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Evaluation and Optimization of ETSI DCC Reactive Approaches for Platooning

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Abstract

IEEE802.11p is considered as de facto standard for road communication. However, channel congestion is still the main challenge of IEEE802.11p based vehicular networks. Target to solve this issue, European Telecommunication Standards Institute (ETSI) has standardized a set of Decentralized Congestion Control (DCC) mechanisms in which mainly provide reactive and adaptive methods to mitigate communication channel congestion issue. Many efforts have been carried out over these years in order to solve this problem. Most of the results show that the DCC framework is capable of Channel Load (CL) control to some extend. Platooning system is one of these topics which needs to achieve reliable CL control, especially when there are large amount of vehicles communicating on the road. It is a pity that there are few papers of investigating on DCC framework for Platooning channel congestion control. For this purpose, we focus on investigating DCC reactive control approaches, aiming to provide comprehensive insights of how DCC framework transmission parameters, i.e. message generation rate, transmission power and datarate, will impact on the stability of Platooning system. Besides, for each instance of transmission parameter, we target to optimize the parameter, and propose more stable control algorithms by running repetitive simulations. According to our results, the method of adjusting transmission power has the best benefits.

Sammanfattning

IEEE802.11p anses vara de facto-standard för vägkommunikation. Kanalstockning är dock fortfarande den största utmaningen för IEEE802.11p-baserade fordonstrafik. Målet för att lösa detta problem har standardiserat ett antal decentraliserade Congestion Control-mekanismer (DCC), där det europeiska telekommunikationsstandardinstitutet (ETSI) grundat sig på reaktiva och adaptiva metoder för att mildra problem med överbelastning av kommunikationskanaler. Många ansträngningar har gjorts under dessa år för att lösa detta problem. De flesta resultaten visar att DCC-ramverket i viss utsträckning kan hantera kanalbelastning (CL). Platonering är ett av dessa ämnen som behöver uppnå tillförlitlig CL-kontroll, särskilt när det finns stora mängder fordon som kommunicerar på vägen. Det är synd att det finns få dokument att undersöka om DCC-ramverket för Platooning kanalöverbelastningskontroll. För detta ändamål undersöker vi särskilt DCC-reaktiva kontrollmetoder, som syftar till att ge omfattande insikter om hur DCC-ramöverföringsparametrar, dvs meddelandegenskapshastighet, överföringseffekt och datarat, kommer att påverka stabiliteten hos Platooning-systemet. För varje instans av överföringsparametern riktar vi dessutom till att optimera parametern och föreslå mer stabila kontrollalgoritmer genom att köra repetitiva simuleringar. Enligt våra resultat har metoden för justering av överföringseffekt de bästa fördelarna.

Contents

CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CL	Channel Load
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCC	Decentralized Congestion Control
DENM	Decentralized Environmental Notification Message
DSRC	Dedicated Short Range Communications
ETSI	European Telecommunication Standards Institute
FCC	Federal Communication Commission
IRT	Inter Reception Time
ITS	Intelligent Transportation System
IVD	Inter Vehicle Distance
IVC	Inter-Vehicular Communication
NED	Network Description
PL	Platoon Leader
PM	Platoon Member
PRR	Packet Reception Rate
TraCI	Traffic Control Interface
VANETs	Vehicular ad-hoc Networks
V2V	Vehicle-to-vehicle
V2I	Vehicle-to-infrastructure
WAVE	Wireless Access in Vehicular Environments

Chapter 1

Introduction

With the increasing road traffic over years, the issues of road safety and efficiency have attracted many attention from industry, organizations and academy. To solve these problems, the merging of VANETs becomes one of the promising solutions, which provides potential technologies to support road safety or efficiency applications. The main purposes of Platooning application are to improve road capacity, release drivers' stress or reduce fuel consumption by the way of grouping road vehicles into platoons. Many industrial projects and academical researches have been carried out continuously to make platoon based driving become a reality. [8] shows how Platooning can reduce fuel consumption, while [30] aims to increase road throughput. However, to achieve those targets, the main challenge of Platooning is to guarantee reliable communications among vehicles no matter how many vehicles are communicating. IEEE802.11p is used as the communication protocol for road users. The issue of IEEE802.11p is that the channel medium is expected to get congested with incremental vehicles. To mitigate this problem, ETSI has standardized a set of DCC mechanisms to adapt transmission parameters based on CL measurement. According to many works, DCC framework is currently being revised and extended. However, DCC mechanisms deserve additional investigations.

1.1 Background

The International Energy Agency reports that there are around 800 million vehicles for the year 2008 and predicts this number to reach

2 billion by the year 2050 [1]. Thus, road traffic management will be a big challenge in the near future, since traffic volumes are projected to increase with respect to the risk of increased traffic jam, resource consumption, emission, and the increasing number of injured and killed. As a result, many industrial and academical organizations have been investing in developing cooperative vehicular systems, aiming to reduce the probability of car accident and improve safety and efficiency for road users. To satisfy these requirements, VANETs, based upon mobile wireless networks, are emerging as a promising solution to provide reliable communication technologies. VANETs comprise V2V and V2I communications. V2I provides internet resources by exchanging with infrastructures, while V2V guarantees the safety for vehicles where an area has no central infrastructure existed. In the other hand, the existence of V2V release the issue of covering the whole city with infrastructures, since deploying infrastructures is super expensive. Therefore, research of V2V communication systems is being more and more crucial for reducing surface traffic.

In the United States, the appeal of vehicular communication system led to the allocation of 70 MHz of spectrum in the 5.9 GHz band by FCC, which is dedicated for V2V and V2I communications. IEEE WAVE [3] specified the standard of communication among vehicles. Specifically, IEEE802.11p specifies the standards for vehicular communications on the physical (PHY) layer and media access (MAC) layer. In Europe, V2V and V2I communication standards are specified by ETSI.

1.2 Challenges

Vehicular network has been recommended an information update frequency of 10Hz [14] to provide reliable communications among vehicles. Thus, one of the main challenges is channel congestion control due to the massive local exchange of packets. To mitigate this issue, ETSI has standardized a set of DCC mechanisms [13], which are implemented through adapting transmission parameters, such as message generation rate, datarate, and transmission power. In this thesis, we focus on developing new control algorithms based on the given transmission parameters.

Many works have demonstrated that channel of IEEE802.11p is expected to get congested with utilizing 10Hz message generation rate without further congestion control mechanism. This is because of the usage of CSMA/CA scheme in MAC layer. Typically, when in a high vehicle density area, the channel medium will get congested easier, which will cause packet loss and thereby will influence the quality of communications. Thus, congestion control is necessary to prevent potential hazards.

Channel congestion condition can be immediately described as CL, higher congestion means higher CL, vice versa. According to [33], the implementation of DCC is through the transition of state machines. For detailed state machine description, see Chapter 3. In different cases, modification and extension of state machines will be necessary. For instance, decreasing message generation rate (beaconing frequency or beaconing interval) to a predefined target when channel is detected as congested is an efficient method for congestion control. However, this method is at the cost of increasing IRT which can affect reliable communications among vehicles. Therefore, the trade-off between message generation rate and IRT is essential.

Instead of changing beaconing interval, modify the datarate on PHY layer is the second strategy to achieve congestion control. ETSI standardizes a series of datarate options of 3, 6, 12, 18 and 24 Mbps to be used in V2V communication. Transmitting packets by utilizing higher datarate means that packets have shorter transmission duration, and thereby increase the channel capacity in time unit to mitigate congestion problem [15]. However, the problem of datarate control is that high datarate will cause significant interferences in wireless transmission, especially where there is no spatial reuse. Hence, the balance among datarate, signal interference and vehicle density is an important topic for datarate control.

Transmission power control is another control method. Some existing transmission power control protocols of VANETs are described in [24, 25]. The reason why we want to investigate on transmission power is that dynamic transmission power can change packet transmission distance. For example, a packet with utilizing high transmission power has a longer broadcasting range. Figure 1.1 further explains why transmission power is important for platooning usage. If Platoon 1 cooperates well with Platoon 3, Platoon 4, Platoon 5 as well as the individual vehicle nearby, it is not necessary to further reach out to Platoon 2. Because this pattern will save more wireless re-

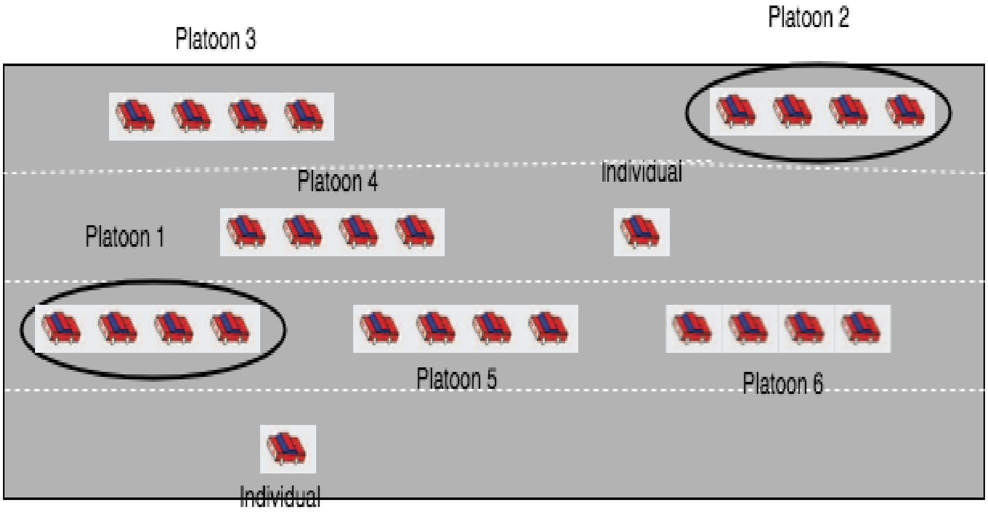


Figure 1.1: A multiplatoon scenario for transmission power explanation

sources, and results in less wireless interference among platoons due to a shorter communication range. However, the most significant disadvantage is that this will cause potential hazard events for the platoon itself, since it will not know the accident which happened beyond its communication range. Therefore, some papers suggest keep using high transmission power in order to keep a long communication distance for preventing the potential danger. But there are two things of strong transmission power, 1) long distance transmission may increase the probability of packet collision, packet loss due to the path attenuation; 2) long distance transmission also occupy long channel access time which results in increased CL.

1.3 Problem statement

Many works have demonstrated that CL control is achievable through adjusting transmission parameters. However, the concerns are 1) for massage generation rate control, the reduction of CL is at the cost of increasing IRT. 2) For datarate control, a higher datarate results in a lower PRR. 3) For power control, less power means that the received power is small due to path loss in wireless propagation, which may affect the signal-to-noise ratio. As discussed above, only reduce CL is not enough, there are still other performances, for instance, IRT and

PRR, need to be considered when designing a beaconing mechanism. Therefore, how to trade off the metrics of CL, IRT and PRR to optimize DCC control mechanism is the main topic of this thesis.

1.4 Purpose

ETSI has standardized a set of DCC mechanisms for VANETs. The first purpose of this thesis is to implement algorithms based on state machines that highlighted in [13], then evaluate performance by adapting control parameters. Finally, to our best knowledge, on top of the standard mechanisms proposed by ETSI, many efforts just evaluated these mechanisms for non-platooning scenarios. Hence, in this work, we focus on investigating and evaluating DCC framework for platooning system.

1.5 Goal

As discussed above, congestion control is achievable, but the trade-off among parameters is essential. Based on the DCC reactive approaches, the goal of this work is firstly to perform a comprehensive data analysis to optimize transmission parameters, secondly to propose optical control algorithms upon the optimized parameters, and finally by comparing the performances among algorithms to suggest the best reactive control algorithm for platooning system.

1.6 Research method

There are many methods to perform researches against this topic. For example, field test or simulation. Considering the cost at deployment of huge amounts of vehicle, simulation is an easier way instead [4]. To implement vehicular network simulation, simulator as ns-2, ns-3, or OMNeT++ can provide vehicular simulation libraries. In this thesis, we investigate on the Plexe project and extend its source code of Plexe-veins, version plexe-2.0[37] by utilizing OMNet++ simulator.

