Development of Cooperative Platoon Based Scheduling Strategies for Intersection Management in V2X Communication

A Dissertation

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ELECTRONICS AND COMMUNICATION ENGINEERING

(With Specialization in Communication Systems)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in the dissertation report entitled **"Development of Cooperative Platoon Based Scheduling Strategies for Intersection Management in V2X Communication"** towards the partial fulfilment of the requirements for the award of the degree of **Master of Technology** with specialization in **Communication Systems**, submitted in the Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out during the period from July 2018 to June 2019, under the guidance and supervision of **Dr. P. M. Pradhan**, Assistant Professor, Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, Roorkee (India) and **Dr.-Ing. Markus Fidler**, Head of the group, Communication Networks, Institute of Communications Technology, Leibniz University Hannover, Hannover (Germany).

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CERTIFICATE

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ABSTRACT

Traffic congestion is a widespread concern since the emergence of automobiles. The most affected areas are road intersections which are vulnerable to fatal accidents and environmental damages. In the past decade, a number of strategies and technologies have been developed to mitigate this problem. The conventional strategies such as traffic lights, use of public transport, *etc.*. have been beneficial. However, innovative strategies are still needed. One of the emerging technologies is autonomous driving in cooperative intelligent transportation systems using vehicle to everything (V2X) communication. Vehicles travel along the road by exchanging information with their surrounding using V2X communication. IEEE 802.11p protocol supports V2X communication for achieving traffic efficiency along with road safety. Furthermore, for increasing the road capacity, vehicles travel in tightly formed groups called platoons following coordinated movements of their leaders. For better traffic flow control, the advanced driver assistance strategy Cooperative Adaptive Cruise Control (CACC) is adopted. CACC is a longitudinal control system for intelligent automatic cruising of platoons.

This thesis work aims at implementing and analyzing the cooperative platoon based scheduling strategies for managing road intersections using V2X communication. The first strategy considers space based traffic control (STC) that involves platoon rearrangement to utilize road capacity and maximize number of vehicles crossing intersection in green phase of signal. The density based traffic control (DTC) allows traffic of greater density to pass through the intersection. The proposed position based traffic control (PTC) prioritizes platoons based on their proximity to intersection. DTC and proposed PTC are decentralized approaches which have platoons making their own independent decisions on crossing intersection. They involve dynamic traffic lights which reserve time space and activate desirable phase for incoming platoons dynamically to reduce waiting delay at red signal. Performance metrics of IEEE 802.11p protocol such as channel load and data packet losses are used for comparing the strategies. The three strategies are implemented using a coupled network simulator with OMNET++ for vehicular communication and SUMO for simulating traffic. Simulation results show better performances of DTC and proposed PTC strategies as compared to STC strategy in terms of travel capacity, throughput and waiting delay criteria. This thesis also illustrates that although DTC has comparable results as those of proposed PTC, it lacks in reliability and safety due to high channel busy ratio and packet loss ratio.

Contents

List of Figures

List of Tables

Abbreviations

ITS	Intelligent Transport System
V2X	Vehicle to Everything
VANET	Vehicular Ad-Hoc Network
ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
MIXIC	Microscopic Model for Simulation of Intelligent Cruise Control
V2V	Vehicle to Vehicle
IEEE	Institute of Electrical and Electronics Engineers
WAVE	Wireless Access in Vehicular Environment
IT	Information Technology
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2D	Vehicle-to-Device
RSU	Road Side Unit
3GPP	3rd Generation Partnership Project
C-V2X	Cellular Vehicle to Everything
DSRC	Dedicated Short-Range Communications
OSI	Open Systems Interconnection
OMNeT++	Objective Modular Network Testbed in C++
SUMO	Simulation of Urban Mobility
VENTOS	Vehicular Network Open Simulator
MAC	Media Access Control
EDCA	Enhanced Distributed Channel Access
OFDM	Orthogonal Frequency Division Multiplexing
WLAN	Wireless Local Area Network
OSI	Open Systems Interconnection
WIFI	Wireless Fidelity

PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependent
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
FCC	Federal Communications Commission
CCH	Control Channel
SCH	Service Channel
ETSI	European Telecommunications Standards Institute
CAM	Cooperative Awareness Message
DENM	Decentralized Environmental Notification Message
WSM	Wave Short Message
TraCI	Traffic Control Interface
LAD	Lane Area Detector
MDL	Maximum Density Lane
CMDL	Complimentary Maximum Density Lane
QOS	Quality of Service
DCF	Distributed Coordination Function
AC	Access Category
CW	Contention Window
AIFS	Arbitration Inter-Frame Spacing
PLR	Packet Loss Ratio
CBR	Channel Busy Ratio
OJF	Oldest Job First
ITLC	Intelligent Traffic Light Control
DAIAC	Decentralized Autonomous Intersection Access Control
STC	Space Traffic Control
DTC	Density Traffic Control
PTC	Position Traffic Control

Symbols

S	Opportunity space
p_j	Current position of vehicle j
$p_j{}'$	Future position of vehicle j
p_T	Position of intersection or traffic light
v_j	Current speed of vehicle j
T_r	Time left for red phase of light to start
$S_{D,j}$	Demanding space of vehicle j
l_j	Length of vehicle j
$d_{\min,j}$	Minimum inter-vehicle distance of vehicle j
$d'_{\min,j}$	Minimum inter-platoon distance of vehicle j
T	Total simulation time
T_s	Simulation time step

Chapter 1

Introduction

Due to the ever increasing number of vehicles on road, issues such as traffic congestion, accidents, environmental pollution, *etc.* have been continuously increasing. Traffic lights, traffic police, stop signs, roundabouts, *etc.* are few traditional methods to regulate vehicular flow on roads. Although these conventional strategies have been effective for ages but they have limited performance in managing traffic. Therefore, enhancement of already existing system is required by new innovative strategies. Due to inefficient traffic system, accident rates are increasing every year. The data recorded by national crime record bureau ministry of home affairs states that per one hundred thousand of population, the accident deaths in India is around 0.4 million and around 0.45 million for year 2013 and 2014 respectively [11]. The situation in the European Union is similar, about 45,000 deaths and 2 million injured people, approximately costing around €150 billion per year. Similarly in the United States, around 120 people dies and around 8000 people are into accidents each day [12].

Intelligent transport systems (ITS) has been a worldwide research subject with many involved groups such as vehicle infrastructure integration consortium in the United States, the Car2Car communications consortium in Europe, and the advanced safety vehicle project in Japan [12]. V2X technology has been widely adopted due to its ability to share information in the surrounding among vehicles resulting in better traffic flow. Information is shared among vehicles using IEEE 802.11p standards of wireless communication. One of the major concept of ITS is vehicle platooning which is grouping of vehicles in closely operating form to increase road capacity. Vehicular platooning employs V2X communication to coordinate movements between platoon leader and followers. Using the aforementioned technologies, strategies are developed to ensure safety, to improve traffic flow, and to decrease fuel consumption, travel time, economical and environmental damages.

Since traffic from all directions traverses intersection, it is considered to be the most vulnerable area for fatal accidents and congestion. Although conventional traffic light manages competing traffic flows and provides safe crossing through intersection, but it has low efficiency due to idle green phase or queuing delay of vehicles. It not only limits throughput at intersections but also causes unnecessary fuel consumption and air pollution. Several promising strategies incorporating vehicular ad-hoc networks (VANETs) aim on scheduling incoming traffic flow in an efficient way. VANETs supports vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) based wireless communication for data exchange to facilitate ITS. The exchange of information plays a crucial role in road safety and throughput improvement scheduling strategies. The communication efficiency depends upon channel characteristics and radio propagation conditions. A reliable, low delay, minimum data packet loss wireless network is needed for safe and efficient traffic system. In VANET, information messages dissemination operates on IEEE 802.11p and IEEE 1609 protocols based dedicated short range communication (DSRC) standards. These protocols support wireless access in vehicular environment (WAVE) to provide ITS based applications. It uses seven 10MHz bandwidth control and service channels in 5.9 GHz band range. IEEE 802.11p uses enhanced distributed channel access (EDCA) for medium access control (MAC) layer and orthogonal frequency division modulation (OFDM) for physical layer (PHY). For communication parameters analysis, performance of PHY and MAC characteristics needs to be taken into consideration.

Literature provides many scheduling and control strategies incorporate above technologies for creating an intelligent way of traversing traffic flow. To increase traffic flow through signalized intersection, various intelligent scheduling strategies have been designed to manage conflicting traffic flows. Some centralized approaches involve role of intersection manager to provide vehicles an optimal course to pass intersection based on the information received from them [13,14]. But this involves high computational cost and load on intersection managers. Other findings focus on interaction among vehicles using V2X communication to take scheduling decisions without any central controller. Researchers have tried to come up with strategies based on game theory [15], heuristic algorithm [16], modified webster's formula [17], online algorithm [8], *etc.* for feasible scheduling. These strategies have shown significant results in reducing the waiting time and queue length at intersection. The OAF algorithm based on oldest job first (OJF) criterion performs better than others by reducing the delay of vehicles using collected knowledge of traffic arrivals at intersection. But this approach is feasible for only light traffic loads. Literature also shows scheduling of traffic flow based on parameters such as flow density, traffic speed, queuing probability, *etc.* [18]. In [7], an intelligent traffic light controlling algorithm schedules traffic based on traffic density and claims to perform better than the OAF algorithm.

In this thesis, different scheduling strategies for platoons has been studied which are aiming to cross intersection with improved throughput and safety. Main focus of these strategies is on reducing the halt time of vehicles at intersection and allowing maximum transfer through intersection. On exploring the possibilities of optimizing traffic throughput and performing various platoon maneuvers for efficiently crossing intersections, two state-of-art strategies along with a novel strategy have been discussed and evaluated. Analysis and discussion of communication performance metrics such as packet losses due to bit errors and collisions, channel busy time due to channel congestion are discussed. These parameters are obtained for the three above mentioned strategies and their behaviour is observed with changing traffic density.

1.1 Literature Review

In the past few decades numerous researches and studies have been carried out to coordinate traffic flow at intersections with an aim to improve traffic efficiency. In many studies, pre-timed static traffic lights are replaced by dynamic traffic lights system which respond to real time data from vehicles. Several factors such as number of vehicles, position, speed, priority of vehicles, etc. are considered for scheduling traffic across intersection. All these scheduling algorithms [18, 19] aims at enhancing intersection performance by intelligent management of competing traffic flow and reducing travel time of vehicles. One of the most widely adopted method is to impart the knowledge of traffic light schedule plan to vehicles [20, 21]. Many researchers [21, 22] utilize the traffic phase data for modifying speed profile of vehicles to escalate number of vehicles crossing intersection within green phase signal. The shortcoming of these approaches is disorderly individualistic operation without any cooperation among vehicles. Further studies suggest cooperative methods that improve the traffic flow at intersections in two ways: cooperative driving system and platoon based control system. Traffic light based cooperative driving systems provide flexibility to vehicles to depart from existing platoon or to join a new platoon for improved cruising through intersection [13]. This method involves intersection manager to provide safe and better trajectory for vehicles crossing intersection. Second system uses information gathered from platoons to adapt the timing plan of traffic light and schedule uninterrupted platoon crossing through intersection [23].

In [10], a cooperative adaptive cruise control algorithm for platoon management in the vicinity of intersections is introduced to increase the throughput. The framework is based on space rearrangement approach to fully exploit road capacity and assigning the available opportunity space to maximum vehicles possible. Vehicles assigned with the opportunity space are required to find their accelerating trajectories to cross intersection with improved throughput. V2X communication is used for broadcasting opportunity space availability and other related information to improve traffic efficiency. However, in the above work the activation movement of algorithm is not clearly stated. Also, since the algorithm is based upon fix scheduled traffic light, halting and waiting delay of vehicles is long. Thus reducing the efficiency of vehicles to cross intersection in the lowest time possible.

In [24], using V2X communication, traffic lights receive information regarding density of vehicular clusters to set its timing cycle. This work considers traffic control at each signalized intersection independently. The studies in [8, 25] represent traffic signal scheduling as job scheduling by adopting OJF algorithm for equally sized platoons considered as jobs. The aim of above adaptive traffic control algorithm is to reduce platoon delay at intersections. In [7], an intelligent traffic light controlling (ITLC) algorithm is proposed to schedule traffic flow based on density calculated in the virtual ready area. This real time data of vehicle crowd present in ready area simulates the traffic light timing cycle. Research presented in [26] discusses a centralized priority based coordination approach at intersection without traffic light. The decentralized priority based traffic control protocol using genetic programming for setting order of priorities to cross intersection is exhibited in [27]. Research in [28] shows a decentralized autonomous intersection access control (DAIAC) strategy which allows vehicles to take localized scheduling decisions and compute actuated signal based on information shared among vehicles.

All the above studies are significantly improving intersection throughput and utilizing road capacity, yet each of them still has the scope for performance improvement. Therefore contribution to the field of optimum scheduling strategies for intersection management is a relentless process. In this thesis, the past techniques are collaborated with some new modifications to explore new domains of existing methods. Decreasing the complexity of previously mentioned algorithms, a new simple technique is also introduced to attain the goal. The comparative studies of the strategies based on space, density and proximity aspects of scheduling is provided.

STC strategy focuses on reorganizing platoons into categories for optimum space utilization in order to maximize the number of vehicles crossing an intersection during green phase of traffic light. It is derived from space rearrangement approach proposed in [10]. This centralized strategy is based on timing schedule of traffic light and explores required platoon maneuvers before and after intersection for improving throughput at intersection. The other two strategies are decentralized traffic scheduling algorithms that takes discrete decisions based on information shared among vehicles. The traffic light phase is actuated based on the farthest vehicle of platoon crossing the intersection. Thus, it reduces load on intersection manager by having a distributed system and also eliminates idle green phase of traffic light. The second strategy which is DTC, involves detectors to compute densities of traffic flow toward intersection. The traffic flow with the highest density is scheduled to cross intersection first by modifying its speed profile. From the findings, DTC is on the concept of the nearly optimum performing ITLC algorithm [7] that has better results than strategies like OJF algorithm [8]. The third strategy which is PTC, is a novel strategy in which every vehicle analyzes gathered information from surrounding vehicles and schedules based on platoons' proximity to intersection.

1.2 Objective

The main aim is to obtain a practical working model of V2X based decentralized and flawless traffic intersection by deploying cooperative platoon based scheduling strategy for intelligent traffic management system. This thesis also aims to study various performance metrics for comparing scheduling strategies in different traffic density scenarios.

1.3 Outline

This thesis is structured as follows:

CHAPTER 2: This chapter provides an insight about the relevant concepts involved in the thesis. A brief description about ITS, vehicle platooning, platoon maneuvering, concept of adaptive cruise control (ACC) and its advancement into cooperative adaptive cruise control (CACC), V2X communication along with its IEEE802.11 WAVE protocol are provided. Information regarding safety messages, traffic light phase planning and non-conflicting traffic routes are provided.

CHAPTER 3: This chapter includes scenario description of the working environment along with details of simulation environments OMNeT++, SUMO and TraCI. The three cooperative platoon based scheduling strategies are described with the help of flowcharts. Also, the working of dynamic traffic light and message dissemination in strategies are discussed. This chapter also includes brief discussion on communication channel performance metrics.

CHAPTER 4: This chapter discusses about simulation scenario setup. The results of simulations are provided and discussed.

CHAPTER 5: Lastly, conclusions regarding scheduling strategies are discussed along with the future scope of the thesis.

Chapter 2

Background

This chapter provides an insight about all the essential theoretical concepts related to the thesis. Brief description of each topic along with their role in the strategies are discussed.

2.1 Intelligent Transport System

This world of internet has brought many technical advancement in our day to day life. From laptops, cellphones, weather forecast, searches, *etc.* everything in our life is affected by information technology (IT). Recently, the new direction of IT is towards the transportation system. The conventional methods of a traffic police or a traffic light is now improved by bringing IT into picture. IT aims not only on safe and secure transportation but also on increasing the throughput of roads and capacity of vehicles. This transformation of vehicular transportation system into an intelligent efficient operation mode brings the concept of ITS. ITS is possible with electronic devices such as sensors, *etc.* and latest wireless technologies. With the help of latest technologies ITS aims to attain the following agendas:

- Safety of drivers and pedestrians by avoiding accidents specially at intersections by using applications such as cooperative intersection collision avoidance.
- Throughput improvement and performance enhancement of vehicles by using techniques such as V2X communication and platooning.
- Taking care of the comfort of drivers and vehicle constraint check with ACC and CACC strategies.
- Environmental friendly transportation by controlling fuel consumption and CO_2 emission.

