for 6G-Enabled Internet of Things: A Comprehensive Survey of Vulnerabilities, Datasets, and Defenses. IEEE Communications Surveys & Tutorials, 25(4), 2654–2713

[61] Feng, C., Han, P., Zhang, X., Yang, B., Liu, Y., & Guo, L. (2022). Computation offloading in mobile edge computing networks: A survey. Journal of Network and Computer Applications, 202, 103366.

[62] Nencioni, G., Garroppo, R. G., & Olimid, R. F. (2023). 5G Multi-Access Edge Computing: A Survey on Security, Dependability, and Performance. IEEE Access, 11, 63496–63533. https://doi.org/10.1109/ACCESS.2023.3288334

[63] Moshiri, P. F., Simsek, M., & Kantarci, B. (2024 (Accepted) Preprint: https://arxiv.org/pdf/2401.10390.pdf). On the Interplay Between Network Metrics and Performance of Mobile Edge Offloading. IEEE International Conference on Communications (ICC).

[64] Soyturk, M., Muhammad, K. N., Avcil, M. N., Kantarci, B., & Matthews, J. (2016). Chapter 8 - From vehicular networks to vehicular clouds in smart cities. In M. S. Obaidat & P. Nicopolitidis (Eds.), Smart Cities and Homes (pp. 149–171). Morgan Kaufmann

[65] Refaat, T. K., Kantarci, B., & Mouftah, H. T. (2016). Virtual machine migration and management for vehicular clouds. Vehicular Communications, 4, 47–56.

[66] He, X., Yang, X., Lv, J., Zhao, J., Luo, T., & Chen, S. (2023). A Cluster-Based UE-Scheduling Scheme for NR-V2X. IEEE Transactions on Vehicular Technology, 72(4), 4538–4552.

[67] Hegde, A., Song, R., & Festag, A. (2023). Radio Resource Allocation in 5G-NR V2X: A Multi-Agent Actor-Critic Based Approach. IEEE Access, 11, 87225–87244.

[68] Sabeeh, S., Wesołowski, K., & Sroka, P. (2022). C-V2X Centralized Resource Allocation with Spectrum Re-Partitioning in Highway Scenario. Electronics, 11(2).

[69] Wang, Y., Zhang, L., Wei, C., & Tang, Y. (2023). Joint optimization of resource allocation and computation offloading based on game coalition in C-V2X. Ad Hoc Networks, 150, 103266.

[70] Björnson, E., Jorswieck, E., & others. (2013). Optimal resource allocation in coordinated multi-cell systems. Foundations and Trends® in Communications and Information Theory, 9(2–3), 113–381.

[71] Goerigk, M., & Hartisch, M. (2023). A framework for inherently interpretable optimization models. European Journal of Operational Research, 310(3), 1312–

1324.

[72] Zhu, F., & Ukkusuri, S. V. (2015). A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment. Transportation Research Part C: Emerging Technologies, 55, 363–378.

[73] 3GPP TS 38.211 V17.5.0. (2023-06-26). 5G; NR; Physical channels and modulation (3GPP TS 38.211 version 17.5.0 Release 17).

[74] 3GPP TS 36.211 version 17.4.0. (2023-09-29). LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 17.4.0 Release 17).

[75] Shannon, C. E. (1949). Communication in the presence of noise. Proceedings of the IRE, 37(1), 10–21.

[76] Kamal, M. A., Raza, H. W., Alam, M. M., Su'ud, M. M., & Sajak, A. binti A. B. (2021). Resource allocation schemes for 5G network: A systematic review. Sensors, 21(19), 6588.

[77] Resource Allocation Management Unit. (n.d.). https://www.sharetechnote.com/html/Handbook_LTE_ResourceAllocation_ManagementUnit.html, (Accessed 16.04.2024).

[78] 3GPP TS 23.558 v17.4.0. (2022-06-13). Architecture for enabling Edge Applications (3GPP TS 23.858 version 17.4.0 Release 17).

[79] Kumar, K., Liu, J., Lu, Y.-H., & Bhargava, B. (2013). A survey of computation offloading for mobile systems. Mobile Networks and Applications, 18, 129–140.