1.7 Literatures review

Authors in [20] specifically studied the impact of DCC-gatekeeper, considered multi-hop packet priority and proposed a brand new algorithm called DCC-advanced. This algorithm shows that it performs better in CL control than using static 10Hz message generation rate. To improve the standard DCC method, authors in [21] proposed a linear adaptive message rate algorithm, named LIMERIC, for DSRC congestion control. LIMERIC allows each vehicle to adapt its message generation rate in such a way that the total channel load will converge to a predefined target. It also avoids fairness problems observed in some binary control algorithms such as DR-DCC. In [21], we can see that, the linear adaptive control formula is given by $r_j(t) = (1-\alpha)r_j(t-1)+\beta(r_g-r_C(t-d))$ where $0 < \alpha < 1$ and $\beta > 0$. However, the Authors did not optimize the control parameters α and β. Bansal et al. [27] compared two congestion control approaches regarding reception interval and tracking error metrics. The result of [27] shows that LIMERIC performs better than reactive DCC algorithm, and further demonstrate the LEMERIC's ability for maximizing channel throughput.

As for datarate control, Math et al. [15] evaluated a datarate based control algorithm which is named DR-DCC, and compared it with transmission power control method. The result shows that DR-DCC performs better in IRT performance, because it guarantees the reliability of V2V communication. However, the algorithm of DR-DCC in [15] remains the unfairness channel load issue for each vehicle. But Kuhlmorgen et al. [16] solved this unfairness issue by the means of introducing packet counts based on DR-DCC control mechanism. In this way, Authors in [16] name their improved datarate control algorithm as PDR-DCC. This algorithm is the enhancement of DR-DCC which effectively avoids the problem of unfair channel load experience in each vehicle .

Regarding to transmission power control, [24–26] present various transmission power control strategies. Principles and protocols for power control are described in [23]. To meet the safety requirements, Torrent-Moreno et al. in [24] proposed a distributed transmission power control algorithm called D-FPAV (emergency message dissemination for vehicular environments) which forces the channel load under a strict fairness criterion. Meanwhile, they also designed another contentionbased strategy called EMDV (emergency message dissemination for vehicular environments) which guarantees an effective dissemination mechanism of alerts in a target geographical area in cooperation with D-FPAV. Further more, Wischhof and Rohling in [25] proposed a UBPFCC (Utility-Based Packet Forwarding and Congestion Control) mechanism which uses a utility function encoded in the packet header for estimating the utility of transmitting an individual data packet at each node. The result shows that UBPFCC has a good PRR performance over conventional reference system in the stochastic scenario. Samara in [26] evaluated the CBR by designing a dynamic BPC protocol. The protocol successfully decreases CL, and thereby improves the system performance depending on the channel status and received power.

Except controlling by adjusting transmission parameters, authors in [19] proposed a new dynamic beaconing algorithm particularly for Platooning usage case called Jerk beaconing without modifying any transmission parameters. The main idea of Jerk beaconing mechanism is that sending packets (bacons) when only needed. The result in [19] shows that it is not necessary to use periodic 10Hz beaconing interval to guarantee reliable communication among vehicles in a Platooning system. Instead, sending beacons (also referred to as packets) at the right moment not only can spare channel load, but also guarantee safety. However, this paper also raises another issue that whether there is a theoretical link between beacon interval and performance of the controller. Hence, the Jerk beaconing algorithm still needs additional investigation.

1.8 Contribution

The main contributions of this thesis are listed as following:

- To our best knowledge, few papers evaluate DCC mechanisms for Platooning system. In this thesis, we particularly compare the performances of DCC rate control in [33], datarate control in [15] and self-proposed power control method to see how they will impact on Platooning system.

- We suggest a best datarate option used in packet transmission of Platooning after reasonable data analysis.

- We provide a set of detailed experimental results of each parameter and make a comprehensive comparison among the results.
- We propose DCC-3 algorithm, which is an enhancement of message generation rate control by the means of increasing sub-active states.
- Instead of only adjusting one parameter, we also propose a mechanism which considering the combination of message generation rate and datarate.
- Finally, we optimize DCC reactive approaches, and suggest the best control mechanism for Platooning system.

1.9 Outline

Chapter 2 gives a brief description of ETSI DCC framework. The Chapter starts with introducing two types of important messages for vehicle communication, and further introduces CAMs dissemination mechanism. Finally, this chapter provides an overview of control strategies, which are discussing throughout the whole thesis.

Chapter 3 describes the simulation tools, such as Veins, Sumo, and OMNeT++. An extensive simulator is named PLEXE also included. Besides, this chapter highlights some important simulation classes of the library, then describes the simulation environment as well as the important metrics which will be used to evaluate Platooning's performance.

Based on three types of control mechanisms, Chapter 4 starts with the optimization of datarate control, and then propose the best datarate option. Furthermore, this chapter optimizes transmission power control method, in order to further compare control mechanisms.

Chapter 5 shows different performances of various control strategies. According to the results, TP-DCC algorithm has the best performance for Platooning.

Finally, chapter 6 concludes this thesis and chapter 7 highlights some future works.

Chapter 2

Platooning

With the rapid development of VANETs as well as the enabling communication techniques such as V2V and V2I communication, nowadays, a brand new transportation approach named platoon-based driving [6] has been defined. Obviously, plenty of vehicles will cause traffic congestion, energy waste, and pollution problems. Even though that investment on road construction can release the these problems to some extent, however, neither the huge amount of construction cost nor the limited land resource is realistic to accommodate the dramatic increment of vehicles. Thus, in order to have a sustainable development, the raise of platoon-based driving pattern becomes extra important. Figure 2.1 illustrates some scenarios of platoon-based driving pattern. Typically, vehicles with the same interest, for example, destination or time, will join in a same platoon of vehicles.

Obviously, platoon-based driving pattern has lots of benefits. For example, on the one hand, this can release the road capacity due to vehicles following closed with the front ones within a same platoon. On the other hand, according to [8], this pattern can reduce fuel consumption since the air drag will be minimized by driving as platoons. Moreover, in the papers of [9] and [10], driving in a platoon can be safer and more comfortable thanks to the advanced technologies - Cooperative Adaptive Cruise Control (CACC) - implemented in Platooning system. This technology can allow the following vehicles automatically follow the platoon leader thereby release stress for most of drivers that driving for a long time. Last but not the least, platoon-base driving pattern facilitates the potential cooperative communication applications (e.g., data sharing or dissemination) due to the relatively fixed position for

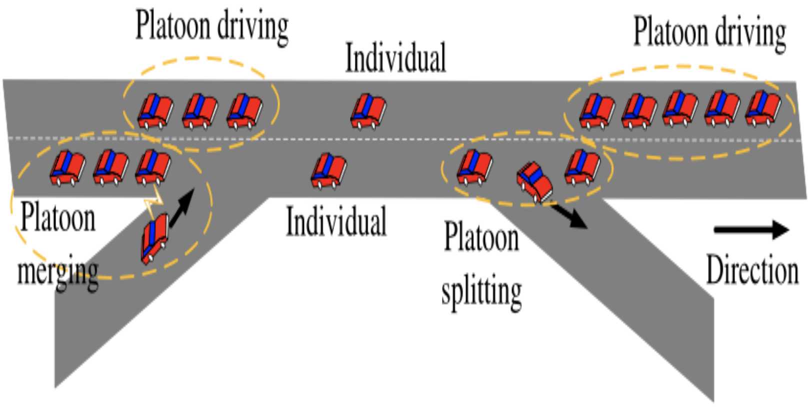


Figure 2.1: Typical platoon-based driving on the road

the vehicles within the same platoon, which may significantly improve the performance of vehicular networking.

Over the last few years, the interest in ITS is growing rapidly. Additionally, this leads to the conception of cooperative applications for road safety which rely on timely message exchanging among surrounding vehicles. Researches of VANETs have already started many years ago, but only a few of them are implemented.

Platooning application is one of these important safety applications. An overview of current projects for evaluating Platooning systems is presented in [28]. Generally, the SARTRE [29, 30] project aims to provide solutions for platoon-based driving on public motorways without modification to any infrastructure. The PATH project focuses on maximizing road throughput and highway capacity based on automated platoons and thereby to reduce the cost of infrastructure construction. While SCANIA-platooning is interested in minimizing fuel consumption and further to reduce environmental effect of transport. Another fuel efficiency distributed control strategy for heavy trucks also can be found in [31,32].

In general, platooning is defined as a group that share the same mobility pattern and maintains a formation [5]. Typically, within a platoon, vehicles will follow closed with the front ones (exclude the head) and maintain a nearly fixed IVD and speed. The first one vehicle in a

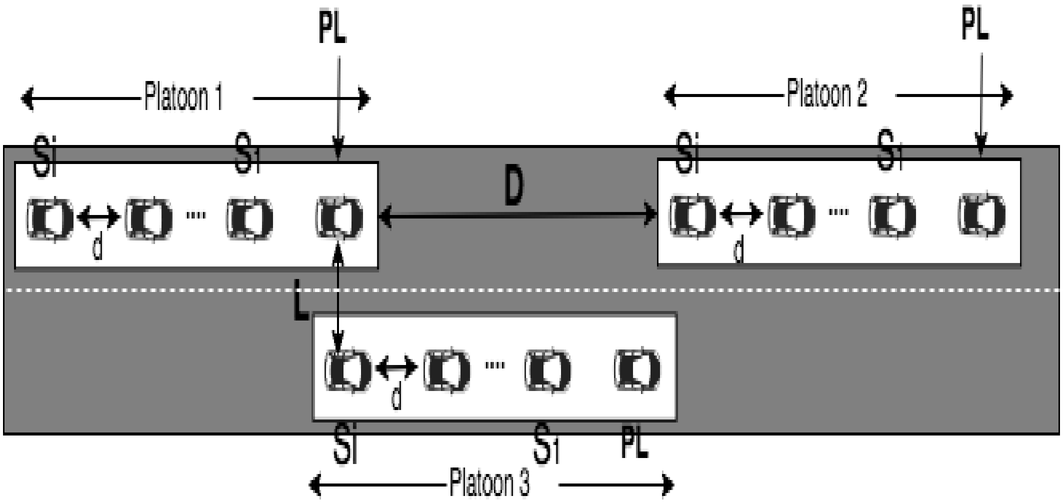


Figure 2.2: A multiplatoon scenario is shown with the main notations marked

platoon is the Platoon Leader (PL) which is responsible for leading the Plaoon Members (PMs). Figure 2.2 depicts the components and features of platoon systems. As mentioned above, PL is the platoon leader which is followed by couples of PMs. Within a platoon, d represents IVD (Inter Vichle Distance) while D represents the inter platoon distance. The stability of platoon systems is ensured through periodic kinematics information exchange among vehicles. The exchanging packets/beacons convey kinematics information to share with all PMs and PLs. Typically, a beacon conveys the vehicle presence, position and acceleration/deceleration information. Within a platoon, beacons are originating from PL and broadcast to its PMs (S1 - Si). Beacons will feed into all the controllers installed in each vehicle. The main job of controller is to control the behavior of the vehicle base on the received information. Hence, to guarantee safety of platoons, timely information updating is required to avoid crash of vehicles since the IVD is very closed.