2.2 Vehicle Platooning

One of the major concepts of ITS is vehicle platooning which aims at increasing the road capacity. Vehicle platooning is grouping of vehicles in closely operating form. Platoons operate in similar way by stopping or accelerating simultaneously. Thus, reaction will be quicker, and hence accidents can be avoided. This ensures the safety from fatal situations. The formation of platoon includes a platoon leader controlling traffic flow trajectories of its followers. The leader vehicle interacts with its followers and surrounding through DSRC enabled V2X devices. Every vehicle of a platoon travels on the same lane while maintaining a safe distance from its preceding vehicle. Compact formation of platoon vehicles maximize the road capacity, and thus provide better traffic throughput. Platooning also improves the efficiency of any strategy implemented at intersection by reducing the communication overhead of wireless interaction among platoons instead of individual vehicles. This is mainly because instead of vehicles interacting among themselves, platoon leader interacts with the surrounding on behalf of its entire platoon. This approach resolves the issue of communication load by taking into account the recent platooning and connected vehicle techniques.

Fig. 2.1. Two platoons of vehicles

Platoon maneuvers such as formation, splitting, merging, etc can be performed at requirement to further improve the road transportation. Vehicle platooning can be environmental friendly by saving fuel consumption as they experience less air resistance by closely grouping together. Fig. 2.1 shows two typical platoons placed on a lane with sizes of three and six vehicles respectively. The first vehicle of platoon is generally the leader and is shown by red color in the figure. Rest of the vehicles are followers of platoon having decreased intensity of color as placed farther from the leader.

2.3 Adaptive Cruise Control and Cooperative Adaptive Cruise Control

ACC is an automatic intelligent way of cruising which controls speeding up and slowing down process by itself. It involves the use of sensors like radar sensors, lasers, cameras, *etc.* to maintain a safe distance or gap from the vehicle in front. This is an autonomous way of driving which keeps the safety and convenience of driver into consideration. This also aims to maintain a minimum separable distance between vehicles to increase the road capacity.

ACC can be modified into CACC which uses technologies like V2X communication for safe and efficient cruising. As the name suggests, Cooperative ACC allows vehicles to cooperate with its surrounding environment by wireless communication. CACC is better than ACC in terms of improved string stability which is amplification of oscillation into upstream direction from leader to followers [29]. Using V2X communication, CACC ensures that vehicles not only communicate with their preceding vehicle but with everything that is surrounding and affecting them. Figs. 2.2 and 2.3 show vehicle platooning using ACC and CACC methodology, respectively.

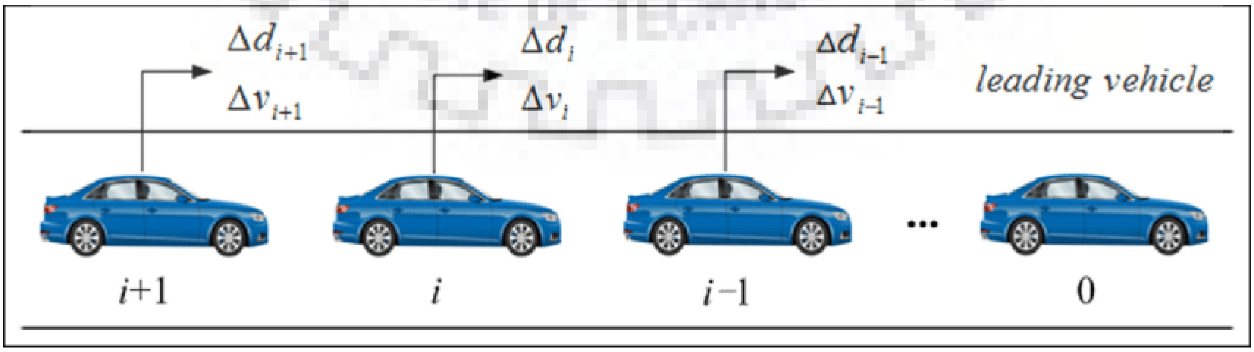


Fig. 2.2. Vehicle platooning using ACC [1]

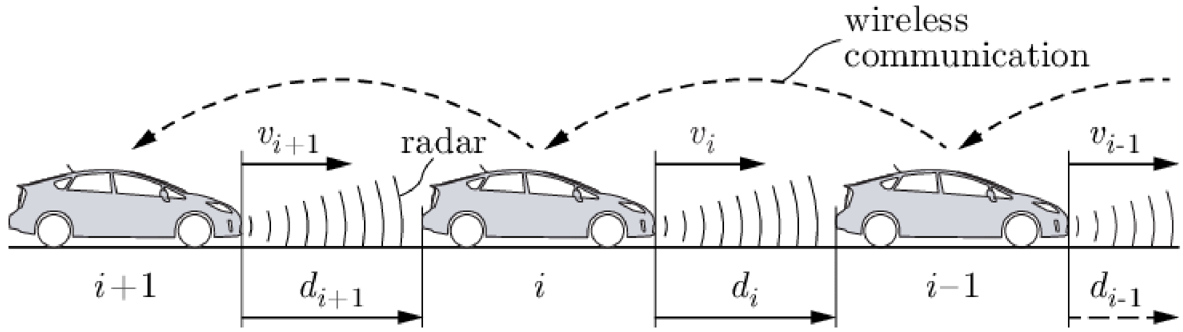


Fig. 2.3. Vehicle Platooning using CACC [2]

2.4 Vehicle to Everything Communication

To mitigate traffic congestion problem, many solutions are proposed in the past including sensors like cameras, radars, *etc.* But these methods have their own limitations, which restrict them to fully improve and handle traffic management problems. Therefore, research in the field of V2X came into picture. This technology turns the dream of autonomous driving into reality. As the name describes, this way of communication includes transmission and reception of information from vehicle to anything affecting its motion or vice-sa-versa. This system includes many different forms such as Vehicle to Vehicle (V2V) communication, Vehicle to Infrastructure (V2I) communication, Vehicle to Network (V2N) communication, Vehicle to Pedestrians(V2P) communication, Vehicle to device (V2D) communication, *etc.*

V2V communication is all about transfer of information between vehicles directly or through other vehicles acting as intermediate hops. V2I communication manages traffic by sharing information between vehicle and road side units (RSUs) in two or more hops. V2N communication handles traffic flow by broadcasting information to vehicles thus creating a non real time way of communication between internet and vehicles. V2P communication shares information between vehicles and pedestrians like any other contributors to traffic. V2D is information sharing between vehicles and any electronic device related to the vehicle.

As mentioned earlier, V2X is the technology which ensures safe and efficient traffic flow on roads. All around awareness of the environment is essential for an autonomous vehicle. This can be achieved if one has the knowledge of nearby vehicles, pedestrians, and everything affecting that vehicle. Thus V2X allows communication among all entities, and hence it makes autonomous driving possible. Fig. 2.4 illustrates a general V2X communication scenario.

Some important characteristics of V2X communication are discussed below:

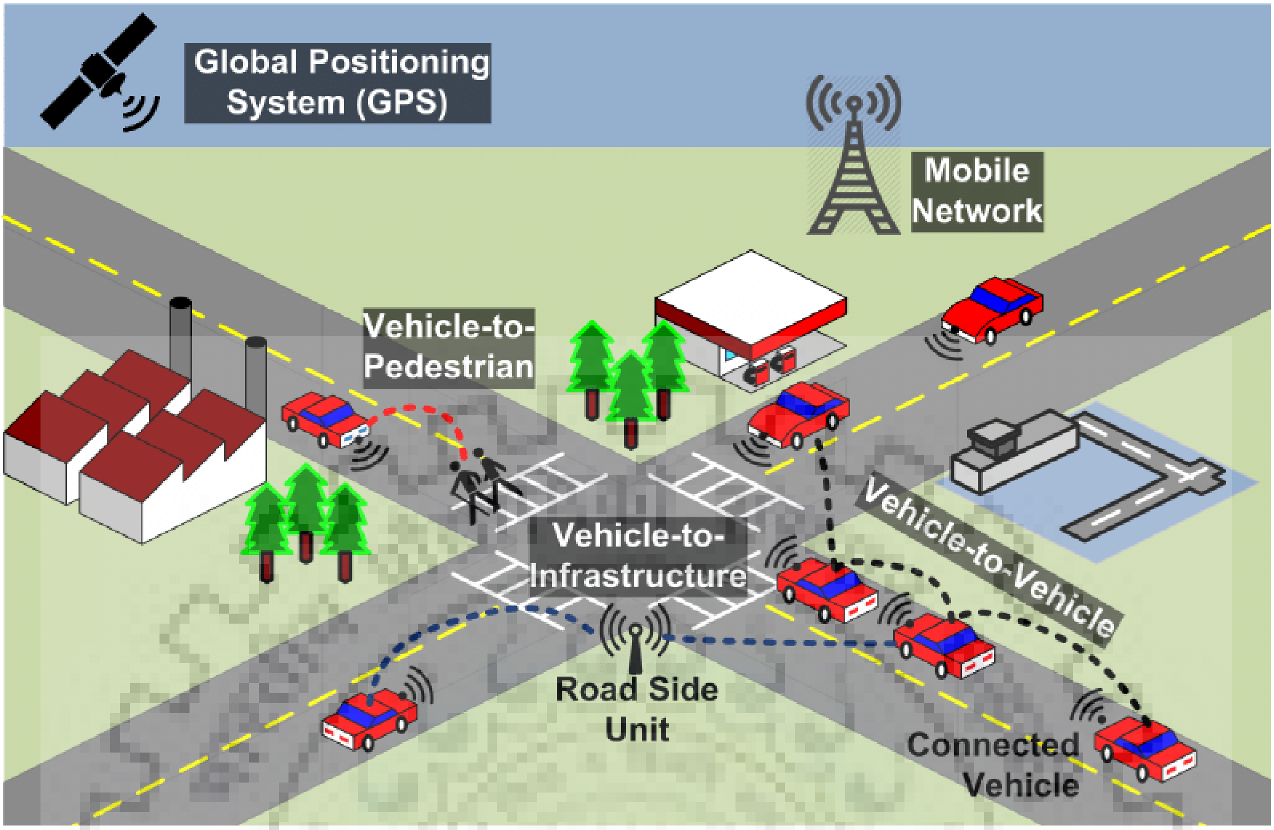


Fig. 2.4. Vehicle to Everything Communication [3]

- **Communication Range**: The effective area of V2X communication is small as it is generally dependent on WIFI based 802.11p protocol having short range communication. In traffic management, since the vehicles move rapidly thus exchange of information and connectivity among vehicles can be weak if a larger experimental environment is considered. It is directly associated to reliability and safety criteria.

- **Security and Privacy Constraints**: Since this technology is based on transmission and reception of data for creating awareness of surrounding, therefore privacy of vehicles does not exist. All the vehicles have to expose their identity as well as other details to the surrounding. Security glitches exist in this technology as anyone can manipulate the transmitted data resulting threat to safe traffic flows.

- **Power**: A vehicle can move for hours depending on its requirement therefore the power requirement of V2X devices has to be low. These devices can also be charged by vehicles battery like any other equipment. V2X devices consumes low power and therefore can work for long hours.

- **Latency**: Communication latency in reception of messages is really essential in urgent safety related scenarios. Therefore, V2X devices are designed to minimize the latency of transmitted messages as low as possible.

Some potential applications of V2X technology are as follows:

- **Safety**: This technology includes communication through two kinds of safety messages including periodic messages and event driven messages which are discussed in later sections. Periodic messages can be used to create timely periodic awareness of surrounding. Event driven messages are transmitted to inform required receiver to take precaution of tragic events or after measures in cases of some unfortunate events such as an accident. Some examples are collision alerting, obstacle warning, vehicle breakdown alerting, *etc.*

- **Non-safety**: These are applications which have no relation to safe road transportation but are needed for providing convenience and comfort to drivers. It can be regarding assisting drivers with information about fuel stations, restrooms, restaurants, toll collection booths, *etc.*

- **Driver Assistance**: V2X communication can provide facilities such as providing road navigation, digital maps, real time traffic information, *etc.*

2.5 V2X Communication Protocol

V2X communication is based on two types of technologies including wireless local area network (WLAN) and cellular networking. IEEE published WLAN based V2X which supports V2V and V2I direct communication whereas 3GPP published cellular V2X (C-V2X) which supports V2N, V2D, *etc.* forms of communication in addition to direct communication.

IEEE 802.11p standard based V2X enables information exchange for high speed vehicle to their surrounding environment by forming vehicular ad-hoc network. This improves latency issues in V2X communication. IEEE 802.11p standard is an up-gradation of IEEE 802.11 standard by adding vehicle communication system called WAVE. For vehicular applications, DSRC is a special wireless protocol based on WAVE technology. For WAVE, the DSRC standard involves protocol families such as IEEE 1609.x for higher layers and IEEE 802.11p for basic low layers of networking. In Fig. 2.5, the WAVE architecture is illustrated.

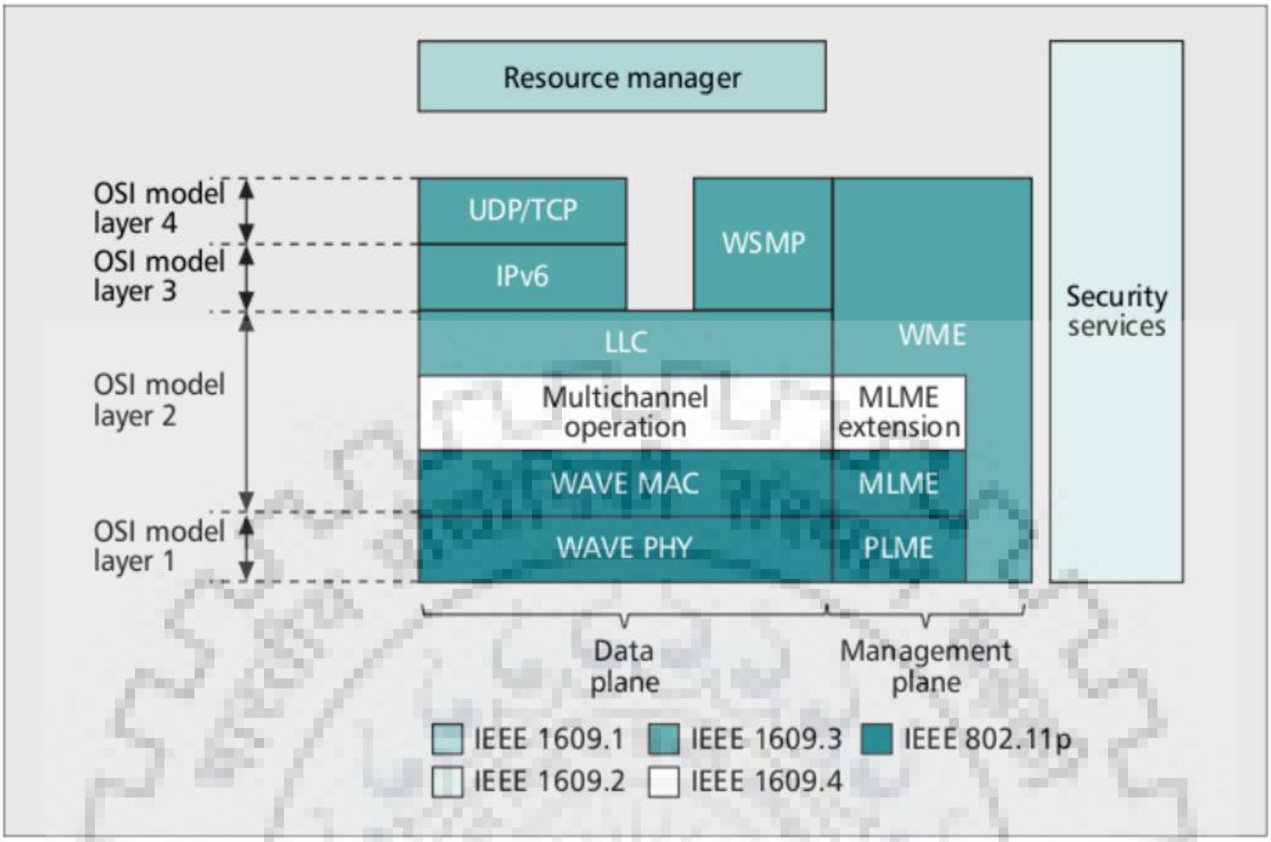


Fig. 2.5. WAVE protocol stacks [4]

WAVE consists of following protocols:

- **IEEE 802.11p:** It is an extension of IEEE 802.11 protocol for vehicular applications. It generally works in PHY layer of open systems interconnection (OSI) model.
- **IEEE 1609.1:** It works in application (APP) layer, and used for resource management.
- **IEEE 1609.2:** It functions in security layer of OSI model for security purposes. It ensures reliable transmission of messages for efficient communication. Thus, it involves functions such as encryption, formatting, *etc.*.
- **IEEE 1609.3:** It is used for providing networking services of communication.
- **IEEE 1609.4:** It manages multiple channels at the same time.