[80] Mach, P., & Becvar, Z. (2017). Mobile edge computing: A survey on architecture and computation offloading. IEEE Communications Surveys & Tutorials, 19(3), 1628–1656.

[81] Zhou, H., Wang, H., Chen, X., Li, X., & Xu, S. (2018). Data offloading techniques through vehicular ad hoc networks: A survey. IEEE Access, 6, 65250–65259.

[82] Sirhan, N. N., & Martinez-Ramon, M. (2022). LTE Cellular Networks Packet Scheduling Algorithms in Downlink and Uplink Transmission, A Survey. International Journal of Wireless & Mobile Networks (IJWMN), 14(2), 1–15.

[83] Hahne, E. L. (1991). Round-robin scheduling for max-min fairness in data networks. IEEE Journal on Selected Areas in Communications, 9(7), 1024–1039.

[84] Kushner, H. J., & Whiting, P. A. (2004). Convergence of proportional-fair sharing algorithms under general conditions. IEEE Transactions on Wireless Communications, 3(4), 1250–1259.

[85] Holtzman, J. M. (2001). Asymptotic analysis of proportional fair algorithm. 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications. PIMRC 2001. Proceedings (Cat. No.01TH8598), 2, F-F.

[86] Jalali, A., Padovani, R., & Pankaj, R. (2000). Data throughput of CDMA-HDR a high efficiency-high data rate personal communication wireless system. VTC2000-Spring. 2000 IEEE 51st Vehicular Technology Conference Proceedings (Cat. No. 00CH37026), 3, 1854–1858.

[87] Medhi, D., & Ramasamy, K. (2018). Chapter 17 - Packet Queueing and Scheduling. In D. Medhi & K. Ramasamy (Eds.), Network Routing (Second Edition) (Second Edition, pp. 596–625). Morgan Kaufmann.

[88] Jain, R. K., Chiu, D.-M. W., Hawe, W. R., & others. (1984). A quantitative measure of fairness and discrimination. Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA, 21.

[89] Wang, H., Lin, Z., Guo, K., & Lv, T. (2021). Computation offloading based on game theory in MEC-assisted V2X networks. 2021 IEEE International Conference on Communications Workshops (ICC Workshops), 1–6.

[90] Kaddour, F. Z., Pischella, M., Martins, P., Vivier, E., & Mroueh, L. (2013). Opportunistic and efficient resource block allocation algorithms for LTE uplink networks. 2013 IEEE Wireless Communications and Networking Conference (WCNC), 487–492.

[91] Abiko, Y., Saito, T., Ikeda, D., Ohta, K., Mizuno, T., & Mineno, H. (2020). Flexible resource block allocation to multiple slices for radio access network slicing using deep reinforcement learning. IEEE Access, 8, 68183–68198.

[92] Masello, L., Sheehan, B., Murphy, F., Castignani, G., McDonnell, K., & Ryan, C. (2022). From traditional to autonomous vehicles: A systematic review of data availability. Transportation Research Record, 2676(4), 161–193.

[93] Jing, Y., & Jafarkhani, H. (2009). Single and multiple relay selection schemes and their achievable diversity orders. IEEE Transactions on Wireless Communications, 8(3), 1414–1423.

[94] Elbal, B. R., Schwarz, S., & Rupp, M. (2020). Relay selection and coverage analysis of relay assisted V2I links in microcellular urban networks. 2020 IEEE Wireless Communications and Networking Conference (WCNC), 1–7.

[95] Pan, B., & Wu, H. (2022). Modeling and analysis of multi-relay cooperative communications in C-V2X networks. IEEE Transactions on Intelligent Transportation Systems, 23(9), 16371–16385.

[96] Abbas, F., Fan, P., & Khan, Z. (2019). A Novel Low-Latency V2V Resource Allocation Scheme Based on Cellular V2X Communications. IEEE Transactions on Intelligent Transportation Systems, 20(6), 2185–2197.

[97] Maglogiannis, V., Naudts, D., Hadiwardoyo, S., van den Akker, D., Marquez-Barja, J., & Moerman, I. (2022). Experimental V2X Evaluation for C-V2X and ITS-G5 Technologies in a Real-Life Highway Environment. IEEE Transactions on Network and Service Management, 19(2), 1521–1538.