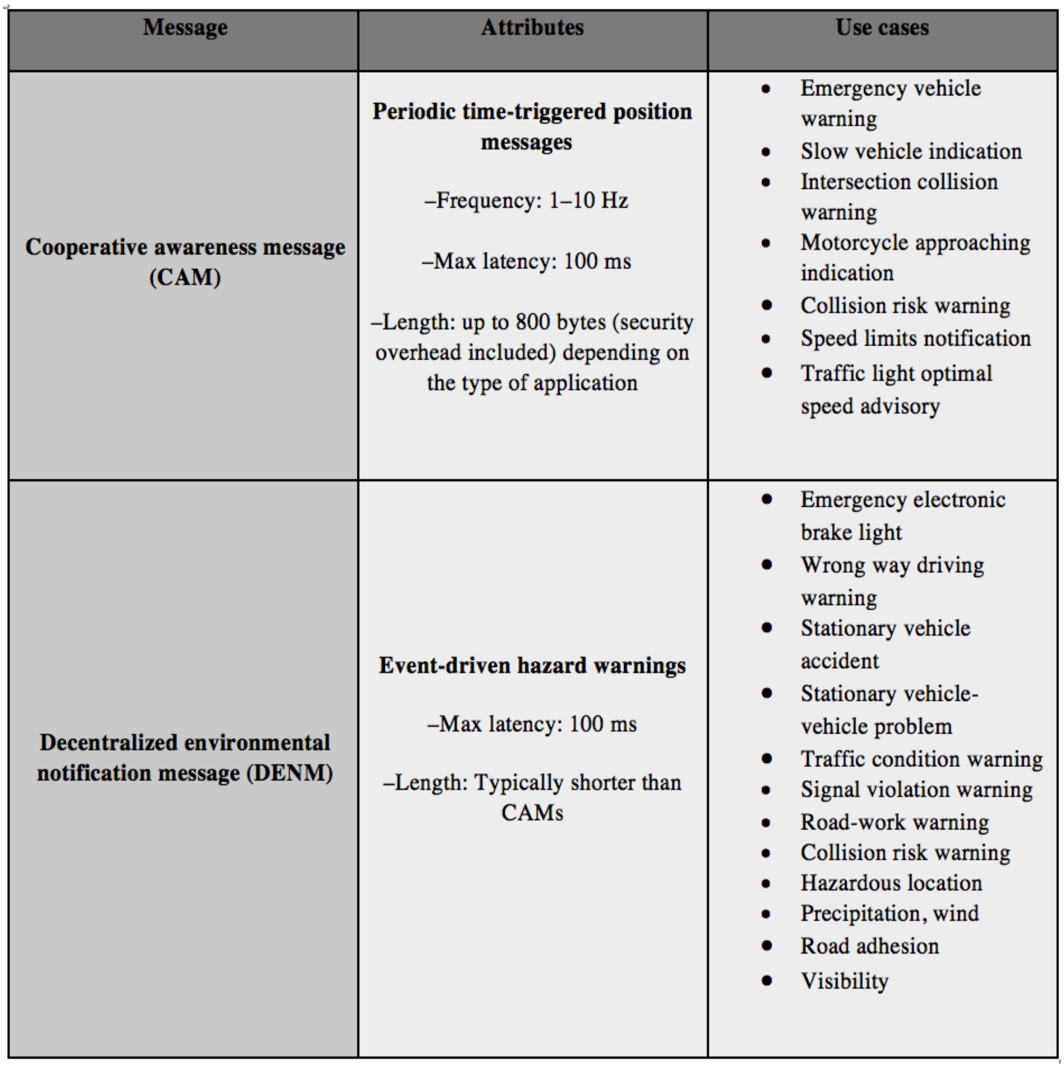
Chapter 3

DCC Mechanism

This chapter specifically studies ETSI standards. Firstly, draft ETSI EN 302 571 V2.0.0 standardizes the allocation of bandwidth where the frequency range from 5855 GHz to 5925 GHz, this provides the wireless resources for road communications. Additionally, the draft ETSI EN 302 895 V1.1.0 defines functional behavior associated with a LDM for usage in an ITS station unit and further specifies functions and interfaces supported by a local dynamic map. These functions and interfaces provide secure access to the LDM to manage data objects stored in a LDM. The draft ETSI EN 302 637-2 V1.3.1 provides the specifications of the cooperative awareness basic service, which is to support the road safety application. While ETSI TS 102 637-3 V1.1.1 indicates the specifications of the DENM basic service, which mainly support the road hazard warning application.

3.1 CAM and DENM

Refer to ETSI EN 302 637-2 V1.3.1 and ETSI TS 102 637-3 V1.1.1, two types of communication messages for VANETs have been standardized, CAMs are periodic broadcasting which are used for timely information exchange. While DENMs are event-triggered, which are used to prevent emergency and hazard events. Figure 3.1 concludes the use cases of CAMs and DENMs.



Message	Attributes	Use cases
Cooperative awareness message (CAM)	**Periodic time-triggered position messages** –Frequency: 1–10 Hz –Max latency: 100 ms –Length: up to 800 bytes (security overhead included) depending on the type of application	• Emergency vehicle warning • Slow vehicle indication • Intersection collision warning • Motorcycle approaching indication • Collision risk warning • Speed limits notification • Traffic light optimal speed advisory
Decentralized environmental notification message (DENM)	**Event-driven hazard warnings** –Max latency: 100 ms –Length: Typically shorter than CAMs	• Emergency electronic brake light • Wrong way driving warning • Stationary vehicle accident • Stationary vehicle-vehicle problem • Traffic condition warning • Signal violation warning • Road-work warning • Collision risk warning • Hazardous location • Precipitation, wind • Road adhesion • Visibility

Figure 3.1: Description of CAM and DENM

3.2 CAMs dissemination

In this thesis, our topic is to investigate the stability of Platooning system, so that we will mainly focus on studying CAM dissemination mechanism to see how to develop new features to guarantee reliable communications for Platooning system. According to ETSI standards, CAM is periodic originated from PL and then propagated to its PMs. Regarding to CAM dissemination mechanism, the following parameters are important:

- T_GenCam_Dcc: Provide the minimum time interval between two consecutive CAM generations
- T_GenCam: Represents the currently valid upper limit of the CAM generation interval.
- N_GenCam: The triggering numbers of consecutive CAMs
- T_GenCamMin: The minimum generation interval of CAMs
- T_GenCamMax: The maximum generation interval of CAMs
- T_CheckCamGen: The interval time to check the generation of CAMs

Where the T_GenCamMin and T_GenCamMax standardized as following respectively:

- The CAM generation interval shall not be inferior to T_GenCamMin = 100 ms. This corresponds to the CAM generation rate of 10 Hz.
- The CAM generation interval shall not be superior to T_GenCamMax = 1 000 ms. This corresponds to the CAM generation rate of 1 Hz.

In the platooning scenario, CAM generation shall be triggered depending on the originating PL dynamics and the channel congestion status. In case the dynamics of the originating PL lead to a reduced CAM generation interval, this interval should be maintained for a number of consecutive CAMs. The conditions for triggering the CAM generation shall be checked repeatedly every T_CheckCamGen. where the constraints is T_CheckCamGen $\leq$ T_GenCamMin, T_GenCamMin $\leq$ T_GenCam_Dcc $\leq$ T_GenCamMax and T_GenCamMin $\leq$ T_GenCam $\leq$ T_GenCamMax.

Additionally, the CAMs triggering conditions with respect to vehicle dynamics could be described as the following:

- CASE A: the absolute difference between the current heading of the originating vehicle and the heading included in the CAM previously transmitted by the originating vehicle exceeds 4°;
- CASE B: the distance between the current position of the originating vehicle and the position included in the CAM previously transmitted by the originating vehicle exceeds 4 m;
- CASE C: the absolute difference between the current speed of the originating vehicle and the speed included in the CAM previously transmitted by the originating vehicle exceeds 0.5 m/s.

3.3 Control strategies

The definition of CBR is time-dependent value between zero and one representing the fraction of time that a single radio channel is busy with transmissions. CBR is a function of CL. The calculation of CBR is given by

$$CBR = \frac{T_{busy}}{T_{tot}} \tag{3.1}$$

where $T_{tot} = T_{busy} + T_{idle}$ (T_{busy} and T_{idle} is the busy time and idle time respectively during periods).

According to the study of ETSI TS 102 687 specifications, DCC mechanisms rely on switching among state machines, RELAX, ACTIVE, and RESTRICTIVE. The state machines adapt parameters such as message generation rate, datarate, and transmission power. Towards these three types of parameters, techniques for controlling CBR include the following:

- Transmit rate control (TRC): Regulate CAMs generation rate between two consecutive packets from a sender. For example, increase the message rate if channel is detected as congested, or reduce if channel is relax.
- Transmit datarate control (TDC): Offering several predefined transfer rate options in wireless systems. During high utilization periods, switching to a higher datarate can lead to a decreased air transmission time.

- Transmit power control (TPC): By altered transmitting power on PHY layer to adjust the detected CL. During a high utilization periods of channel, reducing transmission power can lead to a reduction of interference range and thereby, will experience a reduced CBR.

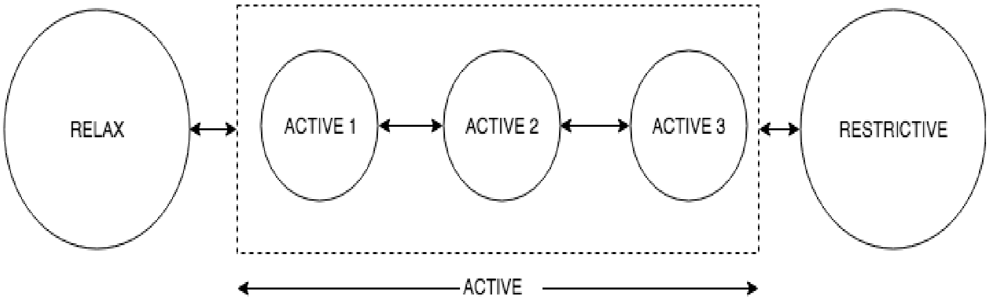


Figure 3.2: A generic outline of state machines of the reactive approach

CBR control relies on the predefined state machines, as illustrated in Figure 3.2. Each machine state represents a predefined massage generation rate, datarate, or transmission power. The condition of transition between two states depends on the current CBR detected from channel. ETSI provides an example of 3 sub-active states machine, the mapping relationship is shown in Table 3.1.

Table 3.1: A table lookup for mapping the CBR with states

State	**CBR**	**Packet rate**	**Generation interval**
Relaxed	< 30%	10Hz	100ms
Active 1	30% to 39%	5Hz	200ms
Active 2	40% to 49%	2.5Hz	400ms
Active 3	50% to 60%	2Hz	500ms
Restrictive	> 60%	1Hz	1000ms

Chapter 4

Simulation Setup

To simulate vehicular network environment, a specific simulator is required. According to [34], both ns-2, ns-3 and OMNeT++ can be used to do vehicular network simulation. For this thesis, OMNeT++ is utilized along with its frameworks to implement all the simulations.

4.1 Simulator

As discussed earlier, all the simulations are performed in PLEXE simulator, which is comprised by three simulators, Veins, Sumo and OMNeT++. Veins is an open source framework for running vehicular network simulation. It is bidirectionally coupled network and road traffic simulator, which is encapsulated in OMNeT++. OMNeT++ is an event-based network simulator. While Sumo is a road traffic simulator. The connection between OMNeT++ and Sumo is implemented via a TCP socket, in which the protocol has been standardized as TraCI. OMNeT++ takes care of the nodes behavior such as mobility, crash, obstacle, etc. Various functions are presented by hierarchy reusable modules written in C++. The relationship among modules and the communication logic are stored in the corresponding NED files. For example, which module serves as input/output gate shall be defined in a NED file. The INET framework inside OMNeT++ simulator provides a set of modules implemented in various layers as well as the cross-layer communication protocols. For example, IEEE802.11p is implemented on MAC layer, which provides the base communication protocol model that ready to reuse or re-write for your own protocols.

Traffic simulation in Veins is performed by Sumo. For the most re-

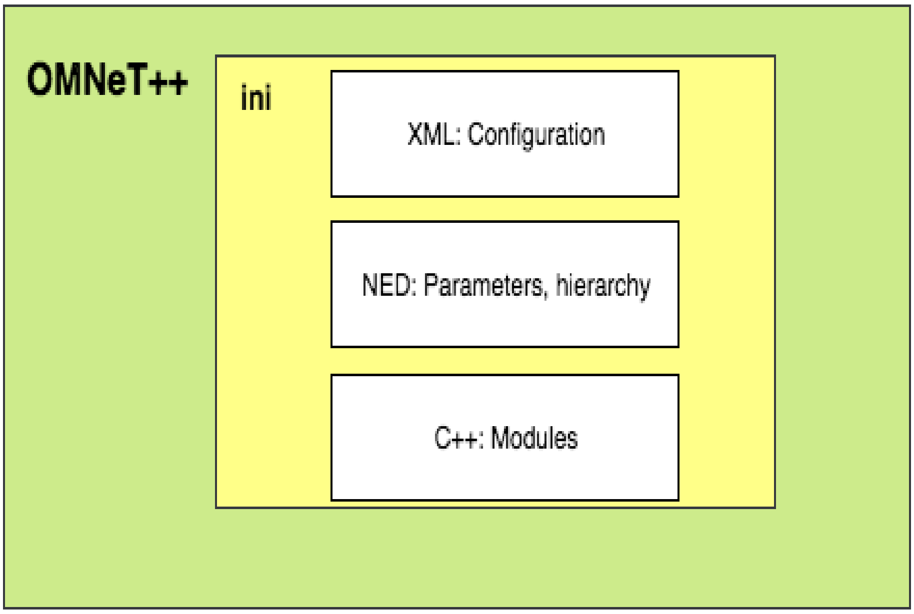


Figure 4.1: Files hierarchy in OMNeT++

alistic simulation of moving nodes, Sumo model them by tracing files obtained in real-world measurement. Simulations in Sumo could be run with or without a GUI. Besides, one of the main function of Sumo is to import an existing city map, which can be directly used for simulating real world traffic. Otherwise, customized your own map is another way to do simulation for running vehicles. Map configurations are written in XML format, when a simulation begins, the configuration parameters will be loaded into a *ini* file.