The IEEE 802.11p standard works on DSRC spectrum band and manages physical and MAC layer of OSI model [30]. IEEE 802.11p physical layer is similar to that of IEEE 802.11a having two sub-layers physical layer known as convergence procedure (PLCP) and physical medium

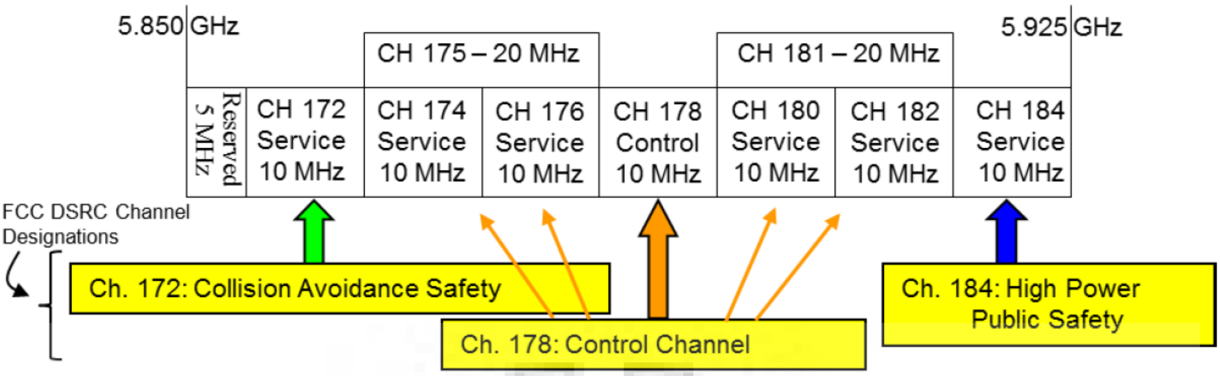


Fig. 2.6. DSRC spectrum band plan [5]

dependent (PMD). The issue of Doppler effect due to sensitivity of carrier frequency offset in OFDM has been successfully resolved in IEEE 802.11p protocol by reducing sub carrier spacing to half. For MAC layer, IEEE 802.11p adopts EDCA strategy of IEEE 802.11e which uses carrier sense multiple access/collision avoidance (CSMA/CA) technique for accessing medium. DSRC spectrum consists of seven 10MHZ channels for this standard and uses 5.9GHZ frequency in the licensed ITS band. According to federal communications commission (FCC) band plan for DSRC, channel 178 is the control channel (CCH) on which safety messages are transmitted, four are service channel (SCH) carrying non safety general purpose user messages and two end channels with channel number 172 and channel 184 are for collision avoidance safety and high power public safety respectively. Fig. 2.6 shows spectrum band plan of DSRC spectrum by FCC.

2.6 Safety Messages

VANET includes broadcasting of two kinds of safety messages. One is regular periodic safety messages which allows interaction of vehicles with surrounding by communicating basic information messages. It includes general awareness information such as vehicles location, length, route, velocity, *etc.* The messages are sent at a certain periodic interval with a frequency of 2 Hz-10 Hz to ensure update of information among vehicles. The second category is event triggered safety messages which enacts on occasions of abnormal situations and thus needs to be informed to destined receiver on emergent criterion. The transmission is ought to be urgent, prioritized and secure to reach destination for event awareness.

Keeping in mind the above two safety messages, European telecommunications standards institute (ETSI) introduced the concept of communicating information of real time vehicular scenarios through message dissemination. The DSRC based wireless vehicle communication technology involves broadcasting of two types of safety messages: cooperative awareness message (CAM) and decentralized environmental notication message (DENM).

CAM involves periodic distribution of real time awareness data to neighbouring nodes located within single hop distance from the sender vehicle. As described in ETSI standards, the structure of CAM involves a header to store information about the message and a body having information regarding senders information. DENM serves as an ITS application that notifies triggered traffic events to specified destination. Unlike CAM, DENM is sent to specific destined receiver only when an event is triggered.

2.7 Platoon Maneuvering

Vehicles travelling in platoons often engage in maneuvers for better rearrangement of traffic along the road. In control laws there exist three basic maneuvers: splitting, merging and changing lanes. In this thesis, splitting and merging maneuvers have been focused upon to increase efficiency. Engaging in these maneuvers, vehicles can perform various tasks such as joining an already form platoon, getting separated from its own platoon, leader leaving its leadership to join succeeding platoon, *etc.* As required in any platoon, the key to successful maneuvers is periodic beacon messaging and event triggered messaging to coordinate the entire procedure with its surrounding vehicles. This information sharing and cooperative autonomous driving through messages is possible by V2X enabled devices. Also, vehicles are CACC capable in a platoon which allow them to travel in closely packed group maintaining a safe gap from preceding vehicle. As shown in Fig. 2.7, the coordination layer of vehicles has required platoon management protocol for enabling platoon maneuvers. Regulation and physical layers of vehicles which manage CACC control logic are also shown in the figure. The detailed procedure of merge and split maneuver is mentioned below.

Merge Maneuver: In this process, a platoon or a group of vehicles sends a request to its succeeding platoon leader for merging into one platoon. On successful reception of the request by succeeding platoon, the two platoons merge to form one big platoon. Platoon leader of rear platoon initiates this maneuver if the combined platoon size of both platoons is less than the optimum platoon size. This procedure functions as shown in following steps:

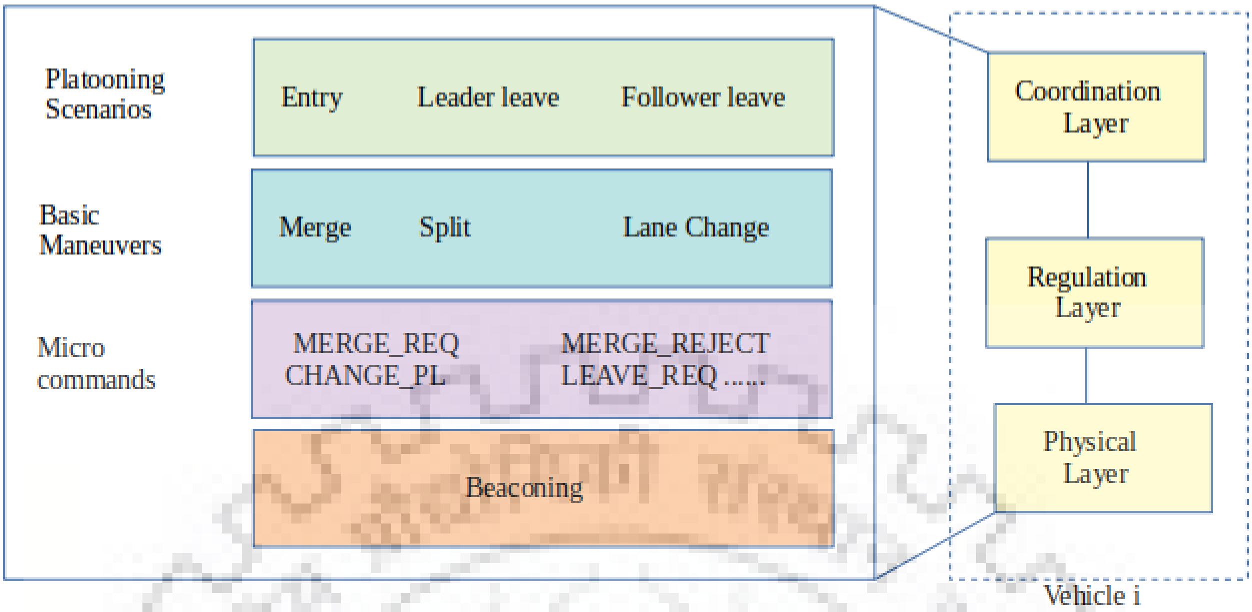


Fig. 2.7. Platoon management protocol resides in the coordination layer of each vehicle [6]

1. The merge initiates for two scenarios: Firstly on receiving a regular periodic beacon message from the front platoon if the rear platoon leader finds that the platoon size is under optimum platoon size or secondly if it gets a command from the RSU or front platoon to initiate the merge manually. In both the cases, the rear platoon leader sends $MERGE\_REQ$ to the leader of front platoon by extracting its platoon ID from received messages.

2. The leader of front platoon can either accept or reject the $MERGE\_REQ$ obtained from rear platoon depending on whether it is available to perform any maneuver at that moment or not. The leader can send $MERGE\_REJECT$ to reject or delay merging of platoons, also when the final platoon size is more than the optimum platoon size.

3. If the rear platoon leader receives a $MERGE\_ACCEPT$, then it readily starts the converging procedure. Firstly, it will change its time gap to intra-platoon spacing, inform its follower vehicles to change their leader to front platoon leader by $CHANGE\_PL$ command and accelerates to higher speed to catch up with the front platoon for merging into it. On successful completion of all tasks, it sends $MERGE\_DONE$ command to front platoon leader to update its configurations such as platoon size, platoon depth, *etc.* and finally changes its state to follower from leader. On the other hand, if it receives $MERGE\_REJECT$ then it has an option of again sending $MERGE\_REQ$ to front pla-

toon.

Split Maneuver: Opposite to merge maneuver, split maneuver involves a group of vehicles or even a single vehicle separating from its platoon to form smaller platoon. Like merge maneuver, this is also initiated by platoon leader to split the platoon at some particular depth of platoon. It usually happens in two conditions: if the platoon size is not able to justify optimum platoon size or if the leader gets split request from the followers or RSU. The procedure of splitting a platoon occurs in following steps:

1. The platoon leader of splitting platoon sends $SPLIT\_REQ$ command to the follower vehicle at which splitting is to be performed.

2. The split request receiving follower can either accept or reject the request of the platoon leader.

3. If the leader receives $SPLIT\_ACCEPT$ command from splitting vehicle, it sends back command message $CHANGE\_PL$ so that the splitting vehicle becomes the leader of new splitting platoon. Also, it sends $CHANGE\_PL$ to vehicles following splitting vehicle to change their leader from earlier platoon leader to new platoon leader i.e, splitting vehicle.

4. Finally, the former platoon leader informs the new platoon leader of successful splitting by sending $SPLIT\_DONE$ command.

5. On receiving command from the former platoon leader, the new platoon can slow down to get separated from its base platoon. To avoid rear end collision of newly formed platoon leader with its followers on deceleration, this step is performed at the end of whole splitting process.

There exists many more maneuvers such as platoon leader leave maneuver, follower leave maneuver, entry maneuver, lane change maneuver, *etc.*.

2.8 Traffic Light

Traffic lights as shown in Fig. 2.8 are light signals used to control the movement of traffic flow. For simulation purpose, SUMO generates real time traffic lights at junctions by providing programs for setting behaviour. While defining traffic light, it is also required to specify its

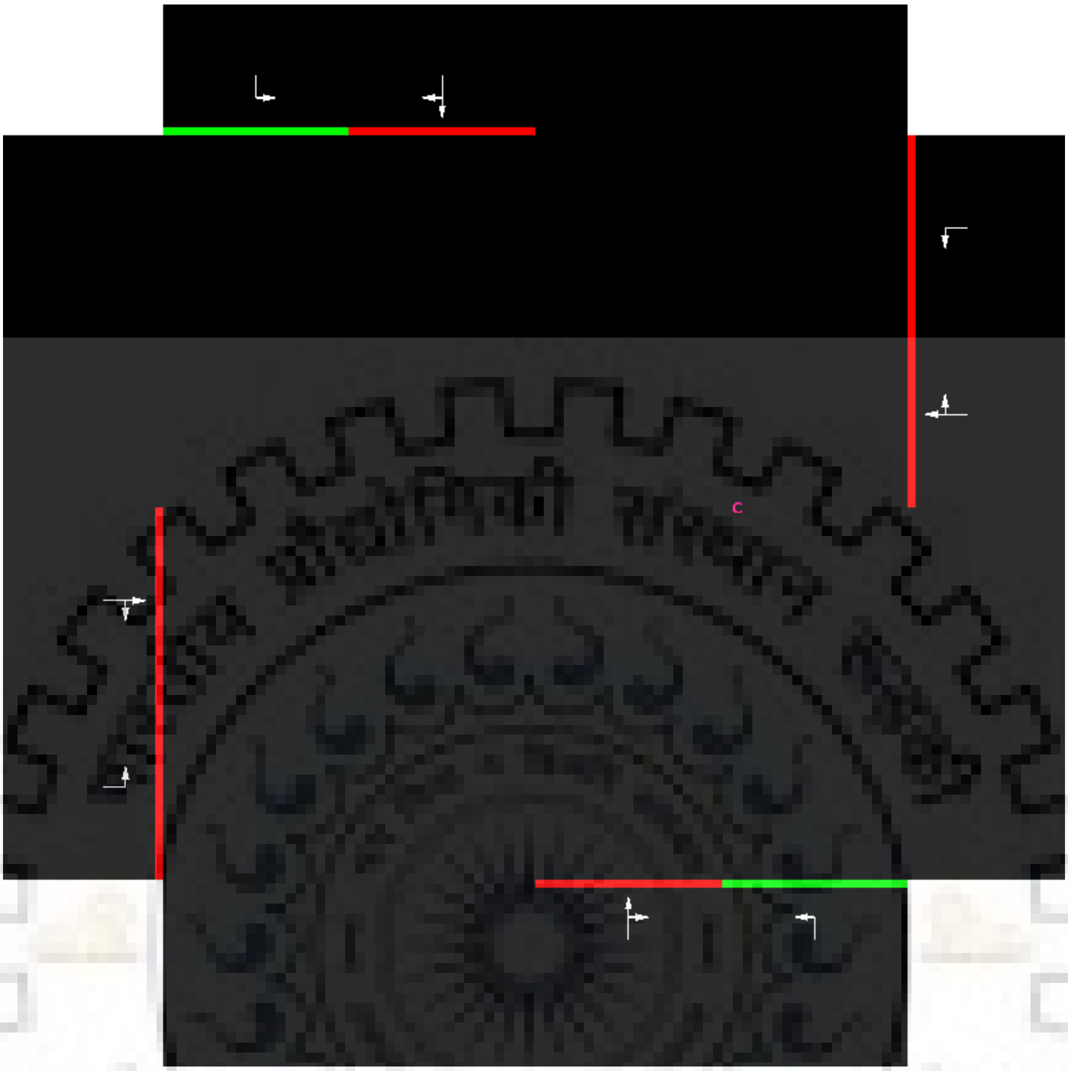


Fig. 2.8. Traffic lights placed at four way intersection

type first. Traffic lights can be static with fixed phase duration, actuated for phase prolongation based on time gaps between vehicles, or delay_based for phase prolongation based on accumulated time loss of queued vehicles. For every program, a new program id needs to be mentioned for particular traffic light. Different programs can be written for same traffic light as it is possible to switch program using TraCI. In each program, phases are defined using attributes such as duration of phase, state of traffic lights in that phase, minimum duration and maximum duration in case of actuated traffic lights, *etc.* The state of traffic light phase mentions signal for each lane by using its characters. A signal mentioned in state controls the links for individually managing movements of vehicles travelling in specific manner through junctions. Table 2.1 describes some commonly used characters of traffic light states and their description.

Traffic Light Phase Characters	
Characters	Description
r (Red)	For stopping vehicles
y (Yellow)	For allowing nearby vehicles to pass and faraway vehicles to stop at junction
g (Green)	For allowing vehicles to pass when no prioritized stream else decelerate them
G (Light Green)	For allowing vehicles to pass without priority constraint
u (Orange)	For alerting about upcoming green phase

Table 2.1: Signal types for controlling traffic

2.9 Non-conflicting Routes

A place on road segment where traffic from all direction try to move to other side crossing the mid point called intersection. When vehicles from all around try to cross intersection simultaneously it causes collisions and accidents. Therefore, signalized intersections allows only non conflicting traffic to flow at a time. Vehicles with priorities are allotted with green light on their lanes to cross intersection whereas other conflicting vehicles are made to stop at red signal and wait for next phase of green signal. This introduces delay in the movement of vehicles and thus reduces capacity of vehicles to flow smoothly.