Figure 4.1 shows the hierarchy relationship of different types of configuration files. In general, the *ini* file serves as the main function of the process. When the simulation triggered, all the configuration parameters will be loaded into the *ini* file. Specifically, network configuration parameters are written into the XML file, some other parameters, such as bitrate, transmission power etc., will be reached directly though the C++ modules or stored in a particular *NED* file. Besides, different *NED* files also define the hierarchy relationship among modules which are implemented in C++ programming language.

Figure 4.2 depicts the detail of the framework architecture of Veins. During a simulation, Veins framework allows simulation running parallel both in network and road traffic. As mentioned earlier, OM-

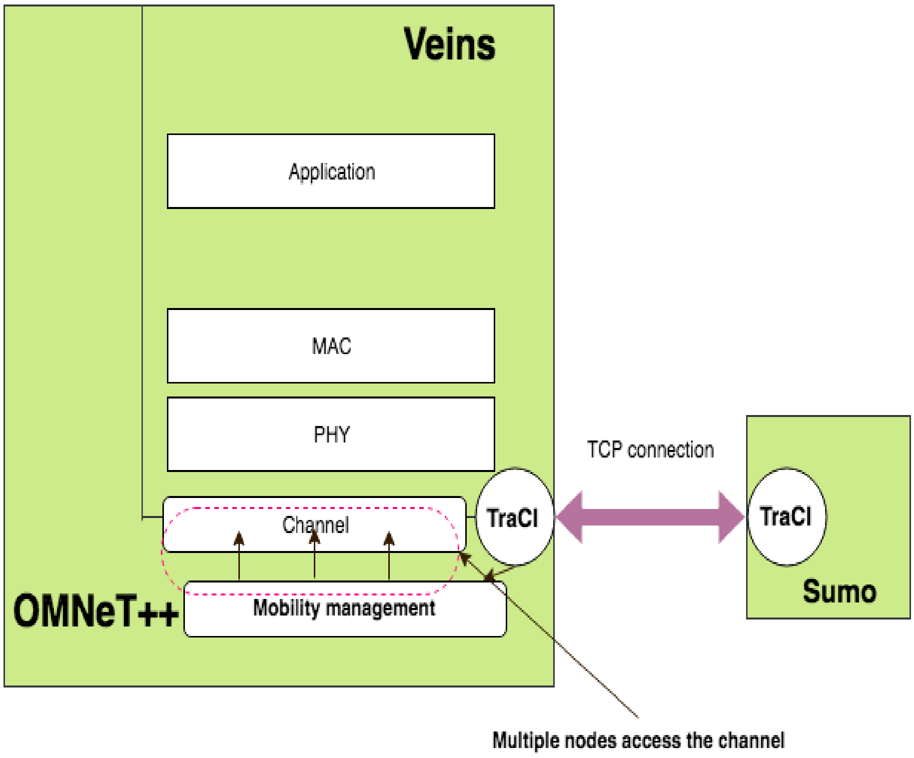


Figure 4.2: Veins framework architecture

NeT++ is an event-based network simulator, thus, it handles mobility by scheduling node's movement at regular intervals. As shown in Figure 4.2, nodes will access the communication channel randomly and separately. Node events happen in various layers, for instance, to schedule a beacon in MAC layer at each 0.1s. To guarantee synchronous execution at defined intervals, at each timestamp, OMNeT++ will send commands to Sumo and trigger the corresponding timestamp of the road traffic simulation.

To simulate platooning scenario, this thesis utilizes Plexe simulator. Plexe is an extension simulator of Veins that permits the realistic simulation for platoon system. Plexe enables the IVC protocols suitable for OMNeT++ and Sumo. For more details of Plexe simulator, see [35].

4.2 Simulation environment

OMNeT++ provides a lot of classes and components for vehicular simulation [36]. For example, `cSimpleModule` is used to implement simulation modules, which means user will subclass `cSimpleModule`, and overwrite its member function such as `handleMessage()` or `activity()`. Modules can be either hierarchical or parallel relationship. The relationship of modules is described in NED files, which means each module associates with a special NED file. Before starting a simulation, OMNeT++ IDE will load all the information of NED files to setup the simulation environment. `cChannel` is one of the important classes, it implements the communication channel by encapsulating properties of connections between modules. For example, the class of `cGate` will specify how a module communicate with others by defining the `output` and `input` gate objects, to allow module communicate with other modules on a lower or higher layer. The exchanging information between modules will be stored in the `cMessage` object. Moreover, `cMessage` need to be encapsulated within a `cPacket` class so that it can across various layers in a vehicular simulation environment.

According to Plexe project [37], IEEE802.11p techniques are already implemented in MAC and PHY layers. In this thesis, we extend the source code [37] to implement new sub-modules (protocols) based on IEEE802.11p to schedule events, detect and calculate CL and modify parameters. Technically, to modify a parameter cross layer, or to get the mobility information from Sumo can be implemented by utilizing pointers.

`ini` file is the configuration file for simulation environment. Configurations are defined for each module during initialization phase and can be further modified by implementing functions in a specific module. The main configurations include protocols, network architecture, Sumo and common parameters such as platooning size and number of simulation lanes. Two screenshots below (Figure 4.3 and 4.4) present the difference by changing the `nlanes` simulation parameter.

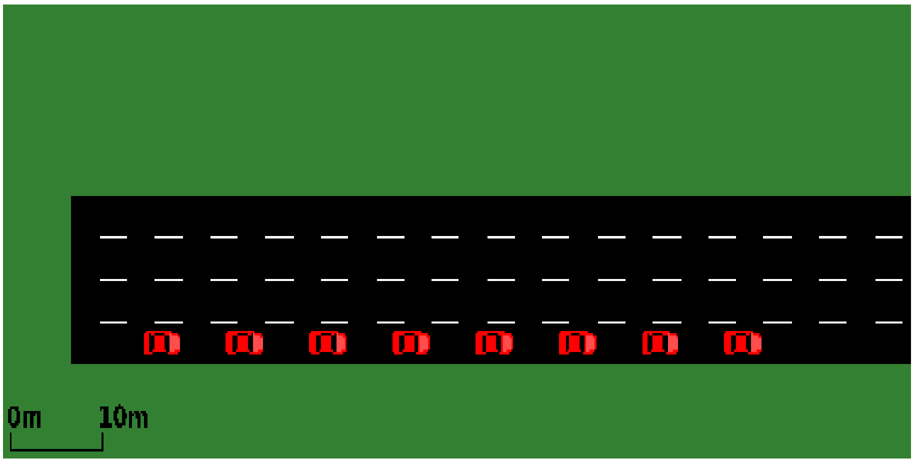


Figure 4.3: A screenshot of platooning simulation of 1 lanes

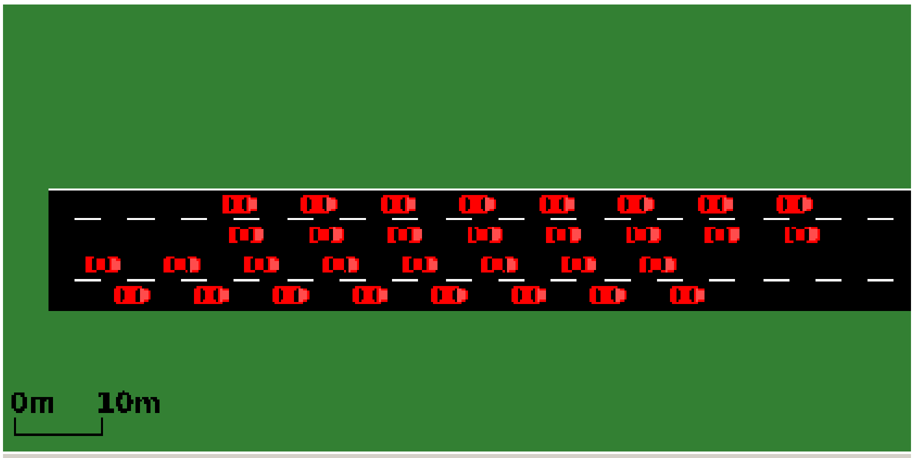


Figure 4.4: A screenshot of platooning simulation of 4 lanes

4.3 Metric measurement

4.3.1 CBR

As mentioned previously, congestion control is the main topic for vehicular network, and thereby, many works have discussed and demonstrated various control strategies to achieve CL control. In general, CBR is used as a metric to estimate CL condition. CBR$_i$(t) represents the fraction of time in the t^{th} observing interval that node i assumes the channel as busy, which means that the signal strength received by node i is higher than the carrier sensing threshold [15]. Note that, this thesis only measures CL generated by CAMs, thus, the actual CBR in the real world should be larger than the simulated one. The formula to calculate a CBR during periods is given by the equation 3.1.

4.3.2 IRT

The definition of IRT is the time gap between two consecutive received packets from the same sender. IRT is essential since the stability of platooning is ensured by timely information exchange. In this thesis, we calculate IRT for a specific vehicle both considering the packets received from PL and the front vehicle of itself within a platoon.

4.3.3 PRR

PRR shows the packet efficiency performance of a platooning system. Higher PRR guarantee more reliable communication. The calculation of PRR is given as following:

$$PRR = \frac{receivedBroadcast}{receivedBroadcast + SINRlLostPackets + TXLostPackets} \tag{4.1}$$

Chapter 5

Control Parameters Optimization

5.1 Datarate based

Several datarate based control algorithms are provided in [15-17]. As mentioned previously, increasing datarate can give packets a shorter air transmission duration, which will decrease CL. This mechanism has also been standardized by ETSI as a kind of reactive approach by providing a series of standard datarate options which are used for data transmitting. The datarate options include 3Mbps, 6Mbps, 9Mbps, 12Mbps and 24Mbps. Authors in [18] suggests 6 Mbps as the optimal option for general cases, which this level of datarate has most benefits to avoid packet loss, delay and interference. In [15], authors proposed a DR-DCC protocol, the principle is similar to ETSI standard reactive approach [13]. However, the problem of DR-DCC mechanism is that it suffers unfairness CL experience problem in each vehicle. This problem gets mitigated in [16], in which the authors proposed a packet count based DR-DCC, this new protocol will force each vehicle to have the same CL level by estimating packet counts during transmission. Unfortunately, all of the mentioned papers only evaluated datarate control mechanisms for non-platooning scenario. Besides, challenges still exist for higher datarate options since high datarate level will cause significant wireless interference. Based on previous literature study, in this thesis, we only discuss the following predefined datarate options: 3Mbps, 6Mbps, 9Mbps, and 12Mbps. Refer to the work in [15], in this section, we target to optimize datarate options by simulating various number of vehicles. The simulation parameters are given in Table 5.1, and the detailed simulation results are shown in the Figure 5.1, 5.2 and 5.3.

Table 5.1: Simulation parameters for static datarate control

Controller	CACC
Transmission Power	1 mW
Beaconing interval	0.1s
Sensitivity	-94 dBm
Channel	CCH
ThermalNoise	-95 dBm
Platoon size	8
Lane	4
Scenario	Highway
Simulation duration	20 s

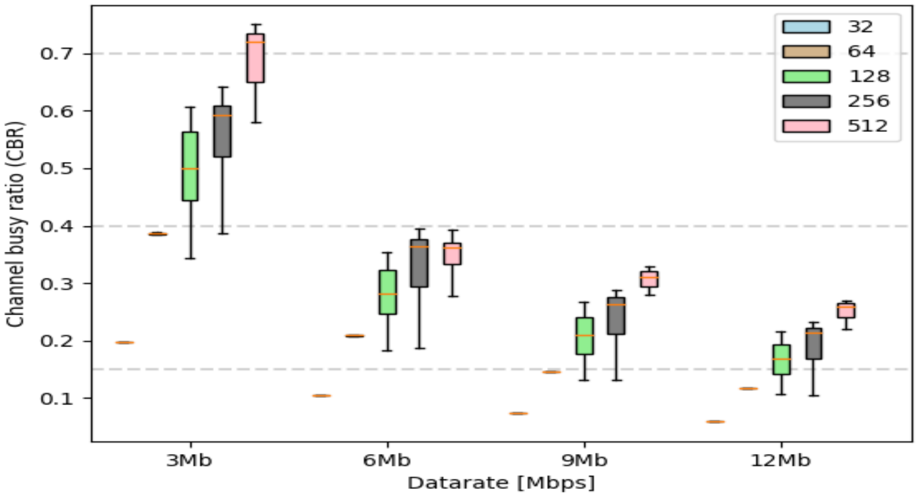


Figure 5.1: CBR values by varying datarate and vehicle number

Figure 5.1 shows the CBR performance at different levels of datarate and vehicle number. According to many researches, 0.7 is a threshold to decide a channel becomes extremely congested. In other words, if a CBR value is higher than 0.7, then the channel is considered as in extremely congested condition. As we can see in Figure 5.1, only one CBR value exceeds the threshold of given by 512 vehicles and 3Mbps datarate. The reason is that, compared to others, it has the maximum vehicles but lowest transmitting datarate. Having the maximum vehicles means the channel will be accessed by nodes more frequently since every node needs to transmit packets in every time interval. However, the provided datarate is too low to make the transmitting packet faster and thereby it cause the packet to occupy longer channel access time, therefore, the channel will easily get congested. For all the data sets that with the same datarate but various number of vehicle, the CBR will rise as increasing the number of vehicle. While look at the data sets that with the same number of vehicle but various datarate, instead, increasing datarate will lead to the reduction of CBR. This is because only increasing the number of vehicle results in a higher channel access frequency, but increasing datarate will make transmitting packets to have shorter transmission duration, which means higher datarate will help to improve channel capacity in time unit so that mitigate the channel congestion problem.

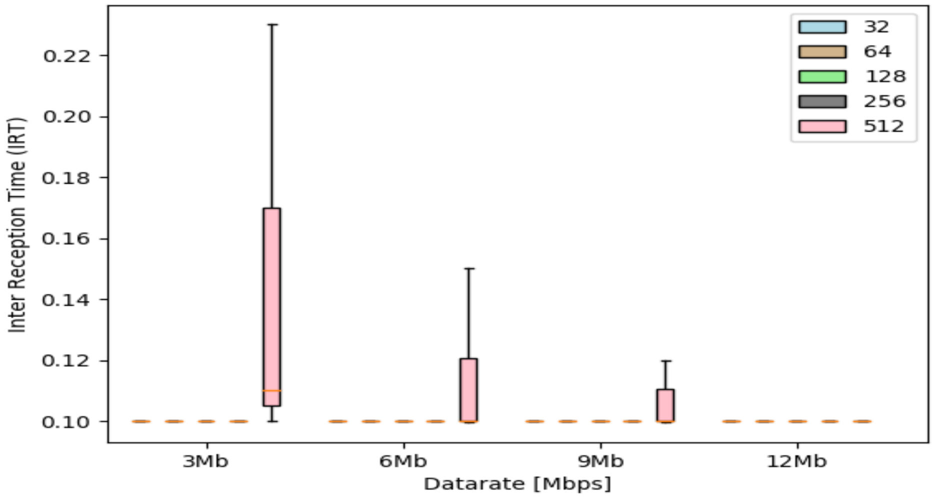


Figure 5.2: IRT values by varying datarate and vehicle number

Besides CBR, IRT is another important metric of channel congestion control, because vehicles have to update information in time to guarantee safety of Platooning. Figure 5.2 shows IRT performances of different levels of datarate and vehicle number. As can be seen from the figure, look at the cases of 3Mb, 6Mb and 9Mb datarate, in which all the data sets of 32, 64, 128 and 256 vehicles have the similar IRT performance around 0.1s, because the default message generation rate is 10Hz. However, when the vehicle number reaches to 512, the IRTs will increase more or less. As pointed out earlier, 512 vehicles' communication may cause channel congestion and further lead to packet loss or packet delay. Thus, longer IRT is expected especially when channel is congested. To mitigate long IRT issue, increasing datarate could be one way according to Figure 5.2, becuase for the case with 512 vehicles, the IRT trends to drop down when increasing datarate. At the end, for all sets that in the case of 12Mb, they remain similar IRT performance around 0.1s. This means 12Mb datarate is good enough to handle 512 vehicles' communication with avoid packet delay. Because every transmitting packet has much shorter transmission time by given a 12Mb datarate option.

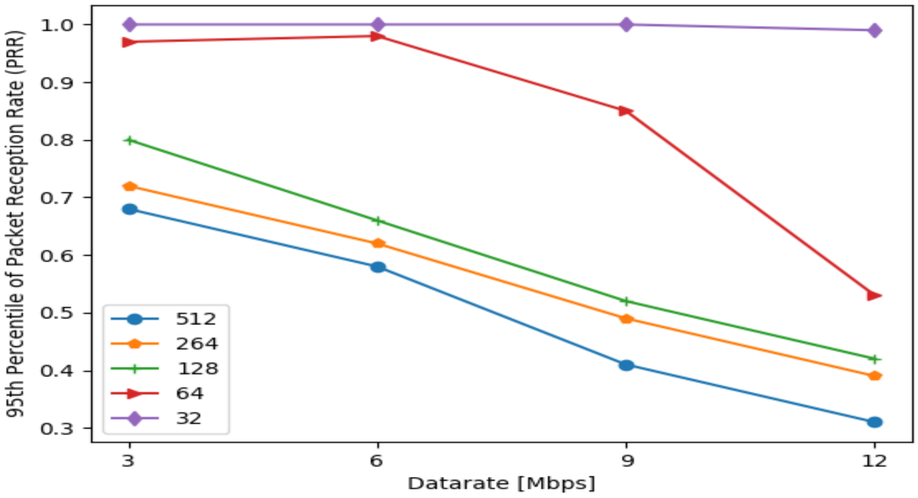


Figure 5.3: PRR values by varying datarate and vehicle number

PRR is also an important metric since it is a measurement that can immediately reflect packet loss level. Packet loss rate is essential, because vehicles require fresh packet information to tell them how to make their reaction. Figure 5.3 shows the results of 95th percentile of PRR of different numbers of vehicle and datarate. For each specific vehicle number, improving datarate results in lower PRR. This is because PRR is related to wireless interference, however, higher datarate causes significant interference. For each fixed datarate set, higher vehicle quantity also leads to lower PRR level, in other words, channel congestion will affect PRR performance as well.

Table 5.2: Conclusion of static dararate control

Datarate	**nCar**	**50th CBR**	**95th PRR**	**95th IRT**
3Mbps	512	0.72	0.68	0.19
3Mbps	256	0.59	0.72	0.13
3Mbps	128	0.5	0.81	0.1
3Mbps	64	0.38	0.97	0.1
3Mbps	32	0.20	1.0	0.1
6Mbps	512	0.34	0.58	0.15
6Mbps	256	0.33	0.62	0.1
6Mbps	128	0.28	0.66	0.1
6Mbps	64	0.21	0.98	0.1
6Mbps	32	0.10	1.00	0.1
9Mbps	512	0.31	0.41	0.12
9Mbps	256	0.26	0.49	0.1
9Mbps	128	0.21	0.52	0.1
9Mbps	64	0.15	0.85	0.1
9Mbps	32	0.07	1.0	0.1
12Mbps	512	0.26	0.31	0.1
12Mbps	256	0.21	0.39	0.1
12Mbps	128	0.17	0.42	0.1
12Mbps	64	0.11	0.53	0.1
12Mbps	32	0.06	0.99	0.1

By collecting of all the simulation results above, Table 5.2 summaries the information into details. Based on the simulation results, we thereby propose the dynamic datarate DCC control mechanism (DR-DCC) as described in Algorithm 1. The rule for the Algorithm is that: (1) CBR is the first consideration, if CBR goes extremely high, that it should be decreased as soon as possible; (2) Keep the PRR level as high as possible without decreasing the CBR. According to Table 5.2, 6Mbps datarate has the best performance because in this level datarate, the related none of the CBR is higher than 0.4, and the 95th percentile PRR performances are over 0.6 even in the case of 512 vehicles. Therefore, this work immediately verifies the work in [22], which suggests the 6 Mbps datarate is the best option for packet transmission. Thus, we will utilize 6 Mbps as the optimal option for designing the algorithms of transmission power control and massage generation rate control later.

Algorithm 1 DR-DCC Algorithm

```
if CBR $\geq$ 60% then
    ptr $\rightarrow$ setMcs(datarate = 12 Mbps)
else if (CBR < 60%) && (CBR $\geq$ 40%) then
    ptr $\rightarrow$ setMcs(datarate = 9 Mbps)
else if (CBR < 40%) && (CBR $\geq$ 15%) then
    ptr $\rightarrow$ setMcs(datarate = 6 Mbps)
else if CBR < 15% then
    ptr $\rightarrow$ setMcs(datarate = 3 Mbps)
end if
```

5.2 Transmission power based

The parameter transmission power also deserves additional investigation on channel congestion control. Similar to datarate, ETSI standardized power for packet transmission in vehicular network as well, both of them are relying on the transition among state machines. Adjusting transmission power to achieve the goal of channel congestion control is not a fresh topic, instead, some efforts have already been done such as in [24] and [25]. However, neither [24] nor [25] evaluated CAMs in vehicular networks, instead, they investigated on DENMs. Some researches also designed new power transmission algorithms, for example in [26], a transmission power calculation model for packet transmitting was proposed, but unfortunately, authors in [26] did not provide the evaluation results based on the model.

Since power control is such an important topic against channel congestion control, in this section, we will analyze our simulation results and do optimization for this parameter based on the results. The power options including 0.1mW, 1mW and 10mW will be discussed in this section. Similarly, Table 5.3 provides the simulation parameters for running power control simulations. Since we demonstrated 6Mbps is the optimal option datarate, therefore we will use it to do further optimization of power control. For the beaconing interval, we still use the default value 0.1s. Later after this section, we will continue to optimize beaconing interval to derive the final conclusion.

Table 5.3: Simulation parameters for static power control

Controller	CACC
Datarate	6Mbps
Beaconing interval	0.1
Sensitivity	-94 dBm
Channel	CCH
ThermalNoise	-95 dBm
Platoon size	8
Lane	4
Scenario	Highway
Simulation duration	20 s

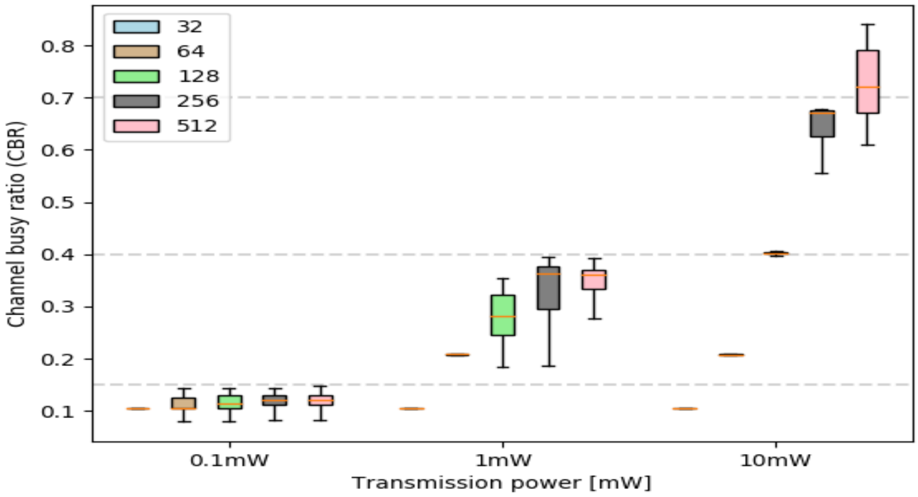


Figure 5.4: CBR values by varying transmission power and vehicle number

As the results can be observed, Figure 5.4 shows the CBR performances by varying transmission power and number of vehicle. For example, with the same power level, increasing vehicle quantity will lead to the increment of CBR. While with the same number of vehicles, increasing transmission power results in higher CBRs, because a higher transmission power has a longer interference transmission distance, which will occupy greater amount of channel assess time and thereby cause channel congested. Moreover, what can be observed from Figure 5.4 is that, less transmission power leads to better performances of CBR for all numbers of vehicle. Specifically, the simulation that having only 32 vehicles does not seems to be affected by these three options of transmission power at all. Furthermore, if given a 0.1mW transmission power, the CBRs are low enough even though the number of vehicle reaches 512.