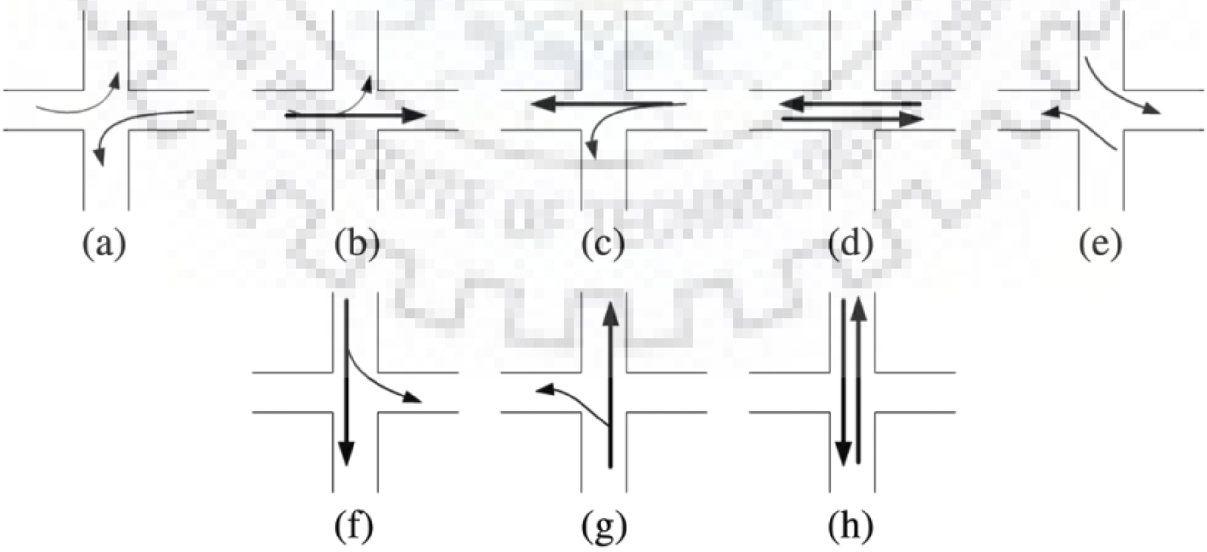


Fig. 2.9. Allowed non-conflicting route movements [7]

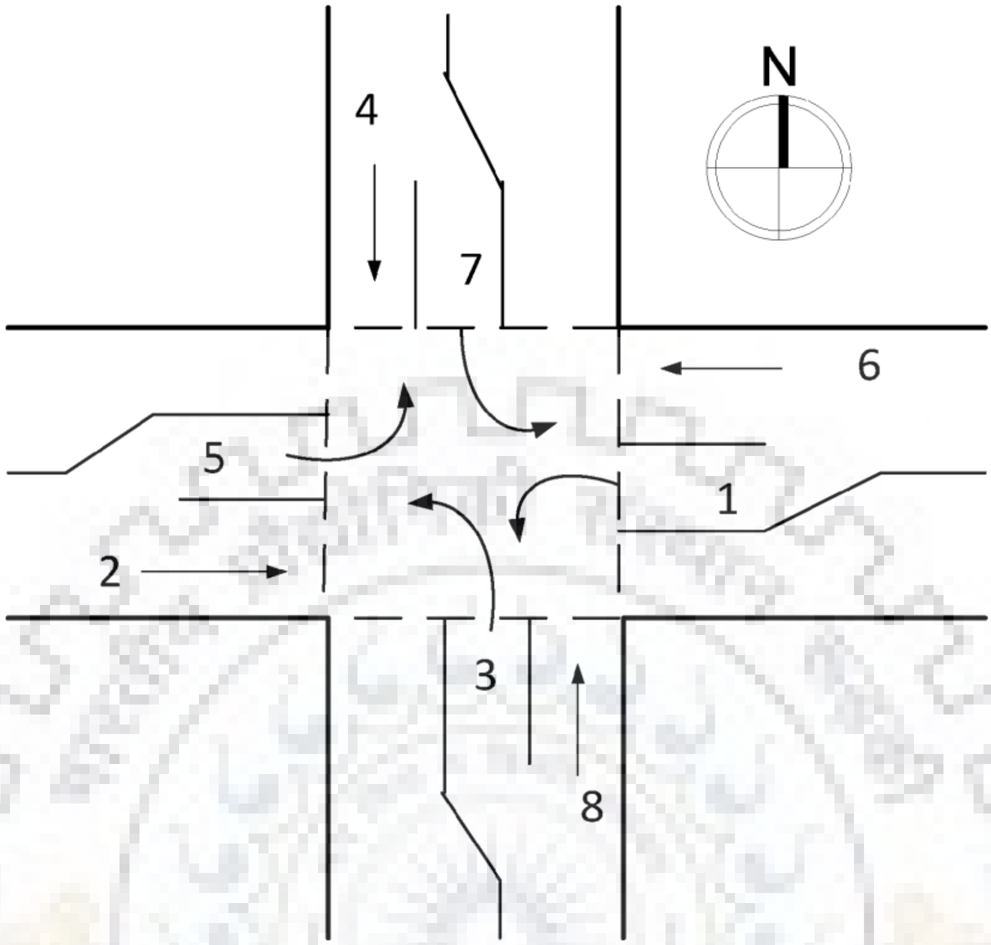


Fig. 2.10. Typical four-way intersection showing different movements on approaching intersection [8]

Fig. 2.9 shows allowed non-conflicting movement of vehicles following numbering sequence of routes depicted in Fig. 2.10. These are the movements which allows crossing intersection without collisions as they do not share a common region to cause any clash.

Chapter 3

Methodology

This chapter provides an insight on the simulation environment platform along with details of road network created for the thesis. Detailed description of the scheduling strategies are also provided. Important concepts related to the strategies such as space time reservation of phases in traffic lights, types of messages and their dissemination, communication performance metrics are discussed.

3.1 Scenario Description

For studying the strategies, all the vehicles are assumed to be installed with V2V devices for communicating relevant information. Also, assumptions are made regarding the homogeneity of vehicles having same size, speed, type, *etc.* Activities such as platoon formation, lane shifting maneuver, *etc.* are considered to be already completed in the beginning of the simulation, and such strategies are already been taken care of before entering the action zone of the algorithm. The platoons are considered to be flexible in nature in terms of performing splitting and merging maneuvers.

To explain the strategies, there are some strategy based scenario modifications. Since STC is following a centralized approach, the flow of vehicles is being controlled by fixed phase traffic lights at intersection. The timing plan of traffic light cycle is provided to platoons of vehicles through V2X communication using which operation of the strategy proceeds in green phase of light. DTC strategy is based on traffic density, therefore requires lane area detectors (LADs) on each lane at some distance ahead of intersection for calculating road traffic. Also, a RSU is placed at intersection to receive information regarding density of vehicles approaching intersection from

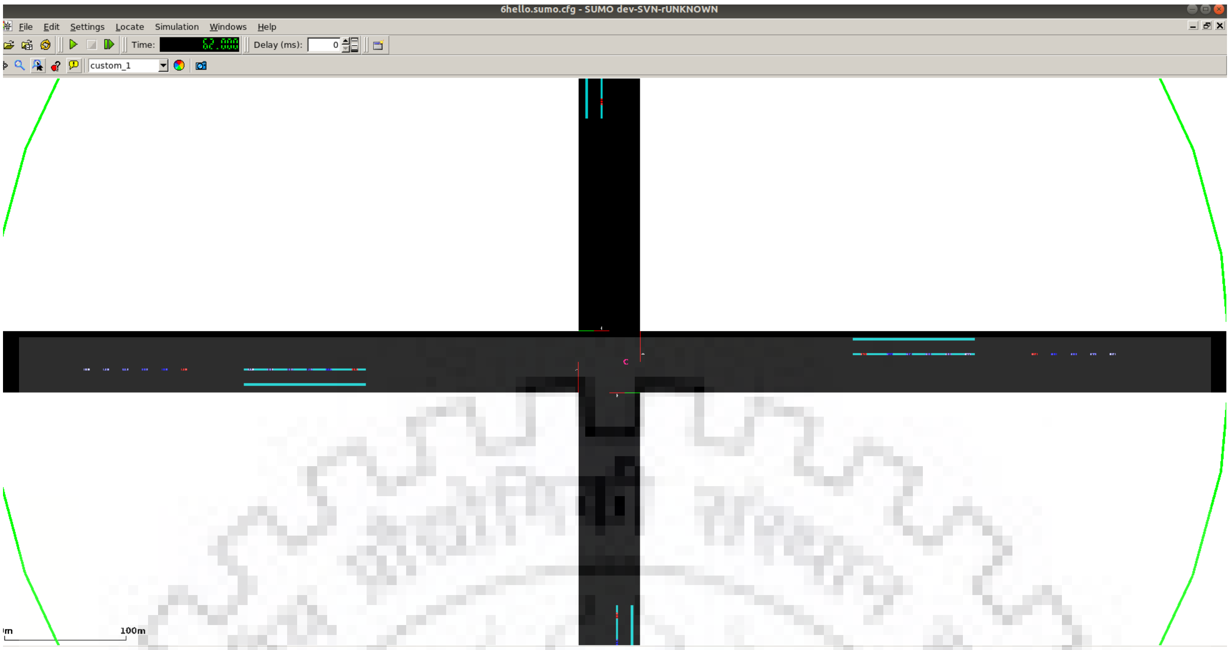


Fig. 3.1. Signalized four way intersection

LADs and broadcast information of heaviest density lane to all platoons through wave short messages. In proposed PTC strategy, no RSU or detectors are required. This strategy is solely based on interaction among platoons through messages and scheduling decisions are taken on the received information. The traffic lights used in DTC and proposed PTC are actuated according to the incoming platoons at intersection. Thus provide a decentralized atmosphere to the strategies for traffic flow through intersection.

Fig. 3.1 shows a signalized four way intersection with RSU placed in the middle marked by red dot mark. The range of RSU is 500 m radius which is shown by green circle. The blue lines on lanes show the lane area detectors used in DTC strategies to calculate number of vehicles crossing through it.

3.2 Simulation Environment

The working environment of the thesis includes vehicular network open simulator (VENTOS) which an integrated software consisting of two operable simulators: OMNeT++ [31] which is a network simulator for vehicular communication and SUMO [32] which is a road traffic simulator for traffic simulation [33]. The two simulators are connected through an interface called TraCI. These are briefly described as follows:

3.2.1 OMNeT++

OMNeT++ is termed as objective modular network testbed in C++ which is a network building simulator. It has C++ framework with many features such as:

- Creating and configuring models.
- Graphical network editor for network description (NED) files.
- Analyzing simulation results.
- Plotting data curves, *etc.*

It has two types of user interfaces including graphical user interface and command line user interface for executing simulations.

3.2.2 SUMO

Simulation of urban mobility (SUMO) is an open source road traffic simulator which simulates traffic on road. It is basically used for vehicle routing, traffic analysis, network performance, *etc.* SUMO has many features such as:

- Modeling from vehicles to pedestrians thus providing microscopic and mix traffic simulations.
- Interaction with TraCI to control simulations.
- Traffic light schedule information.
- Multiple formats like openStreetMap, openDRIVE, VISUM, *etc.*
- Providing tools like NETCONVERT, NETEDIT, GUISIM, *etc.* for simulations.

3.2.3 TraCI

TraCI is traffic control interface which gives permission to get and set values of objects in running traffic simulations and thus can alter nature of ongoing simulation. However its major purpose it to connect both the simulators. TraCI uses TraCIScenarioManagerInet module to initiate the network formulation. By connecting to TraCI server which is SUMO, it starts with generating vehicles, lanes in the network. Alongside a OMNeT++ compound module is generated simultaneously for each network node such as vehicle generated in SUMO. TraCIMobility is used by TraCI to proceed with simulations at periodic intervals in SUMO by revising values if altered. This way a network is generated and gets updated for simulations. Fig. 3.3 illustrates a workflow model of VENTOS simulation frmaework consisting of OMNeT++ and SUMO connected via TraCI.

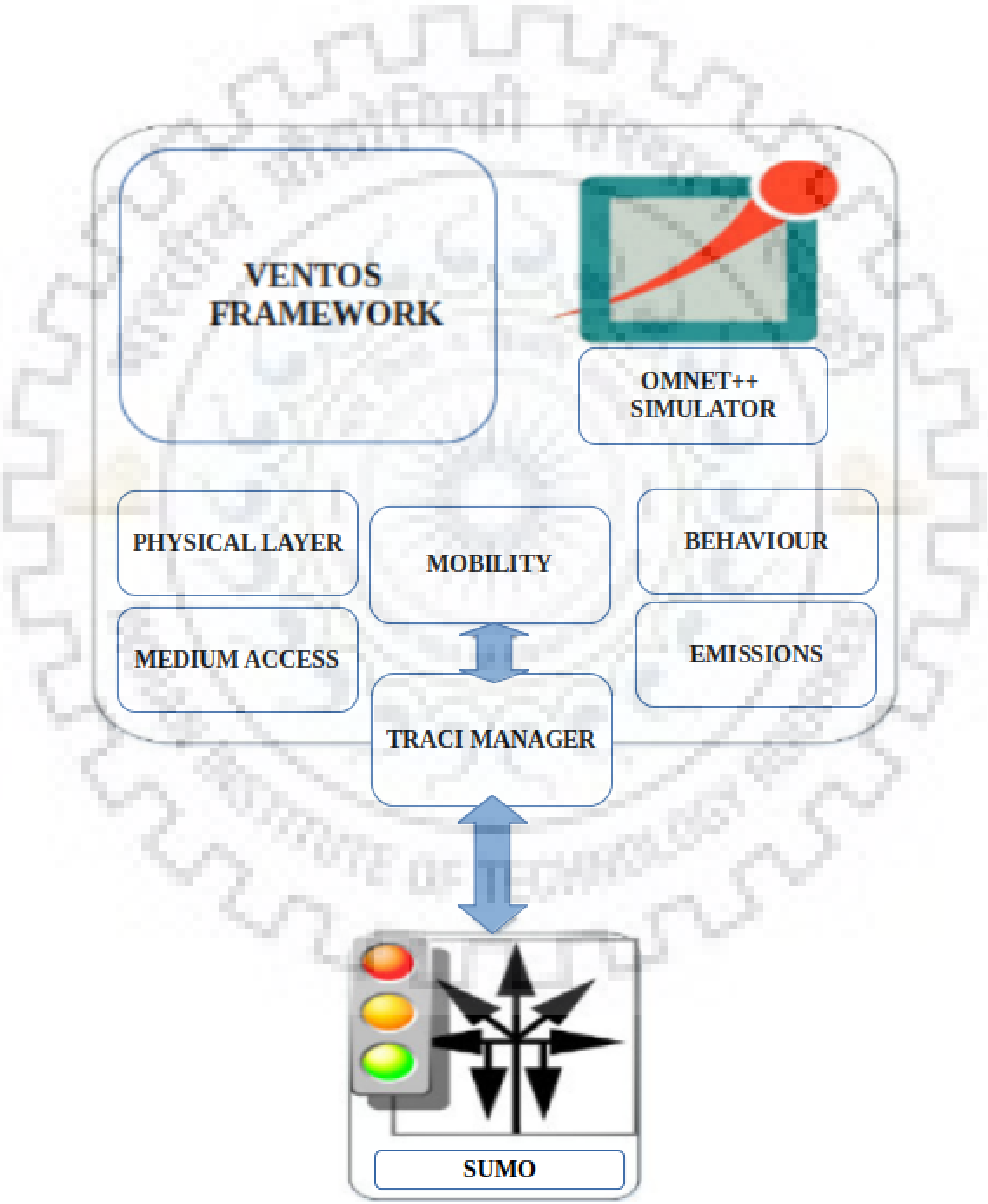


Fig. 3.2. Workflow of VENTOS Simulation Framework [9]

3.3 Traffic Flow Cooperative Strategies

The three proposed strategies for platoon based cooperative intersection management are discussed below. Various factors such as space, density and proximity are explored for scheduling traffic flow through intersection.

3.3.1 Strategy 1: Space Based Traffic Control

The objective of this strategy is to maximize number of vehicles crossing through intersection during green phase of traffic light. The timing schedule of traffic light is made available to the vehicles through beacon messages from RSU. The algorithm works as described in [10] with some minor modifications. In order to maximize road capacity, this algorithm focuses on categorizing vehicle platoons into three categories. First is C1 category consisting of platoons which can pass through the intersection during green phase with no change in their velocity or maintaining the same speed. Next is C2 category having platoons which can pass through the intersection in remaining green phase if they accelerate to a higher velocity. Lastly platoons falling under C3 category are those which cannot pass in the current cycle so they decelerate their velocities till traffic light phase is green again. For this algorithm an important concept of opportunity space S is introduced which can be calculated based on platoons' future position and timing of traffic phase. Each vehicle after initiation of algorithm receives timing schedule of signal using which it calculates its opportunity space. Based on the opportunity space, vehicle takes decision on which category it belongs to.