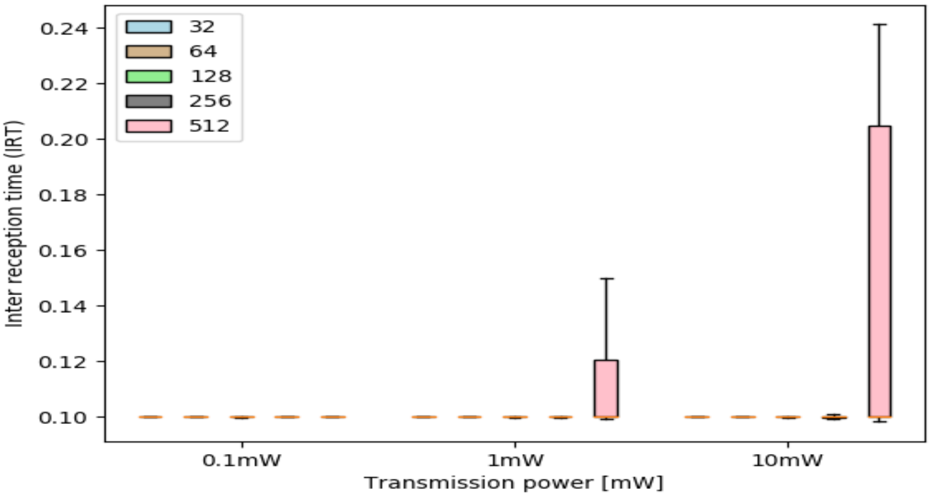


Figure 5.5: IRT values by varying transmission power and vehicle number

As for IRT performance, it's shown in Figure 5.5, in which the results are similar to Figure 5.2. The only factor has significant influence on IRT performance of power control is the quantity of vehicle. All in all, the reason is that the channel will get congested easier with more presence vehicles.

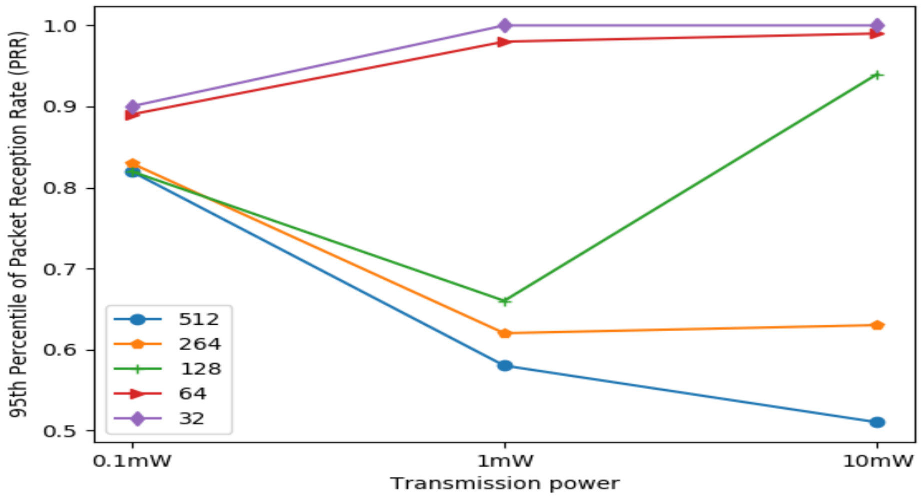


Figure 5.6: IRT values by varying transmission power and vehicle number

Figure 5.6 shows the PRR performances about transmission power simulation. From Figure 5.4 and 5.5, the simulation results with utilizing 0.1mW transmission power have the absolute best performance against others. However, when it comes to PRR, using 0.1mW is not always the best, for example, for the sets of 32 or 64 vehicles, increasing power will help to have higher PRR. This is because low transmission power may result in a lower strength of the received power due to path loss and attenuation. Furthermore, refer to the work in [24], 80% PRR within 100 meters is acceptable, thus, transmission power lower than 0.1mW is not taken into account. Therefore, we suggest the least transmission power is 0.1mW to avoid too much wireless attenuation. To further demonstrate this, we will compare the performance between using 0.1mW and 1mW transmission power in the next section.

Table 5.4 concludes the results of Figure 5.4, 5.5 and 5.6. According the visible results in Table 5.4, we hereby divide CBRs into three levels, RELAX :$CBR \leq 20\%$, ACTIVE: $20\% \leq CBR \leq 40\%$, and RESTRICTIVE: $CBR \geq 40\%$, and thereby propose the dynamic DCC transmission power (TP-DCC) control algorithm as shown in Algorithm 2.

Table 5.4: Conclusion of static power control

TxPower [mW]	nCar	50th CBR	95th PRR	95th IRT
0.1	512	0.12	0.82	0.1
0.1	256	0.12	0.82	0.1
0.1	128	0.11	0.82	0.1
0.1	64	0.1	0.89	0.1
0.1	32	0.1	0.89	0.1
1	512	0.34	0.58	0.15
1	256	0.33	0.62	0.1
1	128	0.28	0.66	0.1
1	64	0.21	0.98	0.1
1	32	0.10	1.00	0.1
10	512	0.83	0.51	0.22
10	256	0.67	0.63	0.19
10	128	0.4	0.94	0.1
10	64	0.21	0.99	0.1
10	32	0.1	1.0	0.1

Algorithm 2 TP-DCC Algorithm

```
if CBR $\geq$ 40% then
    ptr $\rightarrow$ setMcs(TxPower = 0.1 mW)
else if (CBR < 40%) && (CBR $\geq$ 20%) then
    ptr $\rightarrow$ setMcs(datarate = 1 mW)
else if CBR < 20% then
    ptr $\rightarrow$ setMcs(datarate = 10 mW)
end if
```

5.3 Massage rate control

5.3.1 Standard ETSI DCC

Massage generation rate is the direct factor to affect CBR condition. Transparently, improving massage generation frequency will increase CBR. The main purpose of massage generation rate control mechanism is to force massage generation frequency to be decreased to a predefined target when the channel is detected as congested.

DCC control mechanism is relying on the transition of state machines [13]. Thus, we will introduce some constants to determine when and how the state machines react or switch before going to the state machine mechanism.

- NDL_TimeUp: How often state machine react when the CL goes up;
- NDL_TimeDown: How often state machine reacts when the CL goes down;
- DCC_measeurement_interval: Determines how often DCC should do the measurement, which means which state need to transfer to;
- DCC_sampling_time: Determines how often the DCC should be check;
- NDL_min_CL: The minimum Cl to change state;
- NDL_max_CL: The maximum Cl to change state;
- clMinInTimeUp: The minimum CL in NDL_Time_Up;
- clMaxInTimeUp: The maximum CL in NDL_Time_Down.

According to [17], we introduce an state machine as shown in Figure 5.7. In general, DCC_measeurement_interval equals to 1s, this means the CBR measurement is on every 1s basis. Every second, the condition of transition will happen between two state machines can be described as the following: (1) If the CBR in 1 second (NDL_TimeUp) equals or greater than 0.15 , the state machine will initially switch from RELAX state to ACTIVE state; (2) If the CBR in 1 second (NDL_TimeUp) equals or greater than 0.5, the state machine will transfer to RESTRICTIVE state. To the contrary, (1) if current state is RESTRICTIVE, the condition to go to ACTIVE state is the CBR less than 0.4 in 5 seconds, (2) if current state is ACTIVE, the condition to go to RELEX state is the CBR less than 0.15 in 5 seconds. The algorithm can be described as shown in Algorithm 3. And the corresponding CBR is given in 5.5.

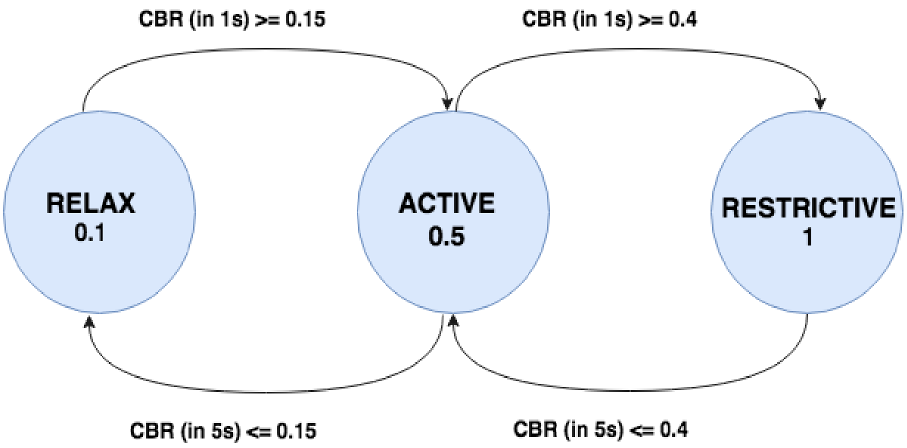


Figure 5.7: An example of state machine transition

Algorithm 3 DCC algorithm

```
if (currentState == RELAX) && (clMinInTimeUp $\leq$ NDL_min_CL) then
    setCurrentState(ACTIVE)
else if (currentState == ACTIVE) && (clMinInTimeUp$\leq$ NDL_max_CL) then
    setCurrentState(RESTRICTIVE)
else if (currentState == RESTRICTIVE) && (clMaxInTimeDown < NDL_max_CL) then
    setCurrentState(ACTIVE)
else if (currentState == ACTIVE) && (clMaxInTimeDown < NDL_min_CL) then
    setCurrentState(RELAX)
end if
```

Table 5.5: A table lookup for one ACTIVE state machine

State	**CBR**	**Beaconing interval**
Relax	$< 15\%$	0.04s
Active	15% to 39%	0.5s
Restrictive	$\geq 40\%$	1s

5.3.2 Experimental enhancement for message rate control

A potential approach to enhance the massage generation rate control is to add sub-ACTIVE states. In this thesis, we particularly investigate on adding 3 ACTIVE states. Table 5.6 shows the mapping between CBR and beaconing interval for 3 sub-ACTIVE states machine (DCC-3). The algorithm is similar to DCC.

Table 5.6: A table lookup for mapping the CBR with 3 ACTIVE states

State	**CBR**	**Beaconing interval**
Relax	$< 15\%$	0.04s
Active 1	15% to 25%	0.1s
Active 2	25% to 35%	0.3s
Active 3	35% to 40%	0.5s
Restrictive	$> 40\%$	1s

Chapter 6

Simulation results

Figure 6.1, 6.2 and 6.5 present the performances of CBR, IRT and PRR respectively of various algorithms. Both DCC, DCC-3, DR-DCC and static beaconing (No DCC) are using 1mW transmission power. In Figure 6.1, TP-DCC outperforms than the others at all vehicle density levels. From Figure 6.1, clearly that the ranking of control ability of channel congestion contorl is TP-DCC > DCC > DR-DCC > DCC-3 > No DCC.

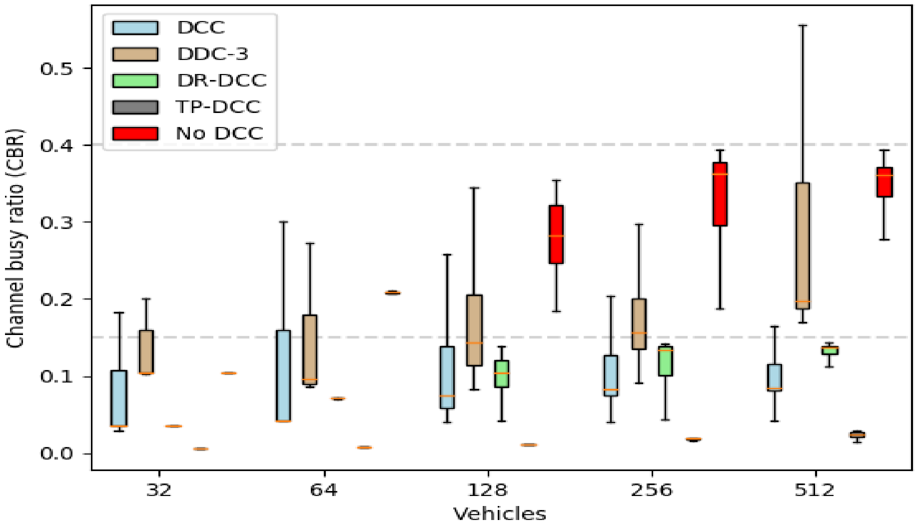


Figure 6.1: CBR performance of algorithms

In Figure 6.2, TP-DCC, DR-DCC, and No DCC almost overlap with each other, because all of them are utilizing 10Hz beaconing frequency. Hence, they stay at the similar IRT levels around 0.1s. This immediately reflects that both TP-DCC and DR-DCC can perfectly adapt IRT for all vehicle densities while there is a little bit increment of No DCC control mechanism with 512 vehicles. Compared with DCC, No DCC performs better at IRT performance, because the latter one is using a fixed 0.1s beaconing interval while the former one will increase its message generation interval if the channel congestion condition reaches to a predefined threshold. In other words, DCC of decreasing CBR is at the cost of increasing IRT, because it reduces the message generation frequency. More specifically, Figure 6.3 shows how DCC will dynamically change the intervals in the case of 32 vehicles. Can be observed that, most of the time, the state machine stays at ACTIVE state, that is 2Hz. Corresponding to this, the 95th percentile of IRT is approximate 0.5s. To reduce IRT for DCC mechanism, a potential remedy is to introduce extra sub-ACTIVE states (DCC-3), aiming to provide more potential probability for staying at low frequency states. As expected and shown in Figure 6.2, DCC-3 performs better than DCC at 32, 64 and 128 vehicles cases, because of extra ACTIVE states introduced and the state machine is more likely to stay at a lower frequency state. Figure 6.4 reveals the status over time going of state machine of DCC-3. As expected, instead of jumping directly to a 0.5s, this mechanism will have changes to stay at the lower states of 0.1s or 0.3s, therefore, this phenomenon will help to improve the IRT performance to some extend. However, we unfortunately to see that DCC-3 may cause some other underlying problems since the IRT level can jump to 1s at 512 vehicles. Up to 1s of IRT is not stable enough to ensure the safety of Platooning, therefore, introducing sub-ACTIVE states is a good solution or not needs additional researches. But at least, if the simulating number of vehicle is not greater than 256, this mechanism works better than the standard DCC.

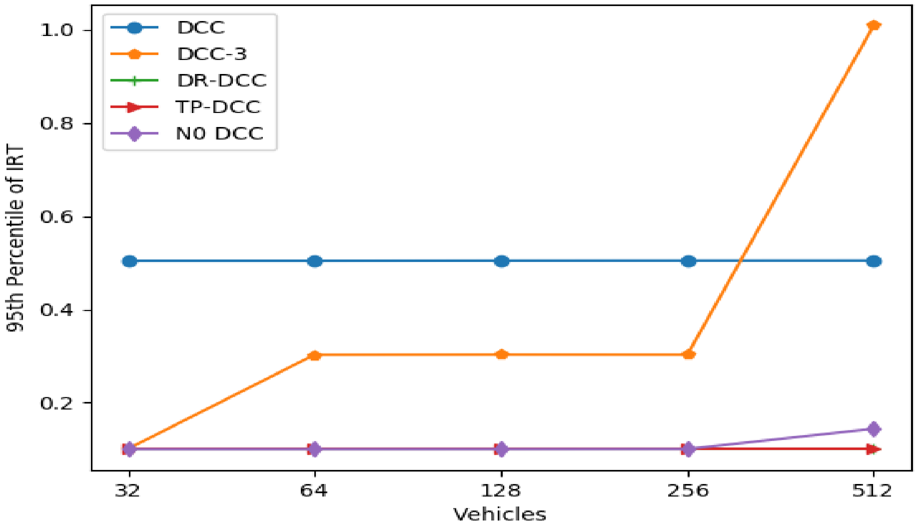


Figure 6.2: IRT performance of algorithms

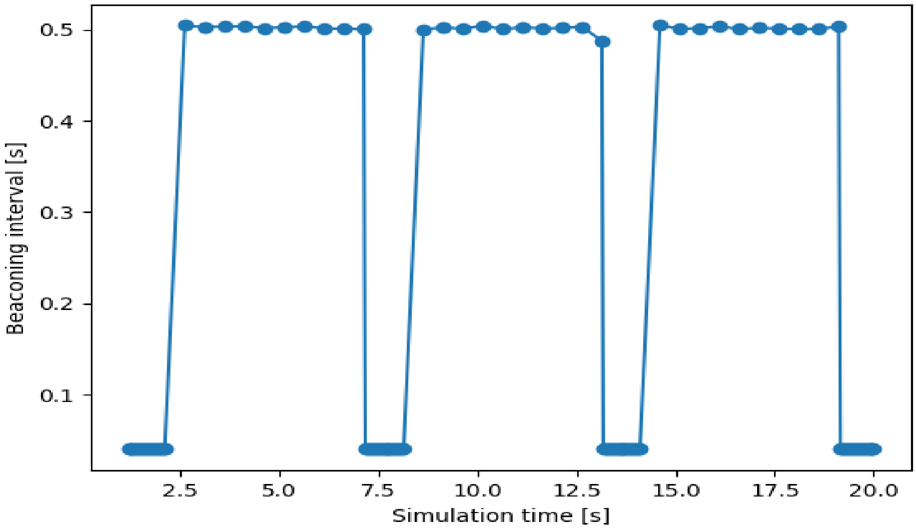


Figure 6.3: Beaconing states of a node at 32 vehicles case of DCC

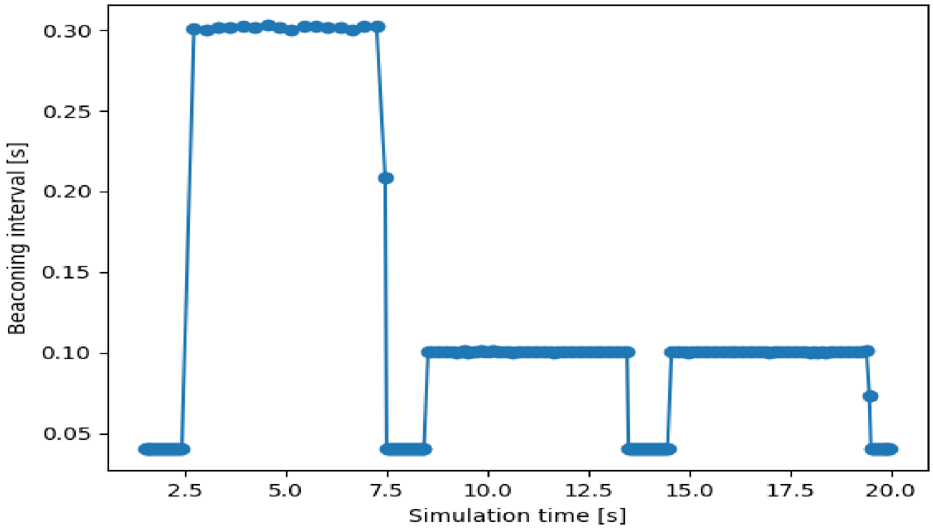


Figure 6.4: Beaconing states of a node at 256 vehicles case of DCC-3

Figure 6.5 shows the PRR performances of various algorithms. Apparently, the PRR performance can be ranged as TP-DCC > DCC-3 > DCC > No DCC > DR-DCC. The result shows that DR-DCC has the worst performance of PRR, though it performs well in controlling CBR and IRT. The reason for this is that DR-DCC will switch to higher datarate option when the channel is congested, however, the increased datarate has a significant influence on interference, and thereby cause packet collision and packet loss.

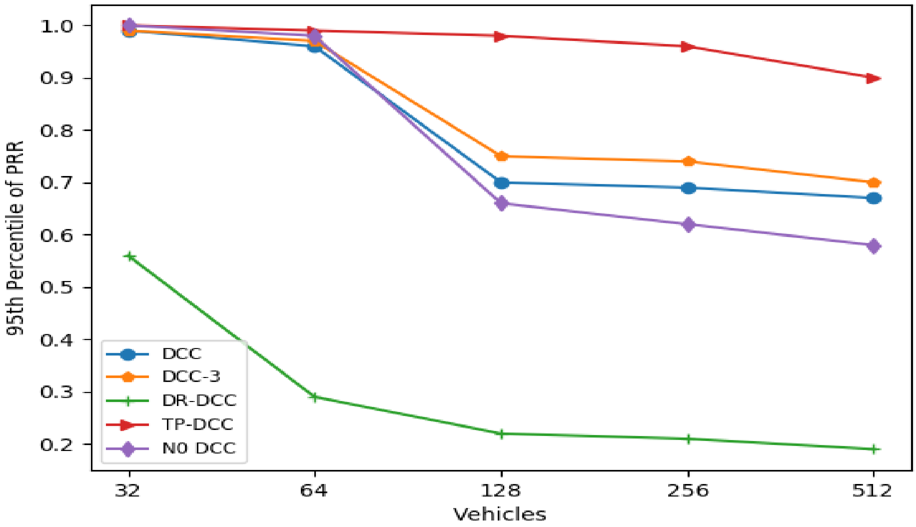


Figure 6.5: PRR performance of algorithms

As known from the results above, we know that decreasing transmission power can lead to better performances. Hence, with changing the transmission power to 0.1mW of DCC, DCC-3 and DR-DCC, we rerun all the simulations. The results are presented in the Figure 6.6, 6.7, and 6.8. In Figure 6.6, we re-rank the control ability of CL as: TP-DCC > DR-DCC > DCC > DCC-3 > No DCC. The ranking is similar with using 1mW scenario. Based on this ranking, we further investigate on IRT and PRR performances. In Figure 6.7, both TP-DCC, DCC-3, and No DCC have best performance, while DR-DCC still performs worst in IRT. In Figure 6.8, the ranking is still the same as Figure 6.5.

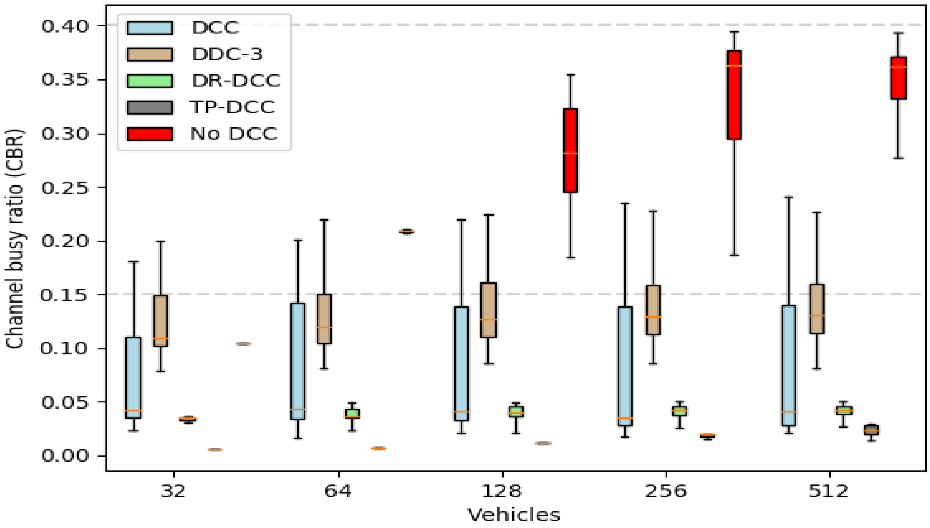


Figure 6.6: CBR performance of algorithms utilizing 0.1mW power

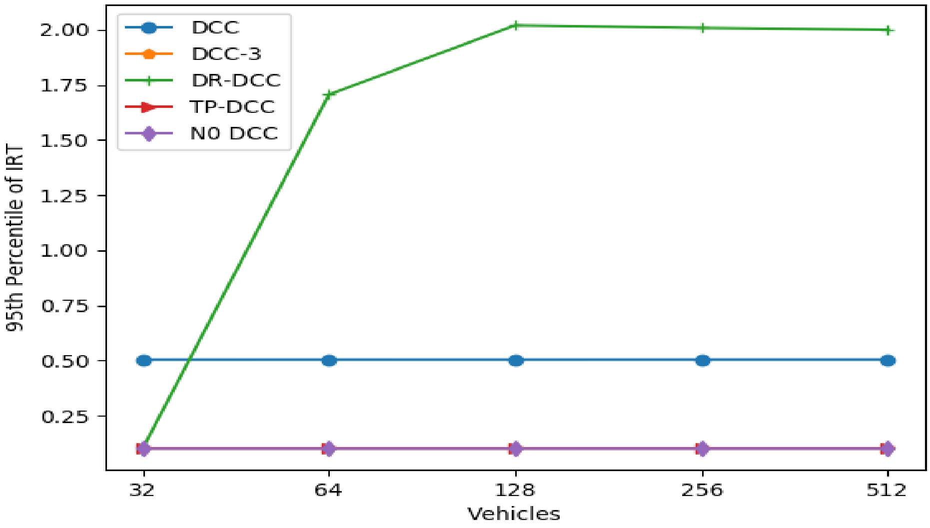


Figure 6.7: IRT performance of algorithms utilizing 0.1mW power

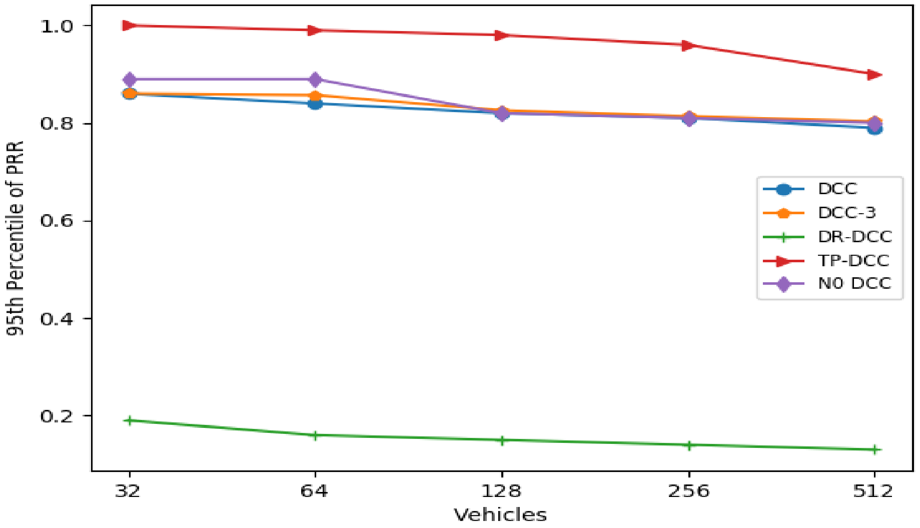


Figure 6.8: PRR performance of algorithms utilizing 0.1mW power

Figure 6.9, 6.10, and 6.11 present a better insight of how transmission power affects the performances of DCC, DCC-3 and DR-DCC algorithms. Generally for all cases, decreasing transmission power to 0.1mW can help to get better performances of CBR, IRT or PRR.