Let v_j be the current steady speed and T_r be the time left for red phase of light to start. So using these two parameters and current position p_j of the vehicle j, the future position $p_j{}'$ of vehicle is calculated. Then with the knowledge of traffic light position p_T and future position of vehicle $p_j{}'$, opportunity space S is calculated as follows:

$$\boldsymbol{S} = p_j' - p_T = p_j + v_j * T_r - p_T \text{ [10]} \tag{3.1}$$

At the end of green phase, vehicles having future position beyond the intersection is considered to be in C1 category. The last vehicle of C1 category broadcasts its opportunity space S using V2X communication for further categorization. For broadcasting opportunity space the strategy uses *SpaceAdjust* message with commands mentioned in *cmdType* as $OPPO\_SPACE$. Based on the opportunity space following vehicles can decide on how many vehicles can be accommodated into that space in future if they accelerate their velocities and thus can go under C2 category. Vehicles will therefore evaluate their demanding space $S_{D,j}$ (length of the vehicle along with minimum inter-vehicle distance) and take this minimum needed space from opportunity space obtained from last vehicle of C1 platoon. The demanding space is calculated as follows:

$$\boldsymbol{S}_{D,j} = l_j + d_{\min,j} \text{ [10]} \tag{3.2}$$

$$\boldsymbol{S}_{D,j} = l_j + d'_{\min,j} \text{ [10]} \tag{3.3}$$

where l_j is the length of vehicle j, $d_{\min,j}$ is the minimum inter-vehicle distance of vehicles within the platoon and $d'_{\min,j}$ is the minimum inter-platoon distance for the first vehicle of the platoon. Leader of the platoon follows (3.3), and followers follow (3.2) to calculate their demanding space. Hence, this strategy aims to calculate and distribute the opportunity space to maximum number of vehicles possible utilizing the available road capacity.

Each time it is checked whether the opportunity space is larger than the demanding space of undertaken vehicle. If it is so then that vehicle is taken into C2 category and on satisfying safety constraints it accelerates till the activated green phase of light. Vehicles in C2 category take out the needed space by it from the opportunity space and pass the left over new opportunity space to following vehicles of its platoon through *SpaceAdjust* message. At the tail of the platoon, left opportunity space is broadcasted for following platoons to receive. If for some vehicle the demanding space is larger than the opportunity space received, then that vehicle goes into C3 category. After initial categorization of vehicles, C2 category vehicles accelerates with maximum speed if their speed constraint is satisfied otherwise placed into C3 category. The C2 category vehicles are informed to accelerate through *SpaceAdjust* message using *SPEED_CHANGE* as *cmdType*. The C2 category's accelerating platoon vehicles split from its following C3 category vehicles to join C1 category vehicles. The information of splitting vehicle in C2 category vehicle is provided to platoon leader through *SpaceAdjust* message with *cmdType* as *SPLIT_DEPTH* and taking *value* as depth of splitting vehicle. After platoons cross intersection, they tend to merge with each other under suitable conditions such as allowed optimum size, similar routes, *etc.* The splitting and merging maneuvers are facilitated by *PlatoonMsg* with *plnMode* set to *platoonManagement* and *cmdType* taken as per requirements. In this strategy, scheduling is dependent on fixed nature of traffic light and RSU, therefore it is a centralised strategy. However since more number of vehicles cross intersection during active green phase of light, it improves the throughput performance of vehicles. Fig. 3.4 shows the flowchart of STC strategy.

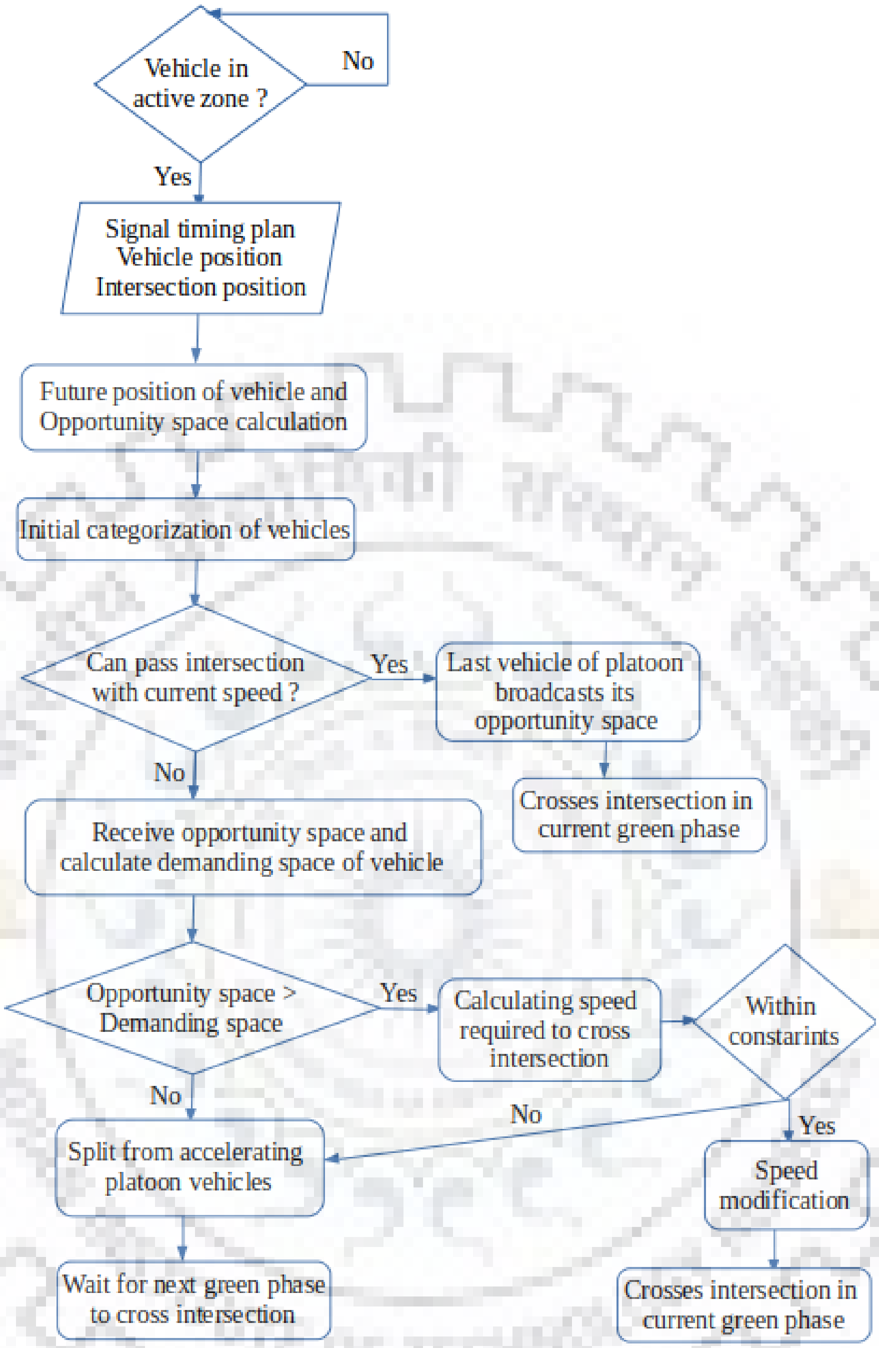


Fig. 3.3. Flowchart of STC strategy [10]

3.3.2 Strategy 2: Density Based Traffic Control

DTC is a scheduling strategy for managing competing traffic flow at isolated road intersections by providing priority to lanes having highest density platoons. Scheduling in this algorithm is based on mixed density of vehicles travelling on non-conflicting lanes to pass simultaneously.

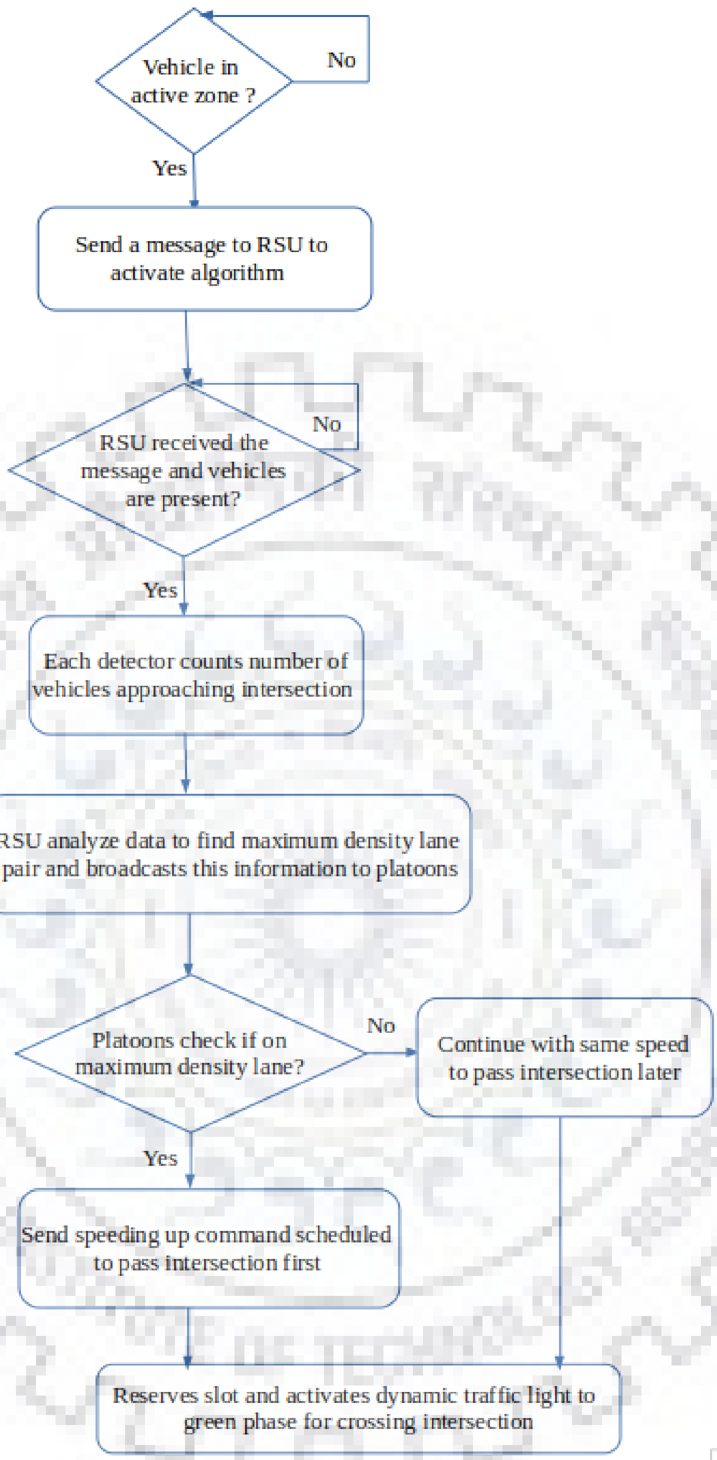


Fig. 3.4. Flowchart of DTC strategy

In Fig. 3.5, the algorithm is introduced briefly through a flowchart. When the algorithm initiates, vehicles request for max density lane pair information from the RSU through $SignalControlMsg$ using $cmdType$ as $ACTIVATE\_ALGO$ and $controller$ value set to true. As soon as the RSU receives the request from vehicles, it demands density data from the detectors of each lane. The detectors used in this algorithm are LADs of SUMO that covers specified length of area along a lane. Sorting the obtained information from LADs, RSU first calculates the maximum density lane (MDL) based on real time traffic. Then complimentary lanes to MDL are found based on non-conflicting route data provided in section 2.9 and traffic densities on them are compared. The suitable complimentary lane traffic is allowed to proceed along with the traffic on MDL. After comparison and analysis of density data, RSU broadcasts message containing information regarding MDL, complimentary MDL (CMDL) and total traffic density on both lanes to all the nearby platoons. For this purpose it uses $LaneInfoMsg$ with required field values obtained from RSU. Platoons on the maximum density pair of lanes are scheduled first through intersection by setting modified phases of traffic light. The prioritised platoons are accelerated to maximum speed using *SpaceAdjust* message and *cmdType* as $SPEED\_CHANGE$. Maximum density lanes are provided with green phase and other set of lanes are provided with red phase for efficient scheduling of competing flows. The strategy for actuation of phases of traffic light according to real time traffic flow is discussed later.

Along with increasing throughput, minimization of waiting delay time is achieved by modifying the speed of platoons on maximum density lanes. These platoons are accelerated to their maximum speed to pass through intersection earlier than others, so that remaining platoons would have less waiting time at intersection. This process of evaluating traffic density beforehand, speeding up of prioritized platoons and activating desired phases of traffic lights are repeatedly performed.

3.3.3 Strategy 3: Position Based Traffic Control

The proposed position based or proximity based traffic control strategy is a fully decentralized approach without the involvement of RSU or any centralized controller. In this scheduling strategy, every platoon leader gathers information and takes discrete decisions based on information shared among surrounding platoons. It then allots priority to platoons having closer proximity towards intersection. This algorithm functions by broadcasting of IEEE 802.11p based wave short message $InfoMsg$ containing platoon information of position, speed, lane, *etc.* to every other platoon leader on adjacent or competing lanes. Since decisions are taken entirely based on the received messages, therefore load on intersection manager is reduced to a great extent and simplicity in prioritizing vehicular flow for higher throughput is achieved. With simplicity and efficiency, this approach also has an advantage of low cost of operation as no additional infrastructure or devices are required.

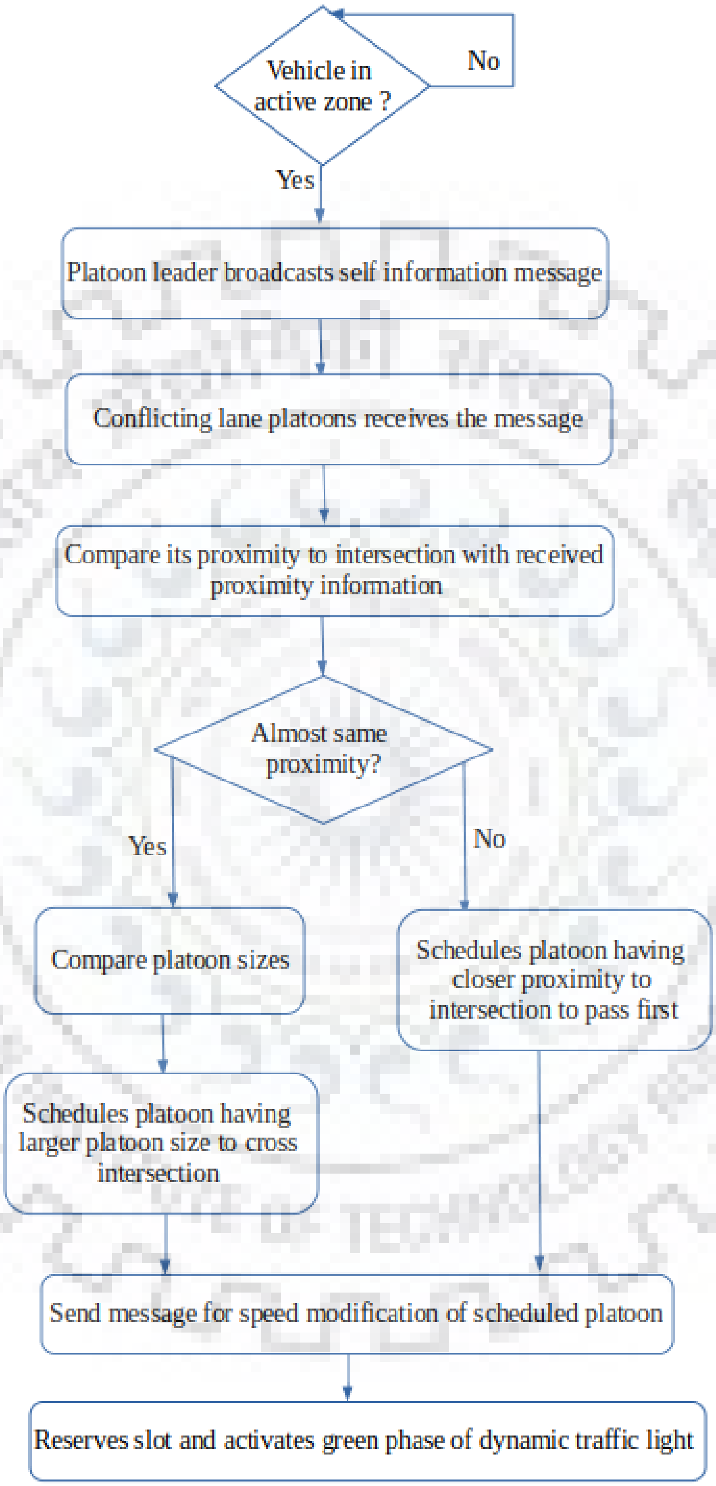


Fig. 3.5. Flowchart of proposed PTC strategy

As shown in Fig. 3.6, the platoon leaders broadcast their information messages $InfoMsg$ as they start approaching intersection. Platoon leaders travelling on conflicting lanes receive the messages from sender platoons through V2V communication. These messages synchronize their clocks like beacon messages using 802.11 standard. On receiving the position and other data, leader makes a comparison primarily on the basis of position and proximity from intersection. If the platoons are within similar range of distance from intersection, then they are further judged on the basis of platoon sizes. Thus in case of almost same proximity from intersection, platoon with greater size is scheduled first to pass intersection otherwise scheduling is performed by prioritizing platoons primarily on the basis of position only.