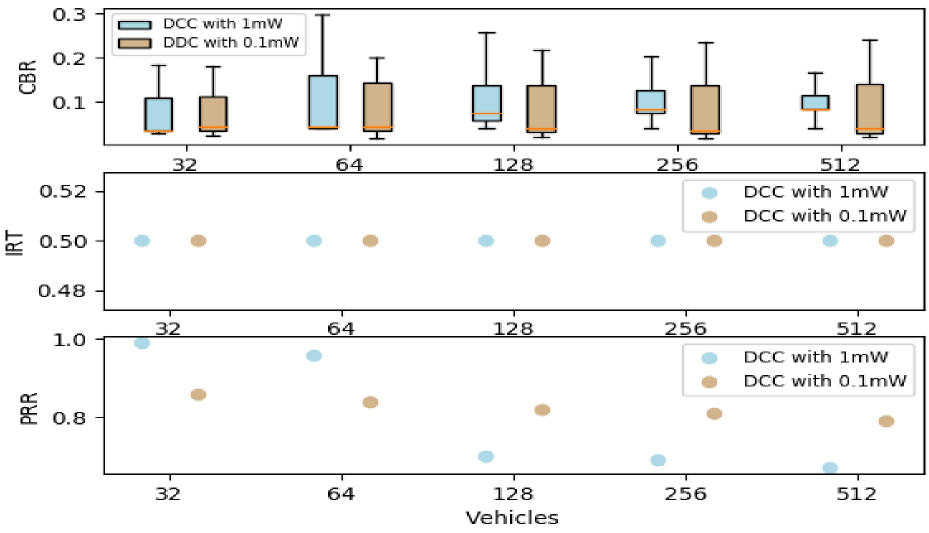


Figure 6.9: Comparison between DCC with changing power

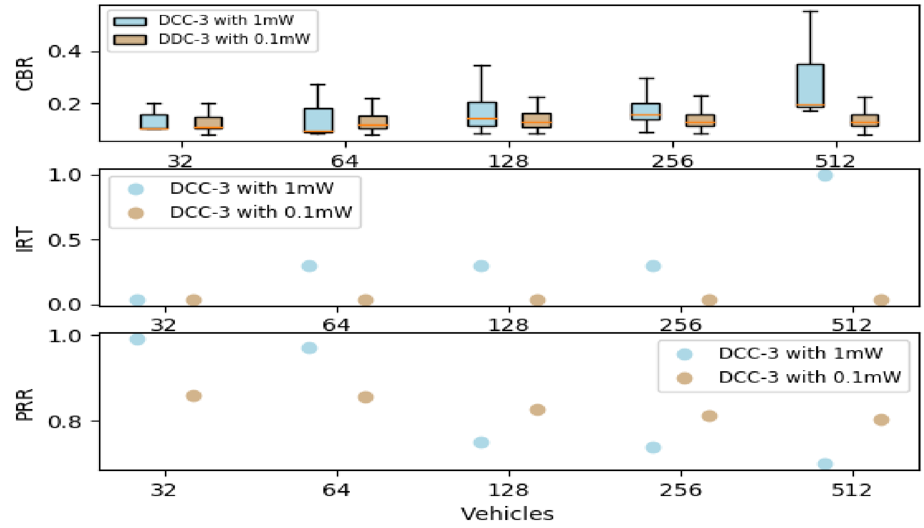


Figure 6.10: Comparison between DCC-3 with changing power

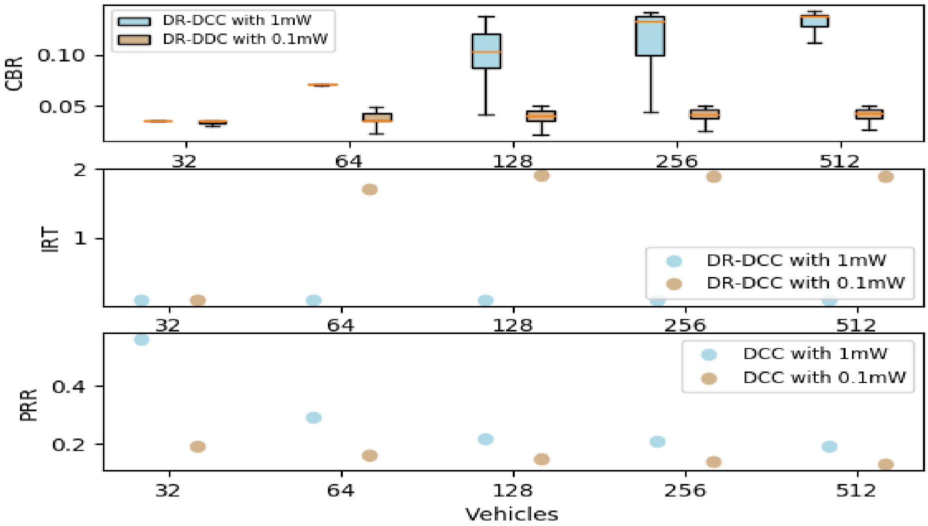


Figure 6.11: Comparison between DR-DCC with changing power

So far, we conclude that TP-DCC has the most benefits for Platooning congestion control based on the MAC layer metrics performance. Figure 6.12 shows the changing of CBR over time with using TP-DCC algorithm. Can be observed that, even at vehicle quantity of 512, CBR stays at low CBR levels, and the maximum CBR of 20s simulation duration is only around 0.03. This immediately shows TP-DCC is capable of channel congestion control. To demonstrate this, we further to analyze the metric IVD which is on the application layer. Given an initial IVD as 5m, the simulation results in Figure 6.13 present the IVD fluctuation of a same node during 20 seconds. According to Figure 6.13, TP-DCC has the best stability since it provides the minimum fluatuation of IVD, thanks to it can provide lowest CBR, IRT and highest PRR performance against other algorithms.

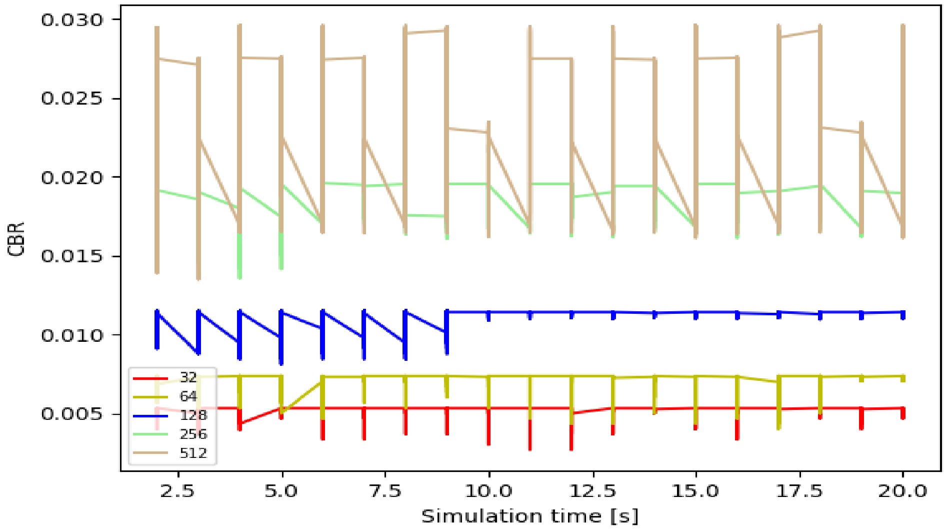


Figure 6.12: CBR over time of TP-DCC

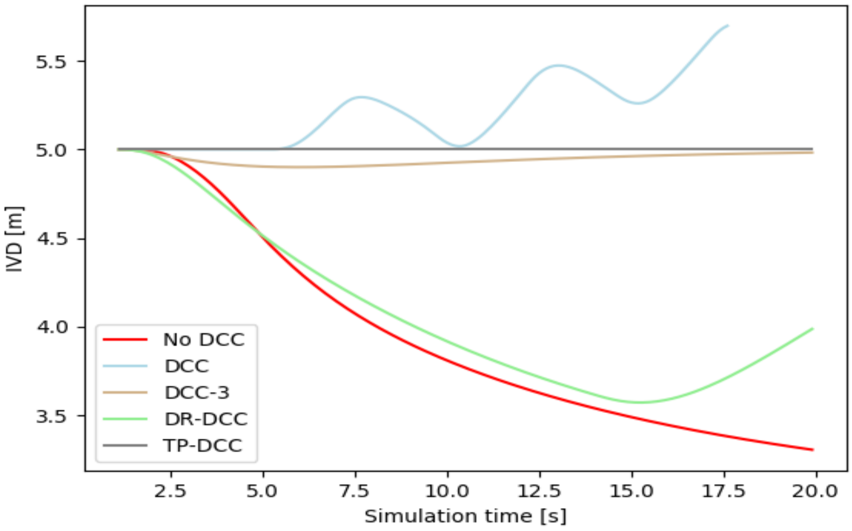


Figure 6.13: Inter vehicle distance fluctuation of a node for various algorithms

Chapter 7

Conclusion

Channel congestion control is the main challenge of vehicular networks. Clearly, CBR can be decreased by adjusting any of the control parameters such as message generation rate, datarate or transmission power. However, the adjustment of a single parameter, or a combination of them, can result in different performances. In this thesis, we focus of analyzing three parameters in order to design dedicated algorithms for each parameter. Meanwhile, on top of some existing works, we proposed and compared DR-DCC, TP-DCC, and DCC-3 algorithms which are specifically used for Platooning system. Through a series of comprehensive comparison, we highlight several points as following:

- First of all, among reactive approaches, dynamic power control has the best performance. Based on the results carried out, we suggest TPC approach of DCC mechanism for platooning congestion control;

- High transmission datarate can decrease CBR by shortening the air transmission time, however, there is still need to trade off together with PRR. According to the results, using higher datarate results in lower PRR which may affect the stability of Platooning system;

- For static datarate control, in this work, we suggest to utilize 6Mbps for vehicular communication. The reason is that in 3Mbps scenarios, the overall CBR level at 256 vehicles is high, specifically, this level can reach 0.72 in the case of 512 vehicles which the channel is considered as extremely congested. Another reason is that, compared with 9Mbps and 12Mbps, the PRR performance is better, besides, if dynamic changing datarate, that is using DR-DCC as the control mechanism, it will suffer low PRR issue as presented in Figure 6.5 and 6.8. Hence, by integrating the information, 6Mbps is the best option over the given choices;

- Introducing extra sub-ACTIVE states is the remedy of IRT performance of DCC algorithm when the number of attending vehicles are not greater than 256.

Chapter 8

Future work

This thesis evaluates and optimizes the control parameters of reactive DCC mechanism. Though the conclusion has suggested the best algorithm for Platooning systems, however, we still need additional investigation on DCC control mechanisms.

Firstly, one of the limitations of this thesis is that only a sinusoidal mobility scenario is evaluated, hence, the first future work is to evaluate different scenarios such like braking or acceleration scenarios. Moreover, due to the equipment limitation, simulations of larger number of vehicle should be performed.

The work suggests TP-DCC is the optimal channel control method for Platooning, however in our future work, we still need to investigate on the relationship among transmission power, interference distance, path loss and signal strength in wireless transmission environment.

Besides, this work only evaluates the DCC reactive approach, hence, for future works, we are interested in adaptive approaches such like LIMERIC. The further comparison between optimized reactive approaches and adaptive approaches is interested.

All in all, DCC control framework needs more investigations and extensions. Finally, the control strategies should not be just stay at the simulation phase, it should step forward into the real world.

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