The prioritized platoons approach intersection earlier than other platoons by speed modification to attain their maximum speeds. This way waiting delay time can be reduced significantly. Also, the traffic light phases are actuated based on the scheduled real time traffic flow such that prioritized approaching platoon of vehicles get a green pass at intersection on its arrival. The phase type and duration are set according to the farthest vehicle of platoon crossing the intersection. Thus vehicles have to wait for lesser time at intersection during each scheduled phase. This way the performance is improved by decreasing the average waiting time delay of vehicles at intersection.

3.4 Space Time Reservation of Traffic Phase

Above scheduling algorithms are scheduling traffic by prioritizing competing vehicles to pass through intersection in a systematic way. These algorithms focus on increasing the number of vehicles crossing intersection, hence maximizing throughput at a signalized intersection. As discussed above, STC is a centralized strategy with fixed traffic lights having permanent phase cycles whereas DTC and proposed PTC are decentralized approaches with actuation type traffic light. The phase type is set and reserved depending on the incoming real time traffic flow so that approaching platoons of vehicles get quicker green pass at intersection on their arrival. Therefore vehicles have to wait for lesser time at intersection during each scheduled phase. This way the performance is improved by decreasing the average delay waiting time of vehicles at intersection.

The dynamic traffic light phase cycles are being controlled by real time traffic characteristics instead of operating according to their usual fixed profiles. It works on the principle of reserving slots at traffic light to activate green phase of light for crossing intersection. A parameter called $SIGNAL\_CONTROL$ is defined which allows reserving slots for manipulation of signal phases if set to true. When signal controlling is not in action, this parameter is set as false depicting that no platoon has reserved a slot to cross intersection. Platoons which are reaching near the intersection send request to RSU for reserving slot at signalized intersection. The requests are sent by *SignalControlMsg* message using command *ACTIVATE_SIGNAL* as *cmdType* and *value* set to true for activating *SIGNAL_CONTROL*. This way platoon approaching intersection earlier gets to reserve a slot at the signal in their favor. RSU accepts the request only if *SIGNAL_CONTROL* is in non reserved mode. If RSU accepts the request, firstly it will reserve slot by setting the *SIGNAL_CONTROL* parameter to true mode of operation so that no other platoon can manipulate phase until current platoon crosses intersection. Even though platoons near intersection keeps on transmitting requests to RSU through *SignalControlMsg* message for slot allotment but RSU refuses all requests until *SIGNAL_CONTROL* is set to false again. From the received information, RSU activates green phase for sending platoon lane and stops flow of other conflicting lanes by showing red signal. The phase duration of externally activated phase depends on the furthest vehicle of platoon crossing intersection. As soon as the last vehicle of platoon crosses intersection, leader sends request to RSU for turning off *SIGNAL_CONTROL* parameter through *SignalControlMsg* using *ACTIVATE_SIGNAL* as *cmdType* and by setting *value* set to false. On successful reception of request, the parameter is turned off making traffic lights again available to be manipulated by rest of the traffic. This way by turning the traffic light dynamic the waiting delay time of vehicles can be reduced as now vehicles would not have to wait for idle green lights of empty flows. Flexible phase duration also allows more number of vehicles to cross intersection in limited time period.

3.5 Message Dissemination in Strategies

To serve the purpose of implementing scheduling algorithms, the basic safety messages encapsulated in wave short message (WSM) are sent outside the context of BSS to the broadcast destination address. The IEEE 1609 standard based WSM has minimum overhead of 5 bytes extending upto 20 bytes. It includes fields such as wsm version, channel number on which packet is sent, data rate with which packet is sent, *etc.* In the studied strategies, the following messages extending WSM features are created to serve various purposes.

- **BeaconRSU**: Beacon messages are basic safety messages which broadcast periodically every 0.1 sec by default. These messages are broadcast on control channel (CCH) by default but can use service channel (SCH) on setting the *useServiceChannel* parameter to true. BeaconRSU is message sent from RSU to nearby units for informing regarding its details such as RSU position, its inbound edges, electronic toll collection *etc.*

- **BeaconVehicle**: Like every beacon message, BeaconVehicle message is also transmitted every 0.1 sec on a periodic basis by vehicles. It contains basic information related to the sender vehicle for generating awareness of its presence in the surrounding. The sender vehicles identity, position, speed, acceleration, lane id, platoon depth (if belongs to a platoon), *etc.* are described in the message.

- **InfoMsg**: It is an event triggered category message which comes into functioning when vehicles approach intersection. This message is used in proposed PTC strategy to make surrounding platoons aware of each other proximity to intersection. The first vehicle of platoons i.e, the leader vehicle broadcasts the message to be received by other platoon leaders travelling on adjacent lanes for making scheduling decisions. Besides sender's information, it contains information such as lane position, speed, lane id, size of platoon, maximum acceleration and deceleration.

- **LaneInfoMsg**: This message also falls in DENM category of event triggered safety messages. This message is used in DTC strategy for scheduling traffic on maximum density lanes. RSU broadcasts this message to nearby platoons which have crossed lane area detectors. It carries the information about the results of platoons on detectors analysed by RSU. Along with sender's information, the main contents of this message are MDL, CMDL and total density on those lanes. Platoons receiving this message cross-checks if they belong to the maximum density lane pairs for taking required scheduling decisions.

- **PlatoonMsg**: This message is used to communicate between platoons for assisting in platoon management operations. If the *plnMode* has been set to *platoonManagement* then platoon sending this message can perform different platoon maneuvers such as splitting, merging, leader leave, dissolving, *etc.* on request. It is used for multiple purposes in enabling maneuver through *command* parameter of the message. Command takes input such as *ACK* for acknowledgement, *MERGE_REQ* for merge request, *CHANGE_PL* for changing platoon leader, *etc.*.

- **SignalControlMsg**: This message has two purposes which is mentioned through *cmdType* field in the message. To enable or disable the command mentioned in *cmdType*, bool type *controller* field is present. This message is transmitted by platoons to RSU for enabling or disabling the desired functioning. First *cmdType* is *ACTIVATE_ALGO* used in DTC strategy which informs RSU that vehicles have approached near intersection so it can initiate analysing the detectors result for scheduling purposes. Second *cmdType* is *ACTIVATE_SIGNAL* used in both DTC and proposed PTC strategies for reserving slot at dynamic traffic light by the sender platoon. On receiving enabled commands, RSU performs accordingly.

- **SpaceAdjust**: Like earlier messages, it is also a multipurpose message which decides upon its task based on *cmdType* field. This message is broadcasted by a platoon to its own vehicles or nearby platoons for sharing information or asking to perform some desired activity. It includes commands such as *OPPO_SPACE* which is used to inform regarding opportunity space of sender platoon to platoons present on the same lane, *SPLIT_DEPTH* which is send from a platoon leader to inform its splitting vehicle of manual splitting, *SPEED_CHANGE* and *SPEED_DEFAULT* which platoon leader sends to its follower vehicles for speed change to mentioned or default value respectively. It also consist of *value* field consisting information of opportunity space, splitting vehicle depth and speed value respective of the command.

3.6 Performance Analysis of Communication Parameters

This section briefly discusses various communication and radio propagation parameters to analyze the performance of IEEE 802.11p. These parameters are studied and observed for the three scheduling strategies for varying density flow of traffic. Simulation proofs of the theoretical claims made in this section are provided in the next chapter.

The flow and scheduling of platoons on road is entirely based upon V2X communication through beacon messages as well as event based messages. The transmission reception of these messages and communication performance is dependent on channel situations as well as characteristics of radio propagation. Thus parameters related to channel and packet delivery are as follows:

1. **Channel Congestion:** IEEE 802.11 EDCA is extension of IEEE 802.11 distributed coordination function (DCF) which supports quality of service (QoS) and has four indepen-

dent channel access categories (ACs) (voice, video, best effort and background). Selecting proper channel access parameters such as CW_{min}, CW_{max} and $AIFS$ one can achieve channel access differentiation and control access of channel resulting in better Qos. EDCA uses CSMA/CA approach which allows a node with frames to sense channel first before transmission for a fixed time. If the channel is sensed to be idle then transmits the frame otherwise waits for random backoff time mentioned in (3.4). EDCA follows exponential backoff mechanism for large contention nodes in which for each failed transmission CW value increases exponentially in range [CW_{min} , CW_{max}] and for successful transmission it returns to CW_{min}.

$$BackoffTime = Random[0, CW] * SlotTime \text{ [5]} \tag{3.4}$$

2. **Packet Losses:** To maintain safe and viable traffic scheduling, packet loss rate in a communication network should be minimum. Packets may be dropped or lost due to network latency, corruption of bits, collision in packets, channel congestion, *etc.*. The PHY layer calculates the PLR which is packet lost in transmission with respect to total packets sent. Packet loss reduces throughput which after a certain limit leads to network malfunction with incomplete and misleading information.

Chapter 4

Simulation and Results

In this section, the three strategies are studied and compared on various criteria. Firstly, the simulation scenario specifications are discussed to create a common environment for studying the performance of strategies. In the next section, the results of simulations are studied in detail.

4.1 Simulation Setup

For studying and comparing the strategies, a common simulation scenario is taken into consideration. This scenario consists of total seven platoons of variable sizes at different lanes willing to cross a four way signalized intersection. The different platoons and their attributes are mentioned in Table 4.1, where Dept. signifies departure. Each path has two lanes of length 975 m allowing straight and right of way traffic on right of the center of the intersection denoted by lane_0 and left of way traffic on left of the center of the intersection denoted by lane_1. Traffic lights are placed at intersection junctions for each outgoing lane. RSU is placed in the middle of intersection at position (1000 m, 1000 m) with a range of 500 m from its centre. It has been assumed that all vehicles are homogeneous in shape, structure, engine, and power. $l = 5$ m and minimum inter-platoon gap is 3 m. All the vehicles are initially travelling with constant velocity $v = 10$ m/sec. The speed limit is set as 20 m/sec, and other parameters are as shown in the Table 4.2 For DTC strategy case, the lane area detectors of length 100 m are placed at 700 m as shown in Fig. 3.1

In this simulation scenario, traffic lights are placed at every outgoing junction of intersection. The traffic light is of static type, and has phases with various states for each lane movements. The states are described in order of straight, right of way and left of way movements for north, east, south and west lanes respectively. The traffic light program for simulation is as shown in Table 4.3. The simulations are performed using VENTOS which is an integrated software consisting of both OMNeT++ and SUMO simulators for managing platoons traffic flow and their communication with the environment through DSRC enabled V2X communication. The total simulation time for strategies is $T = 150$ *sec* and the simulation time-step is $T_s = 100$ *msec*.

Platoon Configuration					
Platoon ID	Platoon Size	Dept. Position	Dept. Lane	Dept. time	Route
1	3	300 m	WC_0	10 sec	WEST to EAST
2	5	270 m	WC_0	20 sec	WEST to EAST
3	4	300 m	EC_0	10 sec	EAST to WEST
4	3	275 m	EC_1	20 sec	EAST to SOUTH
5	3	295 m	NC_0	10 sec	NORTH to SOUTH
6	2	300 m	SC_0	10 sec	SOUTH to NORTH
7	4	270 m	SC_0	20 sec	SOUTH to EAST

Table 4.1: Platoon configuration parameters

Simulation Parameters	
Parameters	Values
Acceleration	3.0 m/sec^2
Deceleration	5.0 m/sec^2
Minimum Distance (Follower)	1 m
Minimum Distance (Leader)	3 m
Comfortable Acceleration	2.5 m/sec^2
Comfortable Deceleration	2.5 m/sec^2

Table 4.2: Parameters for car following model

Traffic Light Program		
Phase Number	Phase Duration	Phase State
1	20 *sec*	rrrgGrrrrgGr
2	5 *sec*	rrryyyrrryyy
3	10 *sec*	rrrrrGrrrrrG
4	20 *sec*	gGrrrrgGrrrr
5	5 *sec*	yyyrrryyyrrr
6	10 *sec*	rrGrrrrrGrrr

Table 4.3: Traffic light program for junctions at intersection

4.2 Simulation Results

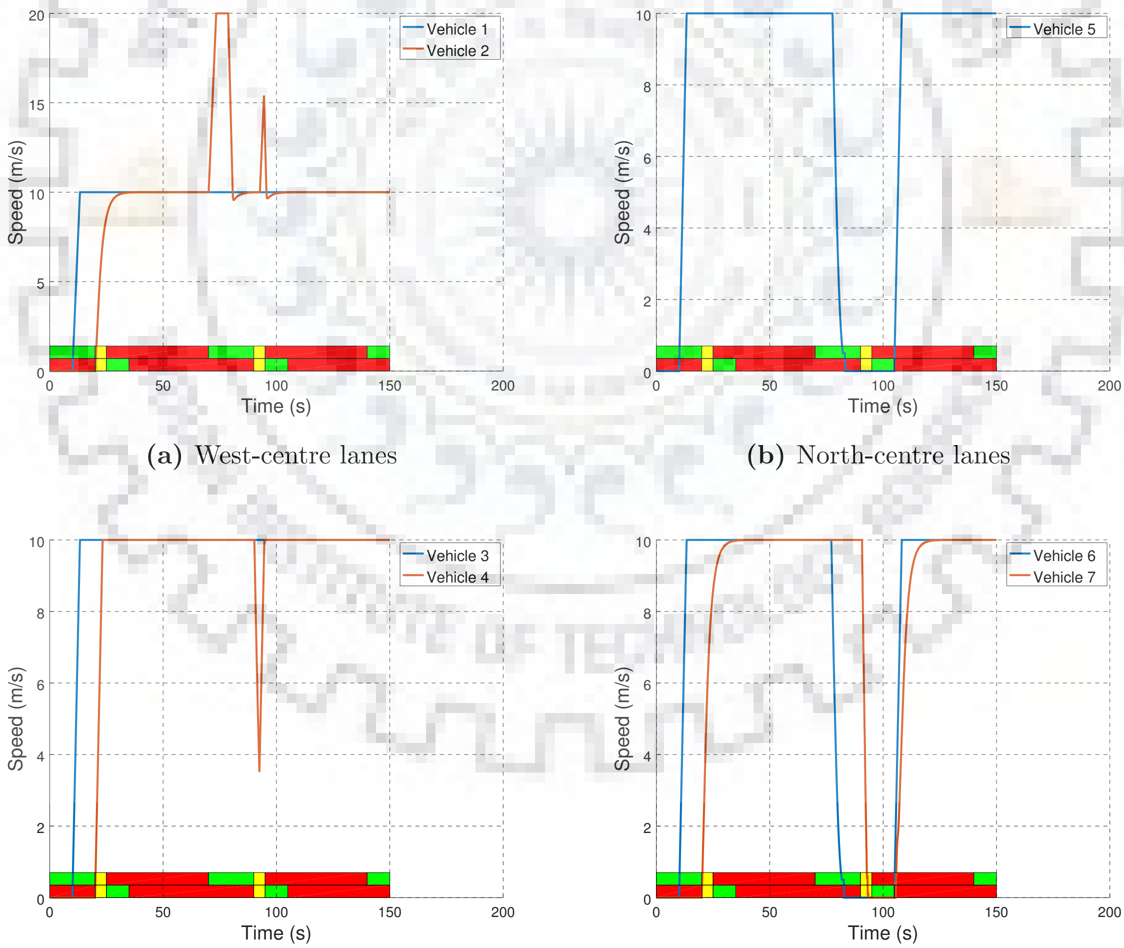
For studying and comparing the strategies, lane-wise position and speed plots of platoon leaders are provided below for the three strategies. In addition, some comparison curves and system performance curves are also shown and discussed.

4.2.1 STC Strategy

STC strategy initiates when platoons enter in the active zone of RSU and has green phase of traffic light activated for them to cross intersection. Since this strategy involves utilization of opportunity space received from front C1 category platoon travelling on the same route, only platoons 1 and 2 perform the algorithm. Based on the simulation results, platoon 1 has positive opportunity space, and thus it is placed under C1 category. Vehicles of platoon 2 are categorized under C2 and C3 category according to the algorithm as shown in Table 4.4 As described in the algorithm, C2 category vehicles accelerate to their maximum speed and split from C3 category vehicles. Therefore splitting maneuver is performed simultaneously on C2 vehicles. As shown in Fig. 4.1, the vehicles are categorized as soon as the algorithm initiates at $T = 70$ *sec*, and C2 category vehicles are accelerated to their maximum allowed speed of 20 m/sec. Vehicles decelerate near the intersection for safe crossing, and accelerate after crossing intersection to merge into optimum size platoons. Fig. 4.2 shows that C2 category vehicles are successful in crossing intersection by the end of green phase of light, and thus increasing the throughput at intersection by 2 vehicles in the studied phase of traffic light. Figs. 4.1 and 4.2 show the lane-wise speed and position curves of all platoon leaders for visualizing overall performance of strategy. For better understanding, traffic light phases for lane_0 and lane_1 are shown below the figures.

Categorizing Vehicles into Categories				
Opportunity Space	Receiving Vehicle	Demand Space	Required Speed	Category
36.33	2	8	18.63	C2
28.33	2.1	6	19.64	C2
22.33	2.2	6	20.64	C3

Table 4.4: Categorization of vehicles



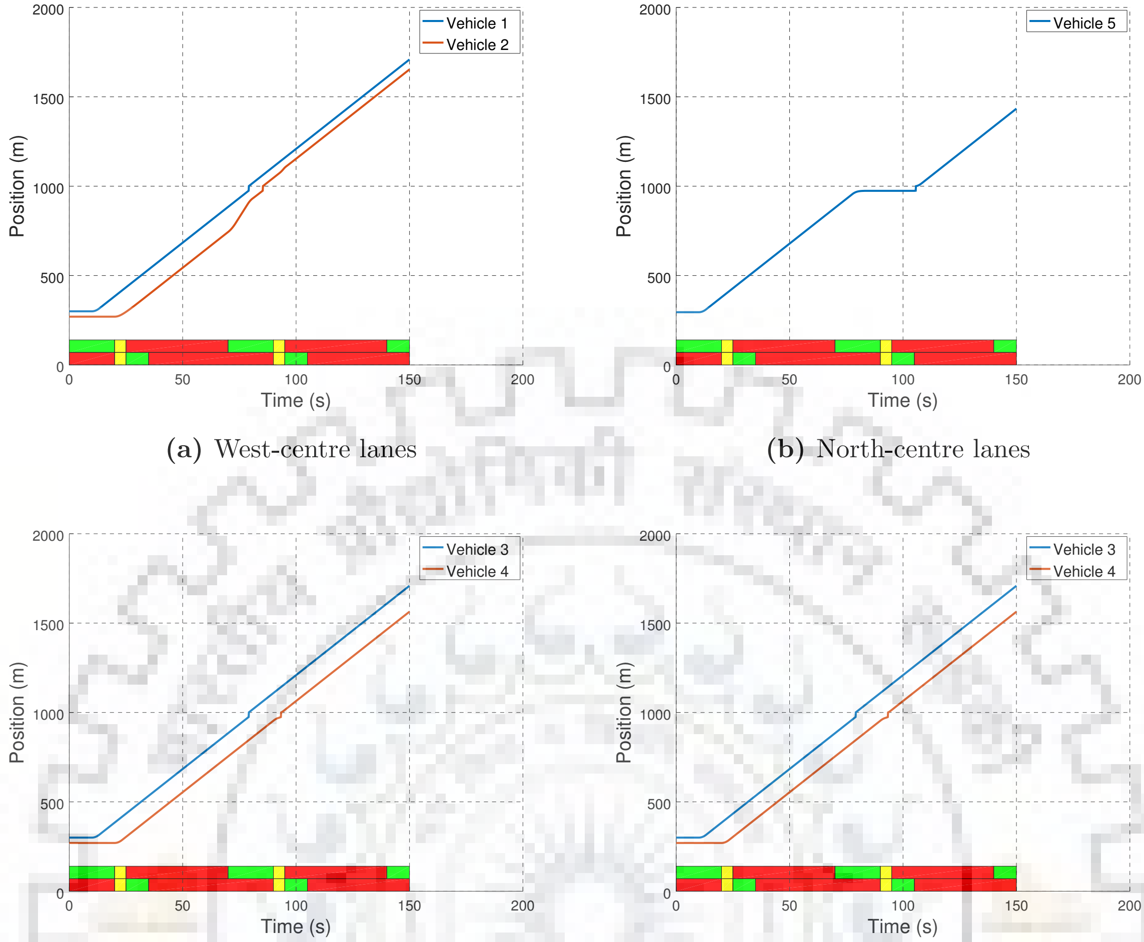
(a) West-centre lanes

(b) North-centre lanes

(c) East-centre lanes

(d) South-centre lanes

Fig. 4.1. Speed profiles of platoon leaders in STC strategy



(a) West-centre lanes

(b) North-centre lanes

(c) East-centre lanes

(d) South-centre lanes

Fig. 4.2. Position profiles of platoon leaders in STC strategy

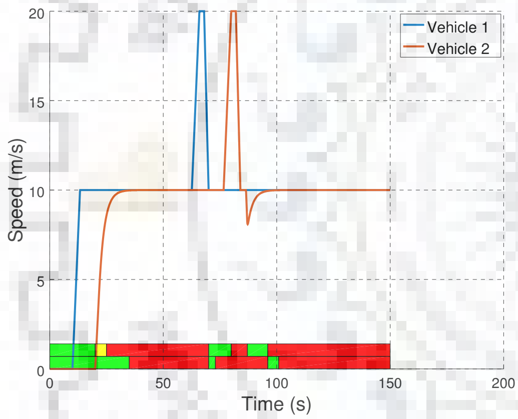
4.2.2 DTC Strategy

In DTC strategy, as platoons approach near to intersection, they start sending requests to RSU for obtaining data regarding real time maximum density lane pair detected by LADs. RSU enquires LADs constantly regarding vehicle densities of lanes. After obtaining data, it analyses data to find out the combined density of incoming non conflicting platoon pairs having maximum density among all. RSU broadcasts the information of maximum density lane pair to all the platoons. If the information receiving platoon has come out of detector zone, and is travelling on either MDL or CMDL, it accelerates to reach intersection earlier. Thus platoons travelling on maximum density lane pair are scheduled first.

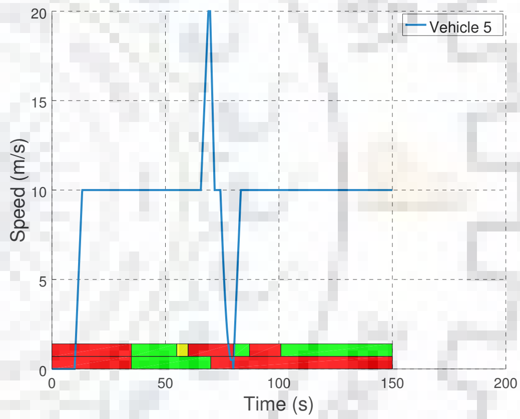
In Table 4.5, combined density comparison at three important simulation time instants (T) is shown to find MDL and CMDL for scheduling incoming competing traffic flow. As shown in Fig. 4.3, platoons 1 and 3 start accelerating around $T = 60$ *sec*, platoon 5 and 6 start accelerating around $T = 66$ sec, and platoon 2 starts accelerating around $T = 75$ sec which verifies data provided in Table 4.5. Also, the traffic light phase states are shown to be varying according to incoming traffic flow. Fig. 4.4 shows the lane-wise position profiles of platoons crossing intersection.

LADs Data										
T	WC_0	NC_0	EC_0	SC_0	WC_1	NC_1	EC_1	SC_1	MDL	CMDL
59.60 sec	3	3	4	2	0	0	0	0	EC_0	WC_0
65.60 sec	0	0	1	0	0	0	0	0	NC_0	SC_0
73.60 sec	5	0	0	4	0	0	3	0	WC_0	-

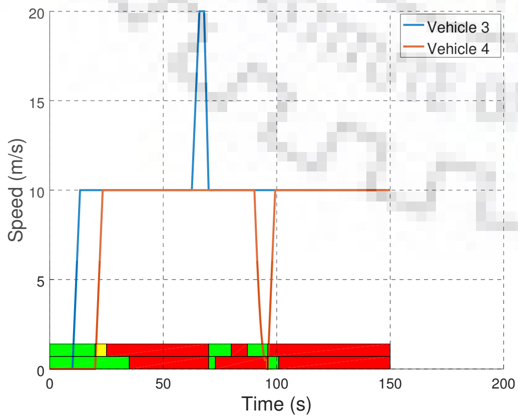
Table 4.5: Finding MDL and CMDL by analysing LADs data



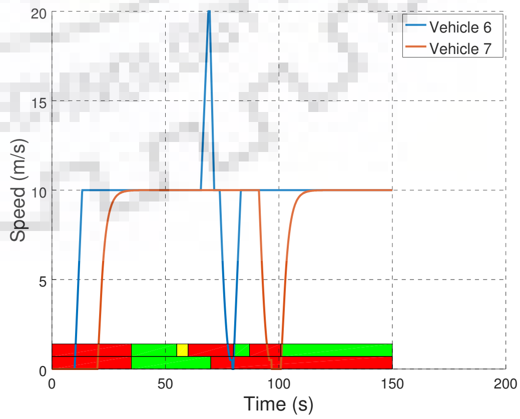
(a) West-centre lanes



(b) North-centre lanes

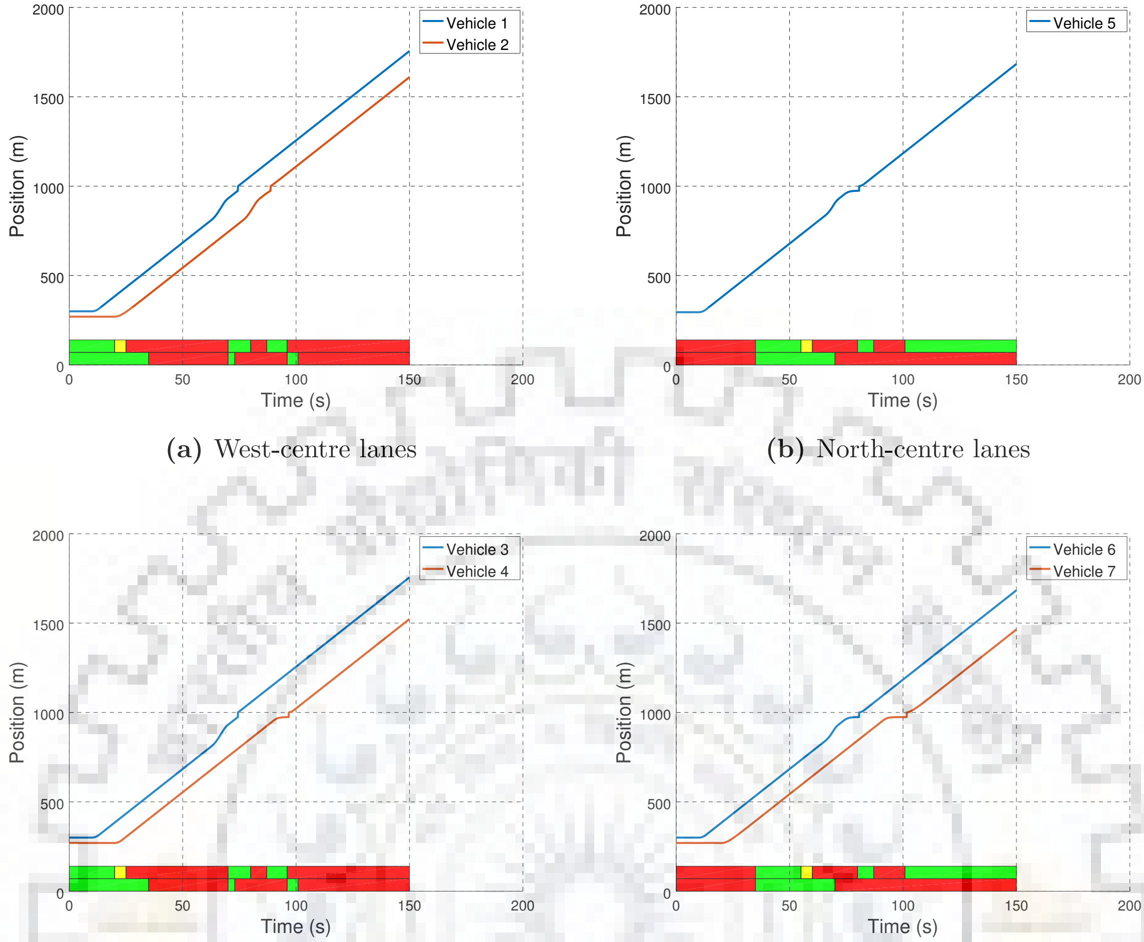


(c) East-centre lanes



(d) South-centre lanes

Fig. 4.3. Speed profiles of platoon leaders in DTC strategy



(a) West-centre lanes

(b) North-centre lanes

(c) East-centre lanes

(d) South-centre lanes

Fig. 4.4. Position profiles of platoon leaders in DTC strategy

4.2.3 Proposed PTC Strategy

The proposed PTC strategy prioritizes and schedules platoons primarily on the basis of proximity toward intersection. In case, if competing platoons are at almost same proximity from intersection, then they are evaluated based on size criterion. This strategy has no involvement of RSU, and therefore it is fully decentralized.

Table 4.6 shows the simulation data of proposed PTC illustrating the functioning of the strategy. It shows competing platoons getting prioritized based on suitable criteria at various time instants. Fig. 4.5 shows lane-wise speed profiles of platoon leaders on a four-way signalized intersection. The figure verifies the data of Table 4.6 by outlining the acceleration of prioritized platoons and deceleration of platoons halting at intersection. Fig. 4.6 shows lane-wise distance profile of platoons crossing intersection at position 1000 m. The small dip in position profiles before crossing intersection is due to deceleration of platoons for safe intersection crossing.

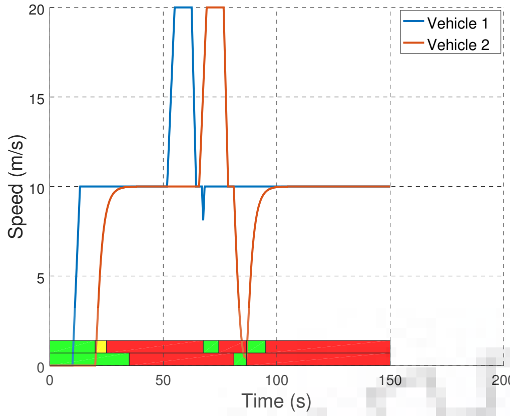
Proposed PTC Simulation Data			
Simulation Time	Competing Platoons	Scheduling Criteria	Prioritized Platoon
51.85	1 & 6	Size	1
52.30	1 & 5	Position	1
51.85	3 & 6	Size	3
52.30	3 & 5	Position	3
66.88	2 & 5	Position	5
66.85	5 & 7	Position	5
66.88	2 & 6	Position	6
66.85	6 & 7	Position	6
66.90	2 & 7	Size	2
66.90	4 & 7	Size	4

Table 4.6: Prioritizing of platoons on proximity or size criteria

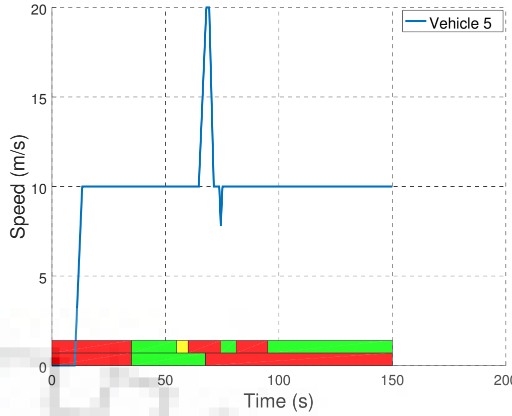
4.2.4 Comparison of Strategies

For comparative analysis of the three strategies, Fig. 4.7 shows the average delay per vehicle at signalized road intersection for four different mobility scenarios. Each mobility scenario is having different number of vehicles and platoons to study the effect of increasing road traffic on strategies. The Fig. 4.7 depicts that the waiting time delay at red light signalized intersection is very high in fixed traffic light cases whereas reduces to a great extent in dynamic traffic light strategies. The maximum waiting delay is when no algorithm is implemented for traffic management. Although STC strategy allows C2 category vehicles to utilize road capacity and pass without having any waiting time delay at intersection, still it has high waiting delay time due to conventional fixed traffic lights having fixed phases at intersection. DTC and proposed PTC have approximately zero average waiting delay time due to their ability to pass traffic as soon as it arrives at the intersection. In the beginning, both the strategies start off with same waiting delay. But as density increases, proposed PTC shows improved results than those obtained using DTC. The result also shows that waiting delay gradually increases with increase in traffic density for these strategies.

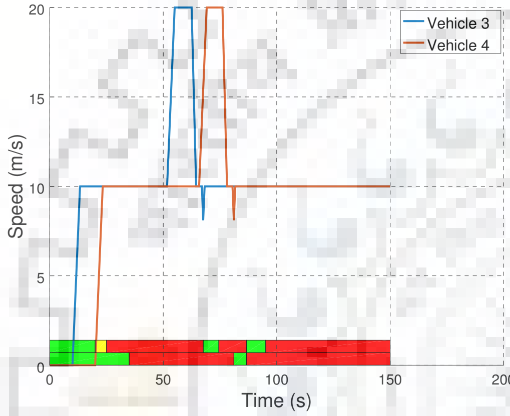
For further performance comparison, the travelling efficiency is calculated in terms of average distance covered per vehicle in a specific period of time. Fig. 4.8 shows that DTC and proposed



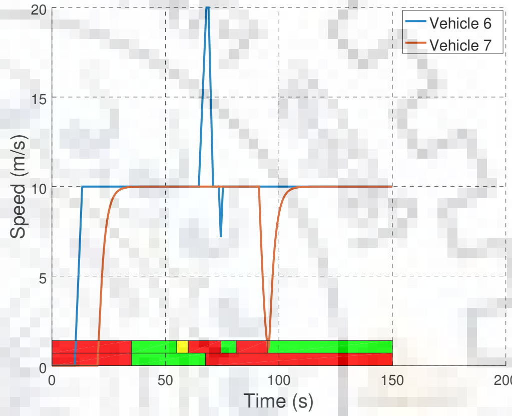
(a) West-centre lanes



(b) North-centre lanes



(c) East-centre lanes

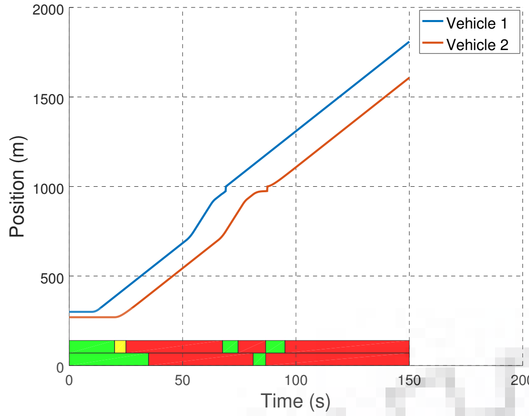


(d) South-centre lanes

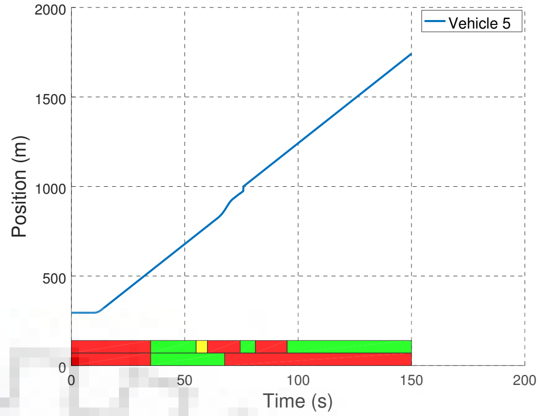
Fig. 4.5. Speed profiles of platoon leaders in proposed PTC strategy

PTC are showing better results than the results of STC strategy, with proposed PTC having maximum travelling efficiency among all. This is due to the fact that DTC and proposed PTC accelerate prioritized platoons to cross dynamic signalized intersection on demand. Travel capacity of vehicles remains almost constant when no algorithm is implemented. It is also shown that the average travelled distance decreases drastically with increasing traffic density. This also states the fact that with increased traffic, efficiency of crossing intersection in minimum time decreases due to latency in communication.

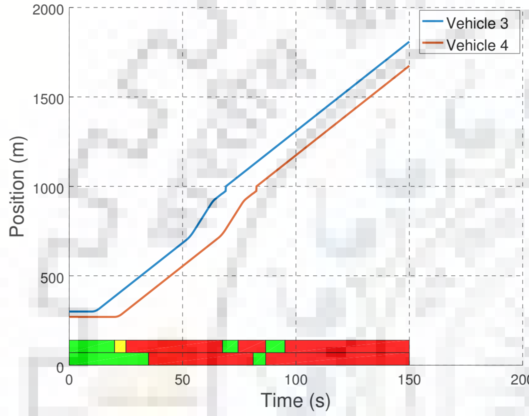
Table 4.7 shows computation time of simulation in seconds when all the studied platoons have crossed the intersection. The aim is to allow traffic to cross intersection efficiently in minimum time possible thus increasing the throughput. This is taken as the throughput metric to evaluate strategies at different traffic density scenarios in Table 4.7. According to the results, the computation time for DTC and proposed PTC is much lesser than that of STC and when



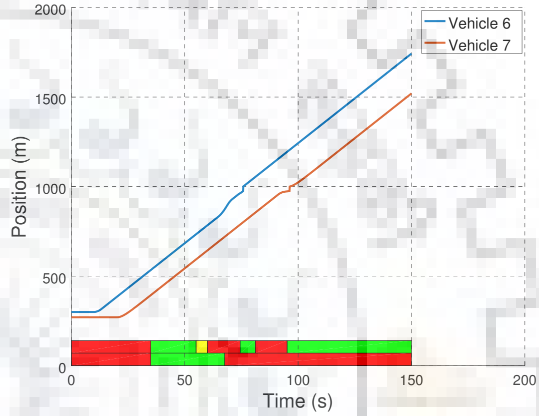
(a) West-centre lanes



(b) North-centre lanes



(c) East-centre lanes



(d) South-centre lanes

Fig. 4.6. Position profiles of platoon leaders in proposed PTC strategy

no algorithm is used. Dynamic intelligent traffic lights with flexible phases increase throughput at a large scale. Due to fully decentralized nature of proposed PTC, scheduling decisions are faster and more frequent. Thus, proposed PTC shows maximum potential in achieving the aim of the thesis.

4.2.5 Communication Performance Metrics

The traffic scheduling strategies are based on messages transmitted for generating awareness in a vehicle regarding its surrounding. The VANET environment is dependent on IEEE 802.11p protocol using CSMA/CA technique of EDCA. Often when the traffic density increases with increased transmission and reception of data among vehicles, channel becomes congested and hinders data transmission. This degrades the performance of traffic as reliability and safety decreases due to delayed or failed transmissions. Therefore, to analyse communication perfor-

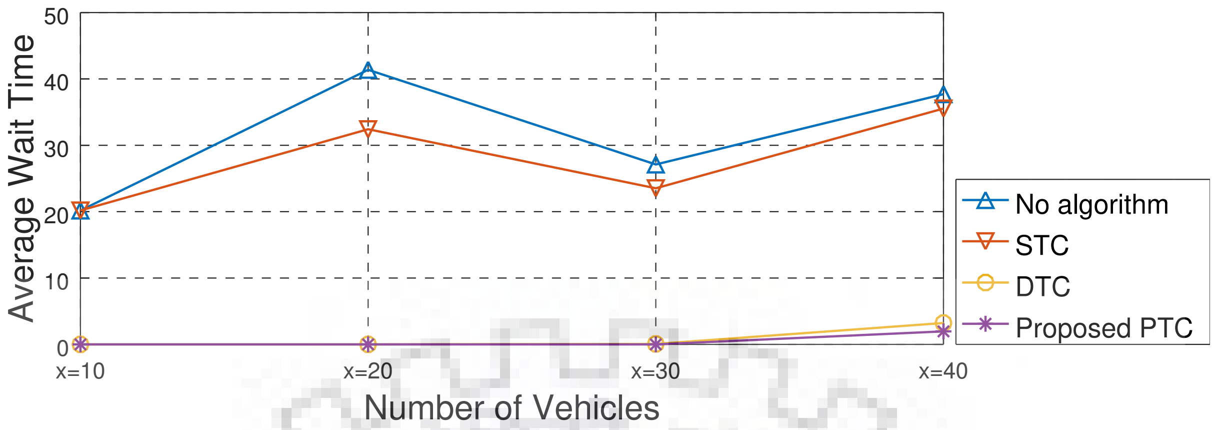


Fig. 4.7. Performance evaluation based on average waiting delay of vehicles at intersection

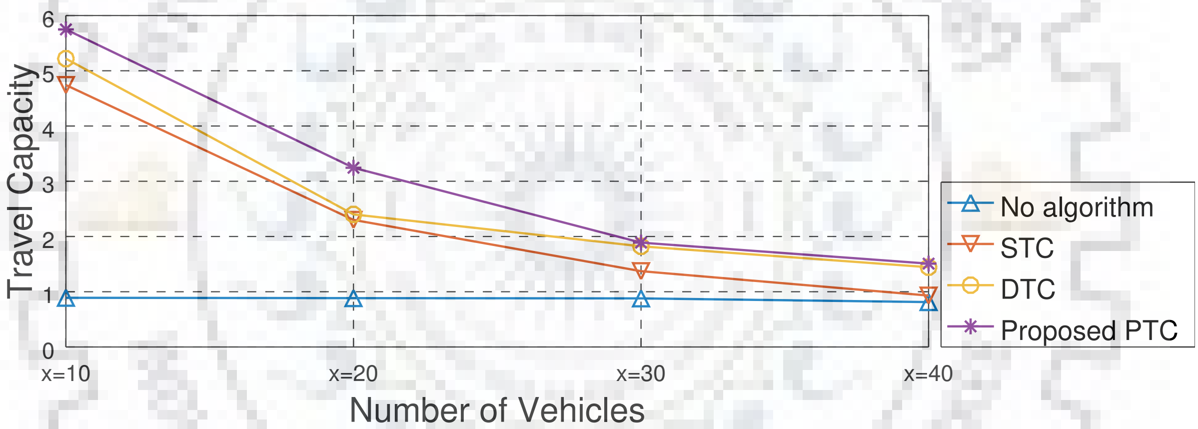


Fig. 4.8. Performance evaluation based on travel capacity measured by average distance travelled in a time period

mance, it is necessary to study CBR during data transmission. CBR is calculated by taking ratio of busy time of channel over total transmission time. Since CSMA/CA channel accessing technique is employed in V2X communication, a sender inspects if channel is free or not for a certain period of time. A channel is considered to be busy when it denies a packet to be transmitted as it is already busy with other packets. In Fig. 4.9, performance of protocol is evaluated for the three strategies at different traffic densities. Average CBR plot shows that DTC has maximum CBR at all densities. This is due to the fact that DTC involves interaction between vehicles and RSU for finding maximum density lane pairs. These interactions are two-hop communications

Computation Time of Strategies				
Strategy	Density = 10	Density = 20	Density = 30	Density = 40
No algorithm	107.80	114.90	148.40	169.70
STC	109	114.60	126.5	151.8
DTC	84.70	93.10	101.3	110
Proposed PTC	82.3	95.80	97.80	102

Table 4.7: Intersection crossing times of strategies

which increases the channel congestion. STC strategy provides better results than that of DTC. It also requires RSU to vehicle interaction for obtaining traffic light schedule, and thus has high CBR. Since proposed PTC strategy involves simpler interaction among vehicles without any RSU, the busy time of channel is much lesser than other two strategies. It is also shown that with increased density of traffic, the CBR increases depicting that channel becomes more busy when more vehicles are involved.

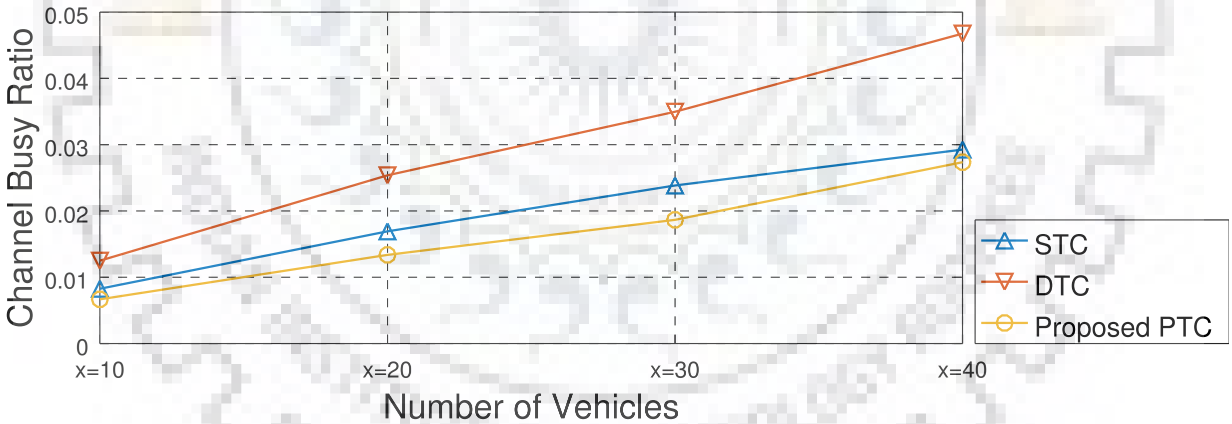


Fig. 4.9. Performance evaluation based on average channel busy ratio

PLR should be minimum to maintain a reliable traffic scheduling. The most common causes of packet losses in channel are corruption of bits, collision of packets, transmission reception errors, *etc.*. The PLR is measured by calculating total lost packets during communication over total number of packets sent by vehicles. Fig. 4.10 shows the plot for average PLR calculated per vehicle for the three strategies at different traffic density. Since DTC involves RSU to vehicle communication as well as vehicle to vehicle communication for taking scheduling decision, the

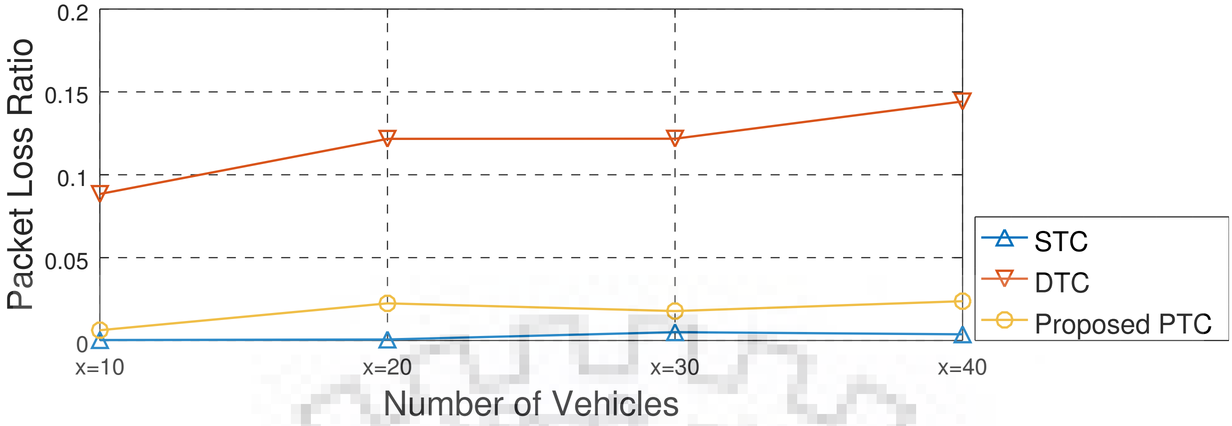


Fig. 4.10. Performance evaluation based on packet loss ratio

network becomes too crowded with data flow. Therefore DTC has the highest PLR whereas STC and proposed PTC has much lesser PLR. Although, DTC is efficient in travel capacity and has reduced wait delay time but its reliability degrades due to higher packet losses. After a certain threshold, high PLR causes faulty communication which risks safe transportation. It can also be observed that with increased traffic density, PLR increases due to increased number of packets in the air.

Chapter 5

Conclusion and Future Work

In this thesis, three cooperative platoon based scheduling strategies are implemented for improving traffic performance at signalized intersection. From the simulation results, it can be concluded that the proposed PTC outperforms STC and DTC strategies in terms of throughput, waiting delay time, travel capacity, cost of operation, complexity, *etc.*. The position and speed profiles of the platoon leaders provide deep understanding of operation of the three strategies. Simulation results show that the proposed PTC results in minimum computation time among all to achieve the aim of successfully allowing all platoons to cross intersection. Thus, it has higher throughput than that of STC and DTC strategies approximately by 28.18% and 3.538%, respectively. Also, the average waiting delay per vehicle at signalised intersection has reduced in DTC and proposed PTC by twenty folds than STC which has the highest delay due to fixed nature of traffic lights. Also, travel efficiency which is average distance travelled in particular time, is highest for proposed PTC strategy. DTC and proposed PTC strategies follow decentralized approach which is not only more feasible but also reduces computation load on intersection manager than the centralized approach. Although STC improves the throughput at intersection, its efficiency reduces due to static nature of traffic lights. As no additional infrastructures or devices are required in proposed PTC, it has lesser cost of operation than other strategies. It follows a simple approach of taking localized decisions based on information collected from the messages of other platoons. The communication system performance for the three strategies is analyzed through CBR and PLR curves. The simulation results show that although DTC results in comparable throughput and waiting delay as those of proposed PTC, it shows the highest CBR and PLR among the three, which affects its reliability and safety performance. The proposed PTC results in much lesser CBR and PLR due to its simple interaction scheme among vehicles to take scheduling decisions. Thus, it can be acknowledged that among the three strategies, the proposed PTC performs the best in all criteria. Lastly the effect of increasing traffic density on system performance is also studied. The simulation results also show that with increasing traffic density, communication channel becomes more busy and results in more data packet losses during message dissemination. Thus, there is a decrease in traffic scheduling efficiency of strategies as number of vehicles increases on road.

Future scope includes improvement of communication capabilities for managing higher demand requests at intersection. Strategies will be implemented in more practical simulation environment consisting of heterogeneous as well as manually controlled vehicles. Also, strategies will be employed on various intersection geometries.

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